LCA FOODS

PUCP

13TH International Conference on Life Cycle Assessment of Foods

11-14 October
Hybrid venue at Open PUCP
Lima, Perú

"The Role of Emerging Economies in Global Food Security"

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Flanders State of the Art

Especialidad de Ingeniería Ambiental y Sostenible

LCA FOODS

Book of proceedings

13[TH] INTERNATIONAL CONFERENCE ON LIFE CYCLE ASSESSEMENT OF FOOD

11 - 14 October

Lima, Perú

2022

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PUCP

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WELCOME

¡Bienvenidos a LCA Foods 2022 en Lima, Perú!

Welcome to LCA Foods 2022 in Lima, Peru!

"The Role of Emerging Economies in Global Food Security"

Lima is hosting in October 2022 the world's leading scientific and technical forum on Life Cycle Assessment linked to the food sector. The 13th edition of the conference arrives as the first fully hybrid edition of the event, after the forceful virtual conference that had to be held in Berlin in 2020 during the COVID-19 pandemic. Despite the setbacks due to the pandemic, Berlin provided a high quality conference in which the number of attendees was comparable to past events. Two years later, distancing is no longer an obligation as it was in the first months of the pandemic. Hence, we are now hosting an edition in which many of us are eager to meet up in-person after 4 full years since we last met in Bangkok for the 11th edition of the conference; however, the virtualization of conferences worldwide showed us that another way of interacting with our colleagues is possible without having to travel thousands of miles to meet those experts that we wish to discuss science with. This led to the conundrum regarding what Lima, the gastronomic capital of the Americas, should offer participants in this edition. The thirst for in-person interaction, offering a low-carbon event in line with what should be expected in a environmentally-centered conference, the need for countries like Peru to participate in the global flow of scientific knowledge and discussion or the fact that the conference travels for the first time to Latin America and the Caribbean were all aspects that we discussed for the past two years in order to determine what type of conference we should offer.

Finally, we have managed to offer a hybrid conference in which we are happy to share an online platform through which we will all unite for 4 full days. When this proceedings book was sent out for publication, over 210 participants had confirmed their attendance from approximately 40 countries worldwide. Approximately 45% will also be joining us physically at Open PUCP in Lima.

Life Cycle Assessment (LCA) is currently one of the most commonly used and scientifically robust environmental management methodologies to determine the environmental profile of products and services. Although its applicability is vast, with notable research in most productive sectors, the agri-food sector has benefited undoubtedly thanks to LCA-related research. In this context, the aim of the 13th edition of the LCA of Foods Conference is to continue with the work done in previous editions of the conference by creating a space for the LCA community to share and discuss about their advancements, foster networking between research groups and industries on a global scale and provide a space for LCA practitioners and developers to exchange ideas on methodological developments. Moreover, in this case we want to introduce policy-makers and industries in the Latin America – Caribbean region to the world of LCA, allowing them to meet the LCA community.

The consolidation of LCA methodologies in the agri-food sector coincides with food security arising as one of the major global challenges for the 21st century. Objectives such as zero hunger and the reduction of poverty and extreme poverty will only be attained if humanity is capable of improving the sustainability of diets, combining environmental issues with social and health needs. For this to be possible, dietary patterns should continue their transition to low carbon choices in the developed world, but changes are also needed in developing and emerging nations. This implies that improvements in terms of environmental impact mitigation must be attained in a number of sectors, including livestock, fisheries, aquaculture and agriculture, but also in the increasingly complex processing and freighting supply chains that have developed through globalization.

We expect that these and other topics will be presented and discussed in Lima for three full days. The workshops planned for Day Zero (11 October) should also be a nice complement to the activities in the main programme. We have also prepared a Special Issue in the International Journal of Life Cycle Assessment. Approximately 20 oral presentations linked to the main topic of the conference have been invited to submit a manuscript to this call, although submission is also open for other manuscripts.

Finally, on behalf of the Organizing Committee, I would like to thank the authors for their presentations and posters. We are also very grateful to the 24 members of our Scientific Committee for their efforts in reviewing the abstracts and selecting the papers for oral presentations. We warmly thank our sponsors for supporting the conference. Last but not least, I would like to thank all those from the PUCP community, especially the members of the Peruvian LCA & Industrial Ecology Network (PELCAN), for their essential contribution to the success of the conference.

We hope that you all have a lovely experience in Lima and Peru during the conference. For those of you who will be traveling around the country in the days before or after the conference, you will visit some of the most beautiful places in Latin America. We hope that the small taste of the Peruvian cuisine that you will get in lunches and the Gala Dinner at the conference will complement this experience.

IAN VÁZQUEZ ROWE
LCA Foods 2022 Chair

LCA Foods Committees

Scientific Committees

Cécile Bessou	CIRAD. France
Leda Coltro	Institute of Food Technology, Brazil
Michael Corson	INRAE, France
Ulrike Eberle	corsus-corporate sustainability GmbH, Germany
Shabbir H. Gheewala	Joint Graduate School of Energy and Environment, Thailand
Kiyotada Hayashi	NARO, Japan
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Diana Ita Nagy	Pontifical Catholic University of Peru, Peru
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Ramzy Kahhat, Co-chair	Pontificia Universidad Católica del Perú, Peru
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María Margallo	Universidad de Cantabria, Spain
Jara Laso Cortabitarte	Universidad de Cantabria, Spain

PELCAN PUCP TEAM

PROGRAMME OVERVIEW

DAY ZERO

Tuesday, October 11, 2022

9:00 am - 1:00 pm	*Dr. Juan Pablo Chargoy (Mexico)* Fundamentals on SimaPro	*Dr. Olivier Jolliet (U of Michigan)* Introduction to the HENI Index	*Dr. Elena Corella Puertas (CIRAIG/ UNEP)* Launch of the UNEP supermarket food packaging LCA META Analysis	*Dr. Ulrike Uberle (Germany)* The main environmental impacts of foods and levers for sustainable production systems
1:00 pm - 2:00 pm	BREAK			
2:00 pm - 4:00 pm	*Dr. Juan Pablo Chargoy (Mexico)* Parameters on SimaPro	*Dr. Sarah McLaren (New Zealand)* Workshop on nutritional LCA		*Dr. Jan Paul Lindner (Germany)* Workshop aquatic Biodiversity Valuing and Valuation
4:00 pm - 5:00 pm				
5:00 pm - 6:00 pm				

DAY 1

Wednesday, October 12, 2022

7:30 am - 8:30 am	WALK IN REGISTRATION			
8:30 am - 9:00 am	OPENING WORDS			
9:00 am - 10:00 am	*José Luis Chicoma (Peru)* Keynote Speaker - "Building strength for food crises"			
10:00 am - 11:00 am	*Peter Tyedmers (Canada)* Keynote Speaker - "Seafood sustainability: achieving the promise while avoiding the pitfalls"			
11:00 am - 11:30 am	MORNING COFFEE BREAK			
11:30 am - 1:00 pm	Parallel Session I (eco-labelling)	Parallel Session II (Sustainable farming systems I - Dairy)	Parallel Session III (Sustainable farming systems - Other meats & eggs)	Parallel Session IV (Rural communities)
1:00 am - 2:30 pm	LUNCH: Open PUCP *(Marine)*			
2:30 pm - 4:00 pm	Parallel Session V (Databases, toolboxes and others)	Parallel Session VI (Fisheries & aquaculture)	Parallel Session VII (Sustainable farming systems II - Nutrients & soil)	Parallel Session VIII (LCIA methods)
4:00 am - 4:30 am	AFTERNOON COFFEE BREAK			
4:30 am - 6:00 pm	Parallel Session IX (Marine plastics & Miscellanea)	Parallel Session X (NEPTUNUS Special Session)	Parallel Session XI (Crops)	Parallel Session XII (Viticulture, wine & others)
7:00 pm	Bus from OpenPUCP to "Museo Larco" Welcome toast and dinner at "Museo Larco"			

DAY 2

Thursday, October 13, 2022

7:30 am - 8:30 am	WALK IN REGISTRATION			
8:30 am - 10:00 am	Parallel Session XIII (meals and other)	Parallel Session XIV (Water Scarcity)	Parallel Session XV (Sustainable Farming Systems III - Livestock)	Parallel Session XVI (Aquaculture
10:00 am - 11:00 am	*Assumpció Antón (Spain)* - Keynote Speaker "25 years of LCA Food, Does LCA serve for the improvement of agricultural sustainability?" (virtual)			
11:00 am - 11:30 am	MORNING COFFEE BREAK			
11:30 am - 1:00 pm	Parallel Session XVII (Nutrition and LCA)	Parallel Session XVIII (HESTIA Special Session)	Parallel Session XIX (Sustainable Farming Systems IV - Crops)	Parallel Session XX (Sustainable Farming Systems V - Livestock)
1:00 am - 2:30 pm	LUNCH: Open PUCP *(Andean)*			
2:30 pm - 4:30 pm	Parallel Session XXI (Miscellanea I)	Parallel Session XXII (Miscellanea II)	Parallel Session XXIII (Spanish Session)	Parallel Session XXIV (Sustainable Farming Systems VI - Miscellanea)
4:30 am - 6:00 pm	POSTER SESSION (in-person only) - *An online session will be available throughout the conference*			
7:00 pm	Scientific Committee Side Event			

DAY 3

Friday, October 14, 2022

7:30 am - 8:30 am	WALK IN REGISTRATION			
8:30 am - 9:00 am	*Olivier Jolliet (U Michigan, US)* - Keynote Speaker "Why Food LCA should always consider nutritional impacts during use phase!"			
9:30 am - 10:30 am	*Maryam Rezaei (FAO, Egypt)* - Keynote Speaker "Potential of nLCA in supporting policy making to transform agri-food systems – An FAO perspective" (virtual)			
10:30 am - 11:00 am	MORNING COFFEE BREAK			
11:00 am - 1:00 pm	Parallel Session XXV (LCA in tropical contexts)	Parallel Session XXVI (Diets)	Parallel Session XXVII (MCDA)	Parallel Session XXVIII (Food Loss and Waste)
1:00 am - 2:30 pm	LUNCH: Open PUCP *(Pan de la Chola)*			
2:30 pm - 3:30 pm	*Melissa D. Ho (WWF, US) - Keynote Speaker "Towards a regenerative and resilient food systems transformation: Can we measure what success looks like and what is the role of an LCA approach?"*			
3:30 am - 4:00 pm	CLOSING CEREMONY			

GENERAL INFORMATION

Registration

The registration fees include:

In-person registration
- Admission to all conference sessions, poster sessions and the exhibition area.
- A conference bag, including your badge, a booklet and a pen to take notes and organic Peruvian chocolate.
- Welcome reception and Gala dinner: cocktail and dinner on 12 October, 19.00 hours
- Lunches: 12, 13 and 14 October
- Refreshments during session breaks
- Access to the International workshops offered on 11 October.
- Admission to all conference sessions and poster sessions throughout the three days through the online platform.
- Access to the International workshops offered on 11 October (online).
- Access to the online platform for 15 days after the conference.

Upon registration you will receive a badge to be worn during the conference.

Online registration
- Admission to all conference sessions and poster sessions throughout the three days through the online platform.
- Access to the International workshops offered on 11 October (online).
- Access to the online platform for 15 days after the conference.

Arrival at the airport in Lima

Please make sure you have proof of your Covid vaccine. Your passport should be valid for at least an additional 6 months; otherwise this could be an issue entering the country. You will also need to fill in this document to show at customs.

Customs at Lima airport are tricky due to delays, so expect a 15-45 minutes wait before you enter the country. If prior to the conference you've got a connecting flight to go to Cusco/Machu Picchu or some other destination, make sure there is plenty of time between each flight, as in all cases you go through customs in Lima. If you need to stay a night close to the airport, we recommend the Wyndham-Costa del Sol Lima Airport Hotel.

Exchange rate

The Peruvian Sol is quite a stable currency in Latin America. 1 USD is currently roughly 3.9 soles, and 1 EUR is about 4 soles. Do not change money at the airport or in banks. You are much better off at the "Casas de Cambio" you'll find in every corner. Food and taxis are cheap, but you may find that imported goods are more expensive than in your home countries.

Climate

October should be warm (approximately 20 or 22°C during the day) and fresh (16°C) at night. However, please note that we are under the effects of La Niña, which could lower temperatures by a couple of degrees. We recommend you bring a warm jumper for the evening activities. Don't expect it to be very sunny in October, although if we are lucky we may get some sunny days during the conference. It doesn't rain in Lima, so unless you are also travelling to the Andes or the Amazon, you don't need an umbrella or raincoat

Taxis at the airport

To get to Miraflores, Barranco or San Isidro, we do not recommend taking an Uber from the airport. It is much better if you stick to the taxi companies that offer services to the city once you pass the baggage collection area (Taxi Green or Direct Taxi are some of the companies you'll see at the desks). The cost of a taxi to Miraflores should be around 60 or 75 soles.

Hotels

Please find attached an Excel file with a list of hotels in the districts of San Isidro and Miraflores. All these hotels have a special rate with our University (PUCP), so if you decide to book with them just make sure you let them know you are attending a conference organized by PUCP.

Plugs

Peru has a hybrid system with American and European plugs in most places. At our venue there are plenty of plugs for laptops and there is a special classroom booked for those of you who need to keep up with your email or connect to other Zoom events.

Moving around town

For moving around the city, we recommend you download Uber or Cabify. They are safe options, especially at night. Public transport in Lima is chaotic, slow and frustrating, but if it is your first time in Lima you may find it an adventure worth trying!

Venue

The conference will be held in OpenPUCP, premises that belong to our University, but are located in a shopping mall called Plaza San Miguel, which is next to the University Campus.

Family

Let us know in advance if you are travelling with your spouse/partner/child/friend so that we can give them tips for visiting the city. If you would like them to attend the Gala Dinner, please let us know.

Dining in Lima

Lima hosts some of the best restaurants in the world. Central, in Barranco, is currently ranked #2 in the world, Maido #11 and Mayta #32. Central is an expensive restaurant, but substantially cheaper than top-10 restaurants in Europe, so if you want to splash out you should book in advance. There are plenty of other options in town, especially in Miraflores and Barranco.

Food at the conference

Remember we are offering lunch the 3 days of the conference and on Day 1 we have a Gala Dinner at the Museo Larco, one of the most beautiful museums you'll find in Latin America. We are making sure that the food at the conference allows you to taste some of Peru's famous cuisine, but we are also trying to make it low-carbon and sustainable!

COVID-19

Peru has suffered a lot with the pandemic, as you may have seen in the news. Therefore, do not expect masking mandates to be as flexible as they are in Europe or North America at the moment. The good news is that no masks are needed outdoors, restaurants or bars, but in most indoor spaces you will be required to use one. We are expecting mask mandates to be dropped in the education sector before the end of the month, which would make things more flexible at our venue, but it is still not official at the moment.

Excursion to a fishmeal plant

We are organizing an excursion to a fishmeal plant in Callao, 15 km north or Miraflores/Barranco on Saturday (October 15th). Whenever we have more information, we will share it with you.

Machu Picchu

Traveling to Cusco, Machu Picchu and the Sacred Valley is an incredible experience. We recommend you buy tickets for the Sanctuary in advance, as well as the train that takes you from Cusco or Ollantaytambo to Aguas Calientes/Machu Picchu. There are many other wonderful destinations you can visit: Choquequirao, Arequipa, Iquitos, Manu National Reserve, Tambopata are just a small bunch of amazing places you can explore. If you want to fit in a beach and sun vacation before the Northern hemisphere's winter, Máncora and Tumbes in the North have some lovely hotels and beaches!

WhatsApp hotline at the conference

We are opening today a WhatsApp account for you guys to contact us for specific questions on different issues, including paperwork to enter the country, travelling information, etc. The number is +51-945656457 and Eizo Muñoz, our Conference Secretary, will be the person in charge of responding.

Participation certificate

Digital participation certificates will be delivered to all participants by October 25th 2022.

Internet access

Free access to the Internet is available through our University WiFi. The username is RED PUCP and the password to get access is C9AA28BA93.

OPEN PUCP

01 Oral Session Day 1

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01 Oral Session Day 1

OptiSignFood: developing more sustainable food products through artificial intelligence

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Introduction

The challenge to meet the UN sustainable development goals (https://sdgs.un.org/) and to bring our food system back into the limits of the planetary boundaries requires concerted efforts at all stages of the food value chain. Furthermore, there are 2 billion obese or overweight people worldwide, while ~800 millions suffering hunger or malnutrition (FAO *et al.*, 2021).

The food industry plays a key role in this respect and can contribute to the mitigation of the environmental impacts of the food system in several respects: 1) by using ingredients with low environmental burdens, 2) by reducing the environmental impacts of processing, packaging, storage, and transports, and 3) by offering a product basket to the consumers with low environmental impact, high nutritional value, high quality, which is at the same time safe, tasty, and attractive.

The challenges for the food industry are that the food development process is time- and resource-intensive, information on environmental impacts is either missing or not readily available, the nutritional value, food safety and quality (e.g. microbial growth, pH value, colour, texture) are difficult to predict. Food developers therefore face a multidimensional optimisation problem, with high complexity and many parameters to be considered. There is a need for a tool providing an integrated, fast and reliable solution that takes into account nutritional, sensorial, safety, health and environmental parameters. The EU project OptiSignFood (https://themakers.ai/optisignfood/) is currently developing such a tool.

Methods

The model builds on scientific data and uses artificial neural networks to solve the multidimensional optimization problem. Food quality parameters are being estimated based on product samples derived from different ingredient mixes. The software is implemented as a cloud application using a modular architecture. The overall concept of the model is shown in Fig. 1.

Environmental impacts

Environmental impacts of food ingredients are calculated using life cycle assessment methodology. Life cycle inventory data from five databases (ecoinvent, Agribalyse, WFLDB, Agri-footprint and SALCA) will be used. Life cycle inventories will be selected according to data quality criteria according to the ISO 14040/44 standards. The data will be prepared, harmonized, adapted (e.g. adjusting system boundaries, electricity mixes or transports) and standardized for integration into the meta-database. For missing data, new life cycle inventories will be created or proxies will be used to approximate the environmental impacts according to the procedure described in Milà i Canals *et al.* (2011). The environmental impacts from the different inventories will be aggregated in case there exist more than one inventory. Three sets of impact categories specific for life cycle impact assessment in the agri-food sector are proposed for impact assessment of the LCI data.

- The restricted set considers a selection of the six most important impact categories for food LCA according to Nemecek *et al.* (2011).
- The full set considers all impact categories of relevance to agricultural systems within the SALCA framework. The SALCA impact assessment method is intended for the LCIA in the agri-food sector.
- The PEF compliant set considers the impact categories given by the EU guideline to assess the environmental footprint of a product (European Commission (EC), 2013).

Data gaps (= missing food ingredients) will be identified by comparing the LCI in the databases with the food ingredients in the EuroFIR database. To guarantee a successful integration of the environmental data into the meta-database, LCI data and their respective impacts will be linked to the food ingredients from the EuroFIR database. This is done by applying LanguaL codes and the FoodEx2 food classification system which help to index and describe food products (Møller & Ireland, 2018).

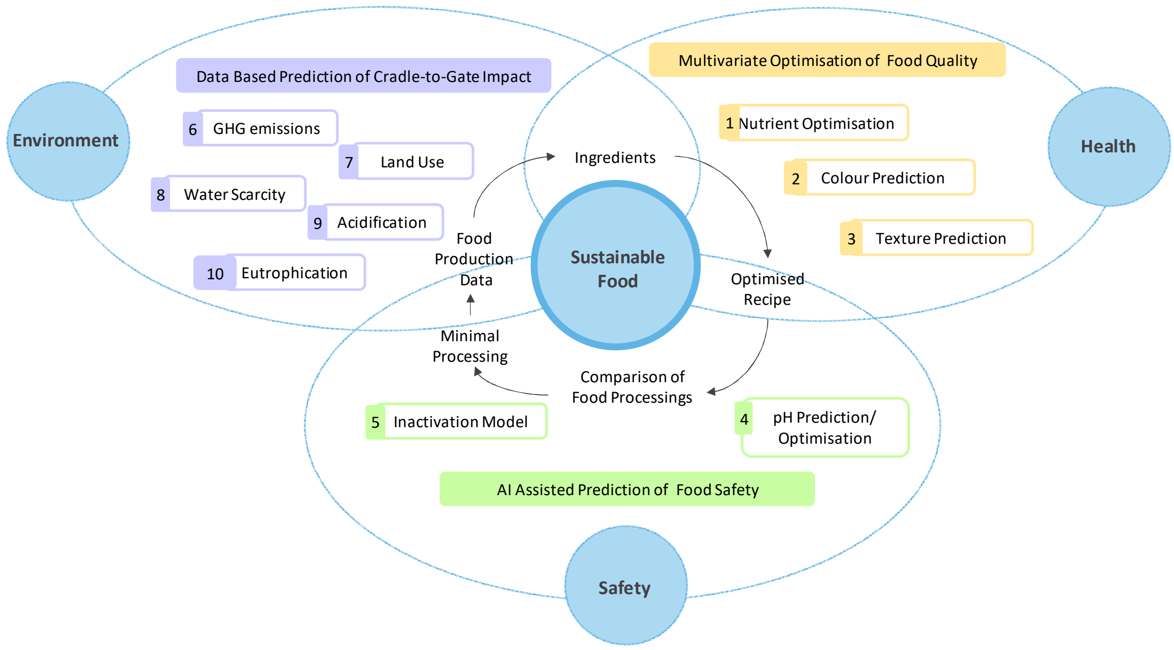

Fig. 1: Concept of the OptiSignFood tool for the food and beverage industry.

Nutritional indices

Nutritional indicators are used to assess the nutritional quality of foods products. They are based on the concept of nutrient profiling, a ranking system to classify foods based on their nutritional composition relative to nutrient needs of qualifying nutrients (nutrients to encourage) and disqualifying nutrients (nutrients to avoid or limit) (Fulgoni *et al.*, 2009). For this project, the EuroFIR database (https://www.eurofir.org/) is used to determine the nutrient contents of different food ingredients. As each nutritional indicator takes into account different nutrients, the values of each indicator might rank foods differently. In addition, some nutritional indicators require a large set of nutrients that might not be available in the EuroFIR database. In this case, when the missing nutrient is not essential for the target population, a modified/adapted nutritional index will be used but if the nutrient is relevant for the target population, proxies from other databases will be included. One aim of the OptiSignFood project is to link and standardize robust, strong and valid nutritional composition datasets from different EuroFIR countries that will allow for better calculations of the nutritional indicators.

The main objective to include nutritional indicators in the OptiSignFood project is to be able to optimize the production of new or modified food products based on the principle that foods with better nutrient profiling scores, encourage healthier diets than those with lower nutrient profile values. However, this has been debated as some reformulation procedures just decrease disqualifying nutrients and increase qualifying nutrients, but might not be synonym of an overall healthier diet. Still, when assessing individual foods or specific food mixtures, nutritional indices help the food industry produce foods with better profiles and the consumer to choose more nutritious options that will at the end increase the overall nutritional content of the diet. In addition, some indices are being associated to health outcomes, such as the Health Nutritional Index (HENI), which will be used in the optimization model, and considers dietary risk factors based on the global Burden of Disease Study (Stylianou *et al.*, 2021).
To facilitate the comparison between different food products, different nutritional indices will be included in OptiSignFood (e.g NRF9.3, Nutri-Score, etc.). The aim is to include not only nutrient information (e.g. grams of nutrients, kilocalories or percentages of daily recommended intakes), but also nutrient indicators that will: 1) help the food industry produce more nutritious foods; 2) enable consumers to evaluate the contribution of a food product to a healthy and balanced diet considering its nutritional composition and; 3) to compare food products of the same category and choose a healthier option.

Database harmonization and standardization
A particular challenge is to link the nutritional, life cycle inventory and the laboratory parameter databases, since all databases use different classification systems and data structures. Figure 2 shows examples of different type of information for food ingredients available in the databases, which need to be connected in between databases.

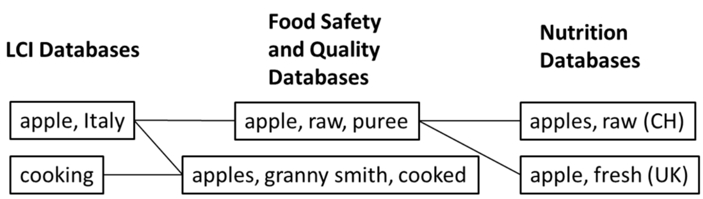

Fig 2: Type of information for food ingredients available in the databases

Different wording (apple vs. apples; raw vs. fresh) and sometimes missing information on the status or processing of the food ingredient in the databases render a connection by names tedious. Additionally, certain information (e.g. cooking/cooked) is sometimes part of the food ingredient, but sometimes embedded as standardized code. To overcome this challenge, the LanguaL standardization system will be applied to the food ingredients in order to standardize the names of the food ingredients consistently. The LanguaL food description thesaurus (https://www.langual.org/) provides an automated method to describe, capture and retrieve food-related data and will be used for this purpose. The EuroFIR nutritional database will serve as a backbone for the meta database and has already LanguaL codes implemented and connected to food ingredients. Other databases (environmental and parameters database) will be connected to the EuroFIR database. Already implemented LanguaL codes in EuroFIR should serve to facilitate the connection of the databases. However, due to inconsistent application of the LanguaL system, the assignments of LanguaL codes to the food ingredients in the EuroFIR have to be checked and validated.

Results and discussion
The EuroFIR databases for different countries differ not only in the number of nutrients considered, but the values can also differ considerably between databases for the same nutrient. A data

harmonization is therefore needed. Environmental impacts also differ and depend on the country of origin, the production system, and the yield level. Representative environmental impacts are calculated for the European food and beverage market.
As a first step, LCI data of food ingredients have been organized, structured and classified into the EFSA FoodEx2 classification system by assigning LanguaL codes. The first overview shows that there are more than 15'000 food LCI out of roughly 42'000 LCI datasets available from selected LCI databases (35%) which can be grouped into 21 different food categories. Those 15'000 inventories cover a total of 952 different and individual food ingredients.
The prediction of the model will be validated in real environments by food and beverage manufacturers.

Information provided to the users
Figure 3 shows the first layer of the design of the software. The user can choose ingredients and their amounts and can see the prediction of a set of the basic parameters and the legally important nutrient values. We are also working on implementing a nutrition and an environmental score, like the Nutriscore. From this general overview, the user can switch to the optimization window where the recipe composition can be optimized based on these and other parameters. We are also planing a window where the parameters of different compositions can be compared with each other. Currently, we are designing another window for the environmental impact of the food composition, which needs a separate tab, since it is multi-dimensional and has several parameters to be calculated and also needs a higher degree of input from the user.

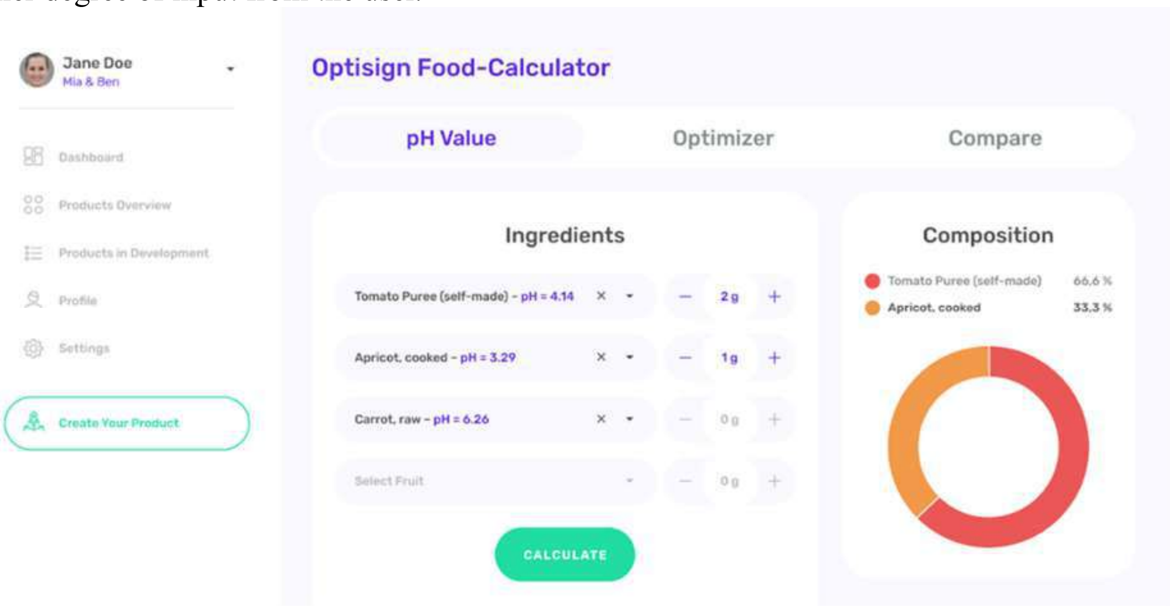

Fig. 3: Possible user interface of the OptiSignFood software.

Conclusions
OptiSignFood should lead to faster product development with less developments being rejected and food waste being avoided. This enables the manufacturers to react faster to societal and market trends, e.g. replacing animal-sourced ingredients by plant-based alternatives. The systematic consideration of environmental impacts and food quality, while ensuring food safety will lead to more nutritious food with lower environmental impacts and improved resource efficiency. Potential trade-offs between different parameters can be clearly shown.
OptiSignFood will enable the food and beverage industry to deliver nutritious food with high quality and safety as well as low environmental impacts and thus to contribute to the sustainable development of the food system.

4

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Calculation of the environmental labeling of food products based on the packaging information

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Keywords: *environmental labeling; food; nutritional data ; ingredients*
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This paper outlines the main aspects of a more detailed article recently published (Coste and Hélias 2022). The environmental footprint of products is a story of trade-offs: the assessment has to be accurate, adapted to the production and processing choices in the value chain. Unfortunately, this need for specific data quickly becomes an obstacle and makes the work too complex and too expensive to be done on a large scale. In contrast, generic data offers a quick and cheap result, but these default values only allow comparisons between product categories and differentiation of products within the same category is impossible.

For food products in France, the Agribalyse (ADEME, 2020) database provides 2,500 'generic' food products. The main factors determining the environmental impact of a food product are the ingredients, which are often more important for the overall result than the transport or processing. The agricultural stage therefore requires particular attention. Production methods are thus a determining factor, but the quantity of each ingredient is also obviously a specificity that must be integrated into the calculations. Generic recipes, as is the case in Agribalyse, are an average recipe and when we are interested in a specific market product, this can often prove to be unrepresentative. We have developed the PEFAP calculator (Product Environmental Footprint According to Packaging data) which automatically estimates environmental impacts based on the information available on the packaging.

Based on the partial list of ingredients (an ordered list, but with often unknown proportions) and nutritional data available on packaging, the algorithm explores the range of possible recipes through a Monte Carlo approach. In each iteration, the masses of ingredients are randomly chosen according to the possible proportions of ingredients and ensuring the best possible preservation of nutrient contents (the nutrients of the product being considered as the sum of the nutrients of all its ingredients). PEFAP retrieves, for each ingredient, the environmental impacts from Agribalyse and the nutrient data from Ciqual database (ANSES 2020), the French national nutritional database for food ingredients. It finds the most likely footprint by the convergence of the result over Monte Carlo runs. From a barcode, the user obtains in a few seconds a specific footprint of the product : data tables and summary web page of the evaluation, see Figure 1 for an illustration. This allows intra-category comparisons and provides more accurate footprints than the generic values from Agribalyse.

Particular attention has been devoted to the correspondence between the databases. The OpenFoodFact (2012) database enables the automatic association of packaging information with a barcode. The ingredients identified in Agribalyse (which are the same as in Ciqual) were matched to this nomenclature of ingredients. When the environmental (from Agribalyse) and/or nutritional (from

Ciqual) information is not available, the average value of the " children " or " parents " ingredients in the OpenFoodFact nomenclature are used.
Footprints have already been calculated for the 150'000 reasonably reliable products of the Open Food Facts database. This includes a subset of 30,000 products with data that are considered fully reliable. This makes it possible to see the variability of impacts within the same product category and the variability of impacts induced by the recipes. The creation of this algorithm makes it possible to better specify the characteristics of food products and makes environmental footprints and labeling more reliable.

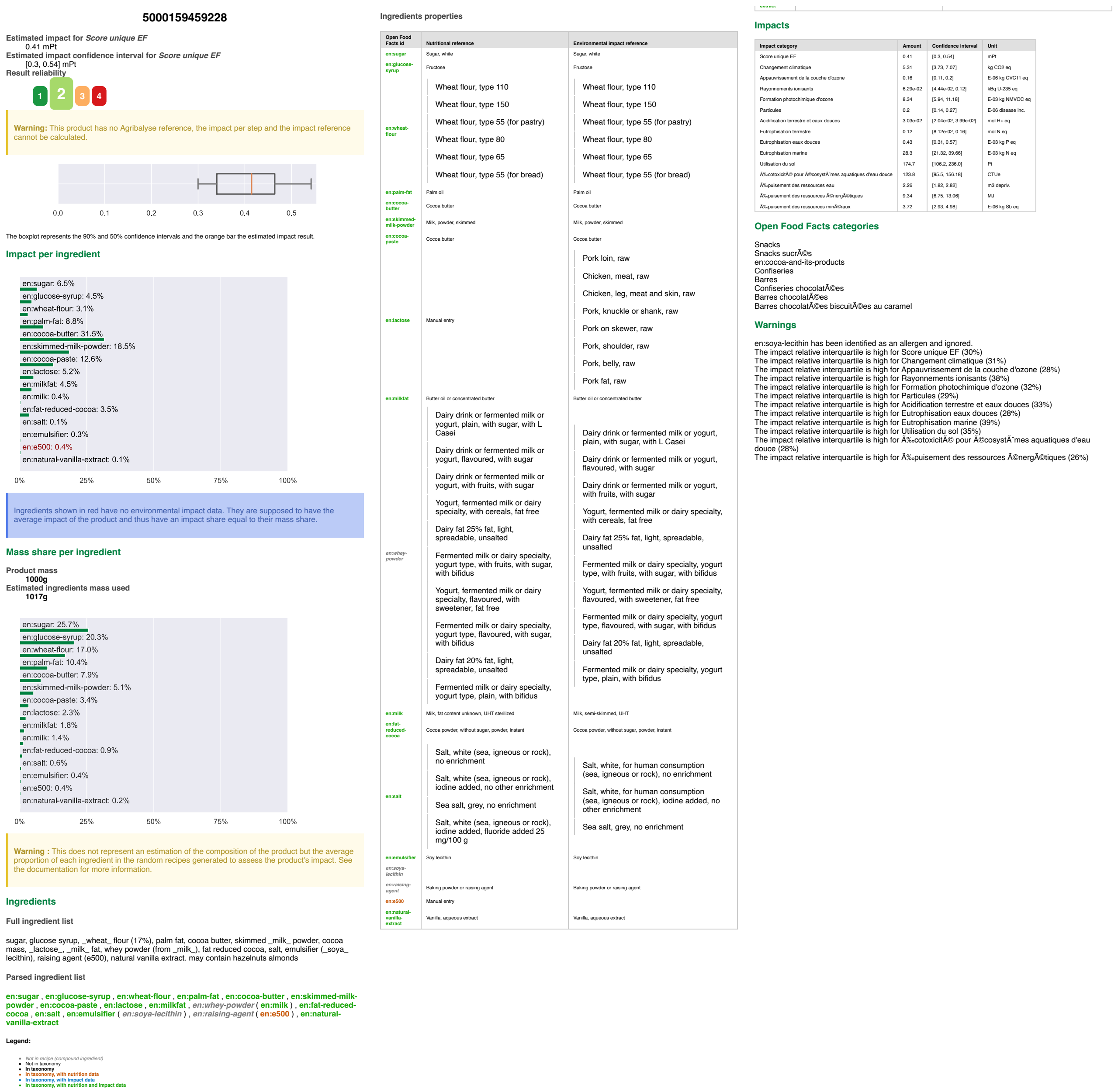

Figure 1. Example of an impact sheet generated automatically for a given food product

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ENVIROSCORE: Easy-to-understand label to communicate food LCA results to consumers

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Keywords: *Product Environmental Footprint; consumer; labelling; LCA; sustainability; communication*

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Rationale and objectives

There is a growing body of evidence on how climate change, water scarcity or water pollution will compromise the capacity for nations to feed future generations (IPCC, 2019). Food production and consumption have been reported as primary drivers, influencing environmental impact (Sala and Castellani, 2019). Hence, a major change in the way food is produced and consumed is of tremendous importance to achieve Sustainable Development Goals (SDGs). In this framework, consumers could play a significant role by demanding sustainable produced food and drink products. For instance, making shifts between different food categories, i.e. by switching from beef to alternative protein-rich vegetable product, or within same product categories, i.e. by choosing local product instead of ultra-packed imported product could push the whole production chain towards more sustainable behavior (Notarnicola et al, 2015; Poore and Nemecek, 2018).

In this sense, Life Cycle Assessment (LCA) (ISO 14040:2006) appears as a robust methodology for evaluating the overall environmental impact of a certain product or service and for identifying the potential environmental reduction due to the implementation of different environmental improvement strategies on manufacturing and supply-chain management (Hellweg and Milà I Canals 2014).

However, available information nowadays does not reflect differences in the environmental impact between and/or within food products (Khan and Lan, 2019).

Following the recommendations about communicating environmental impacts to consumers (Lupiáñez-Villanueva et al., 2018) the goal of the current study is to develop an easy-to-understand label based on Product Environmental Footprint (PEF) which captures 16 environmental impact categories. The newly developed score aims to capture differences of the environmental impact within and between food products to steer consumers towards more environmentally friendly food consumption.

Approach and methodology

A stepwise approach was used to develop the Food Enviroscore.

First, a set of normalization factors was developed to aggregate 16 environmental impact categories into a single dimensionless index adjusted to the European food basket, coined the European Food Environmental Footprint Single Index (EFSI). Following ISO 14040:2006 we defined the environmental impact of the average European Food Basket as a reference situation for the new

normalization factors.
Next, the effectiveness of the EFSI index was evaluated and the thresholds to stablish easy-to-understand Food Enviroscore (using an A, B, C, D, E scoring grid) were defined. The index and score are both based on the Product Environmental Footprint methodology.
Last, a Delphi method was used to assess the relative validity of the Food Enviroscore based on 149 food items categorization.

Results and discussion

The environmental impact characterization results of the selected representative food items (N1=23) are presented in the figure 1. Those results will be used as reference universe for the normalization factors of the EFSI method. In the assessed European Food Basket, animal-based items comprise 28 % of the total food consumption and overall contribute to the 37 % of the environmental impact. Within the animal-based food group, milk is consumed most (27 %), while beef accounts for most of the environmental impacts (31 % of the total impact).

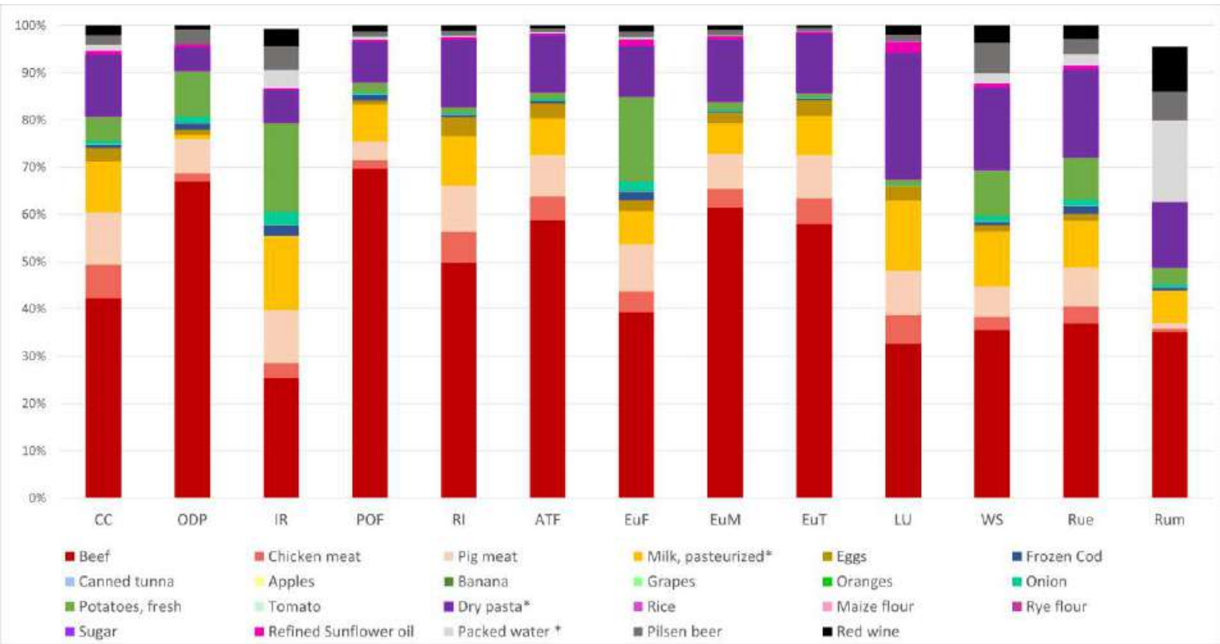

Figure 2.: Environmental impact characterization including the 13 impact categories of the ILCD methodology of the representative food items of the European Food Basket. Where CC is climate change; ODP is ozone depletion potential; IR is Ionising radiation; POF is photochemical ozone formation; RI is respiratory inorganics; ATF is acidification terrestrial and freshwater; EuF is eutrophication freshwater; EuM is eutrophication marine; EuT is eutrophication terrestrial; LU is Land Use; WS is water scarcity; and, RUe is resource use, energy carriers and RUm is resource use, mineral and metals.

The impact characterization results of the European Food Basket were used as baseline for the normalization factors according to the Equation 1 (ISO 14040:2006). Both Normalization and weighting values of the EFSI are reported in Table 1.

Table 1. The European food environmental footprint single index normalization (EFSI-NF) and weighting factors. Where CC is climate change; ODP is ozone depletion potential; IR is Ionising radiation; POF is photochemical ozone formation; RI is respiratory inorganics; ATF is acidification terrestrial and freshwater; EuF is eutrophication freshwater; EuM is eutrophication marine; EuT is eutrophication terrestrial; LU is Land Use; WS is water scarcity; and, RUe is resource use, energy carriers and RUm is resource use, mineral and metals.

Impact category	Unit	EFSI- NF	EFSI-NF, per capita*	Weighting factors[1]
CC	kg CO2 eq	1.23E+12	2.42E+03	22.19

ODP	kg CFC11 eq	6.55E+04	1.29E-04	6.75
IR	kBq U-235 eq	6.69E+10	1.31E+02	5.37
POF	kg NMVOC eq	5.49E+09	1.08E+01	5.10
RI	disease inc.	1.24E+05	2.44E-04	9.54
ATF	mol H+ eq	2.00E+10	3.93E+01	6.64
EuF	kg P eq	1.94E+08	3.81E-01	2.95
EuT	kg N eq	7.25E+09	1.42E+01	3.12
EuM	mol N eq	8.07E+10	1.58E+02	3.91
LU	Pt	1.24E+14	2.43E+05	8.42
WS	m3 depriv.	3.99E+11	7.83E+02	9.03
RUe	MJ	9.98E+12	1.96E+04	8.92
RUm	kg Sb eq	2.21E+06	4.33E-03	8.08

* European NF per capita shall be used (European population in 2013: 509,718,000 people) 1Sala et al., 2018.

After analyzing the details of the EFSI results distribution we stablish the threshold values (Table 2) in order to categorize the EFSI results into five scale score, the Enviroscore.

Table 2: Cut-off values and categorization of EFSI index considering the relative environmental impact of the food items

Enviroscore	Environmental impact	EFSI
A	Very low	< 0.4
B	Low	≥ 0.4
C	Medium	≥ 1.45
D	High	≥ 2
E	Very high	≥ 10

Food items with EFSI results below 0.40 have been considered as very low environmental impact. 'A score' food items encompass for example orange, rye flour or soybean beverage. Products with EFSI values between 0.40 and 1.45 receive a 'B score', low environmental impact, which includes food items such as pasta, grapes or potato. Food items with values between 1.45 and 2.00 are categorized as products with a medium environmental impact and receive a 'C score'. For instance, fruit juices or refined sunflower oil can be found in this category. The 'D score' products include those with EFSI values between 2.00 to 10.00. In this category, we find high environmental impact food items such as avocado, chicken meat or pig meat. Finally, products with EFSI values above 10.00, such as beef or canned tuna, have an 'E score', very high environmental impact (Figure 5).

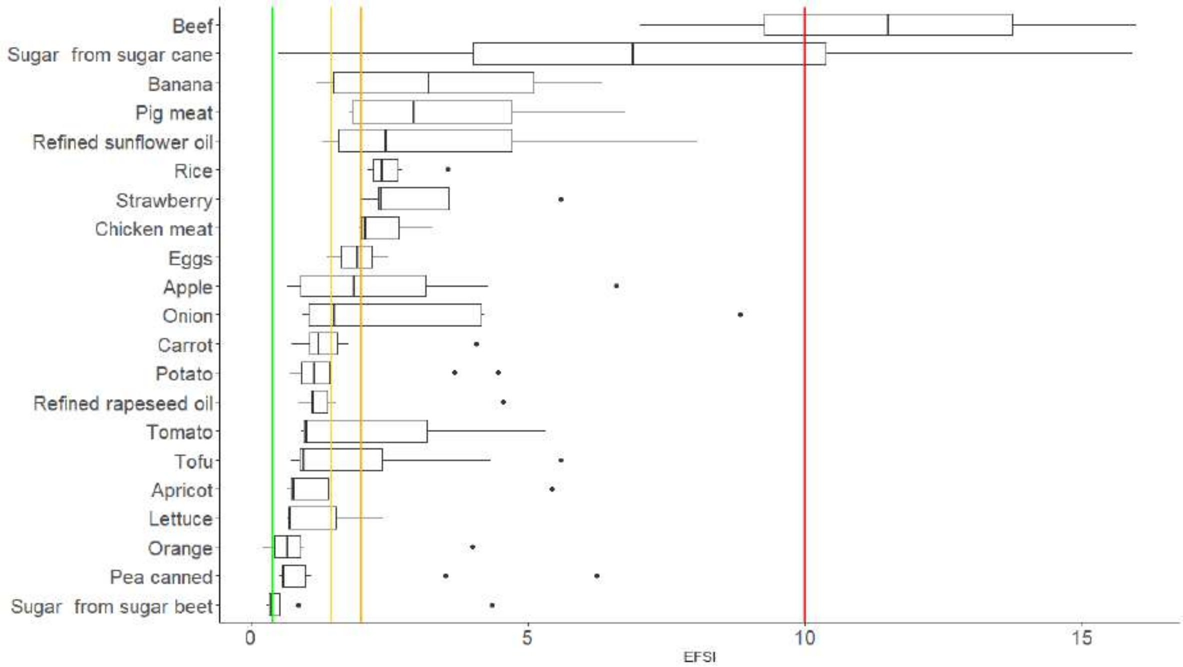

Figure 5.: Distribution of EFSI result of the N2 = 149 hypothetical food items. Colored lines represent threshold values for the categorization. Being the green line the stablished threshold value (0.4) between very-low and low impact; Yellow line the threshold value (1.45) between low and medium impact; Orange line the threshold value (2) between medium and high impact; and Red line the threshold value (10) between high and very-high impact.

Results showed higher environmental impact value for animal-based food products (EFSI median 2.47 (Interquartile Range (IQR) 3.50)) in comparison with plant-based products (EFSI median 1.16 (IQR 1.96)). EFSI was able to account for variability between (inter) and within (intra) food products, particularly due to country of origin and mean of transportation, such as plane transportation average EFSI value of 4.80 (IQR 4.48)) vs the average of 0.97 (IQR 0.69) value for local transportation Additionally, results indicate that differences in water stress are captured better by the EFSI index (r = 0.624) than by other aggregated indexes, such as Single Score (r = 0.228) developed by the European Commission (EC).

In line with the EFSI results, the Food Enviroscore reflects variability inter and intra categories. Moreover, good agreement was achieved between the classification resulting from the Delphi method and Food Enviroscore (weighted Kappa 0.642; p = 0.0025). Results confirm that the newly developed index and score capture the environmental impact variability inter and intra food products, which should allow consumers to make conscious decisions.

Conclusion

The ENVIROSCORE has been validated with the Dephi test and the assessment with the hypothetical food items. The methodology is unique as it is based on European PEF methodology and reflects between and within food product variability in environmental impacts. Currently, we are working on real-scale piloting with the aim of having the product in the market by the end of 2022.

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Towards a large-scale food eco-labelling scheme. Outcomes of the "French Experimentation 2019-2021".

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Keywords: Eco-*labelling, environment, AGRIBALYSE, PEF, agricultural and food products; Life cycle assessment*

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Introduction

Following a first experiment on public eco-labelling in 2010 and inspired by the existing nutrition front-of-pack labelling system, the French government is developing a harmonized environmental information display system backed by public authorities. The article 2 of the Climate and Resilience Act, issued in 2021, requires a broad scale public environmental labelling scheme for all consumer goods in the next 5 years. Food and textile are the more advanced sectors, beneficiating from public experiments and coordination. Learnings from those sectors will then be extrapolated to the rest of the market. The labelling scheme aims to inform consumers and to guide the reduction of the environmental impacts of food via diet change and eco-design of food products. The EU Product Environmental Footprint (PEF) method and the Agribalyse life cycle inventory (LCI) database of French food products are cornerstones for the eco-labelling scheme.
This article explains the process and the main outcomes of the French 2019-2021 Experimentation on food eco-labelling conducted by the ministry of ecological transition and ADEME (the French Environmental Agency), with support of the ministries in charge of agriculture and economy, and a scientific committee. Ongoing steps and expected outcomes are finally presented.

Material

Figure 1: Governance and deliverables of the French food experimentation 2019-2021

Much knowledge was obtained during the experimentation, based on "real life" projects, expert workshops and "lab experiments". Amongst the 18 projects, a diversity of approaches was found: from carbon footprints to LCA indicators combined with other indicators, proposed by professional organisations (dairy, oil, meat…), food companies, retailers, and creators of consumer apps.

Private projects could be classified according to:

- the use of "primary/specific information" vs "secondary and average data",
- use of non LCA approach (qualitative); carbon footprint, LCA or LCA + additional indicators.
- Priority to promote eco-design of food products and/or diet shift
- "Internal calculations" vs. "consumer testing"

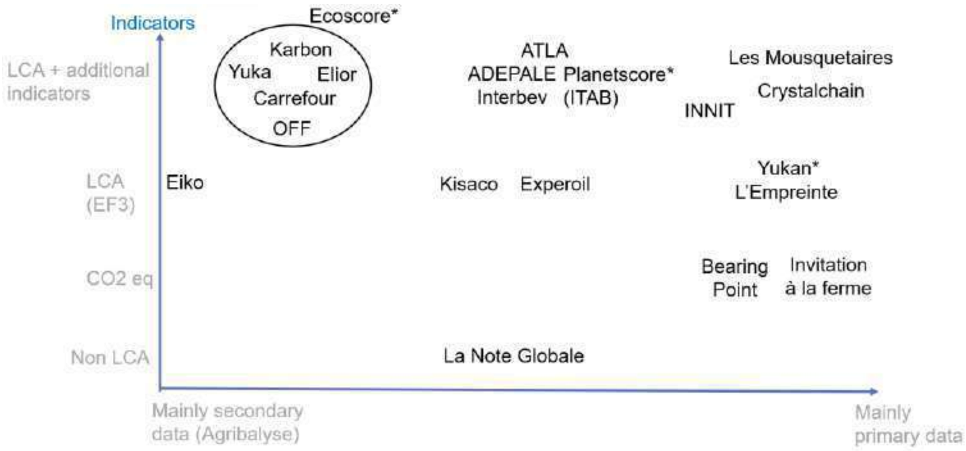

Figure 2 : List of projects according to the type of indicators and the use of primary/secondary data. *Ecoscore, Planetscore and Yukan are the three main initiatives which are still expanding in French and European market in 2022.

Main results and recommendations from the experimentation

The conclusions and recommendations of the Experimentation have been presented in reports from its independent scientific committee (Soler and al. 2021) and the government (French Government, 2021).

- **<u>Technical recommendations</u>**: a combined use of generic and semi-specific data is necessary for a broad and affordable labelling scheme. Default data from the Agribalyse database (ADEME 2022) are a good starting point and must be specified on key parameters with public and/or private data. Minimum primary data requirements are farming system (conventional, organic etc.), recipe, packaging type and product origin. More specific parameters can then be added and should be defined by categories (ex: livestock feed type, truck type etc.). It could result in a potential "3 levels system", going from the simplest to the most complete set of specific parameters. Priority should be given to specific data when available. No ideal functional unit could be found for all food categories; therefore, a mass unit is preferred to align with other approaches like Nutri-score, or price labelling. The Agribalyse database is central in the scheme and needs to be maintained and updated to reflect more accurately the French food market and provide semi-specific data for intermediate products (ex: agricultural stage) as well as generic data at the food level.

Regarding the environmental indicators, the Environmental Footprint 3.0 methods is recommended, but some adjustments on five priority topics are needed:

- *Field-level biodiversity:* ongoing testing of a relative biodiversity indicator based on existing labels (ex: organic fields hold 30% more species in average compared to conventional farming) and/or LCA based indicators (ex: Lindner 2022, Chaudhary and Brook 2018). Discussion is also taking place at the PEF level.
- *Carbon sequestration in soil:* default values for common farming practices (Pellerin et al. 2019) are now available in Agribalyse 3.1 and for environmental labelling.
- *Eco-toxicity and human toxicity indicators:* EF3 indicators have been adjusted. Time horizon is set to 100 years instead of infinite time horizon, negative emissions for metals are set to 0, some CF for inorganic molecules are adjusted (ex: sulphur). Furthermore, the question was raised on the way to communicate on the Human toxicity indicators
- *Packaging and single use plastics:* due to methodological limitations, current LCA/PEF approach is likely to promote single use plastic compared to the other alternatives. A malus will be proposed to reflect the risk of plastic leakage in ecosystem and align environmental labelling with other environmental regulations.
- *Biotic resource depletion and overfishing*: Missing in EF3.The method of Helias and al 2018 indicators will be tested in 2022-2023.

Those adjustments will allow to better assess and compare agricultural systems, including extensive livestock and organic farming systems. It will induce to redefine ponderations for the final score (from EF3 starting point).

Finally, there is a large consensus that label format should provide an overall rating expressed as letters (A to E) and colours. On-pack information can be complemented by information on-line.

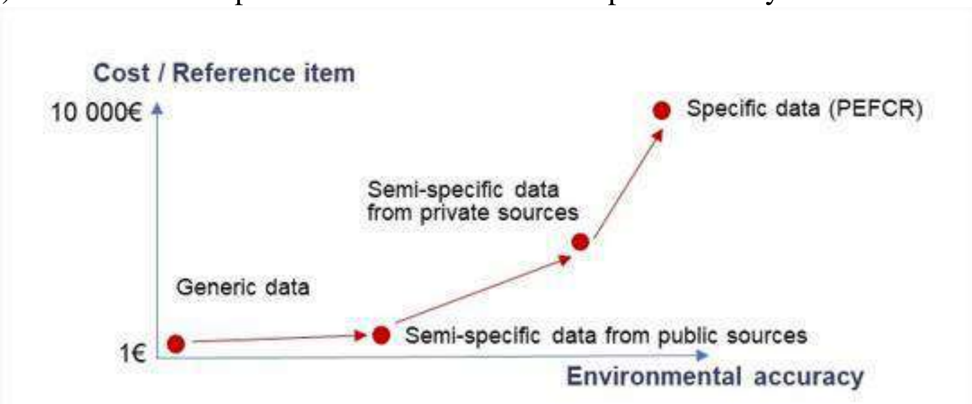

Figure 3: Cost estimate depending on the level of specific data required.

- **<u>Strategic recommendations</u>**: the labelling scheme should allow comparisons both within and among food categories. This transversal scheme at food level maximises environmental benefits and cost efficiency for consumers. Adjustment of the PEF method should be science-based within the LCA framework, rather than via an external bonus-malus system. Priority should be given to simplicity and cost-effectiveness. The scheme should consider environmental issues only (so exclude animal welfare, GMOs, worker conditions etc.).

- **<u>Consensus building</u>**: the governance of the project is based on four main bodies: an interdepartmental steering committee, an independent scientific committee, expert groups, and a large stakeholder committee. It allows each party to participate in the debate, representing different viewpoints: support or concerns, debate about LCA/PEF suitability for agriculture, competition between different private schemes. This method aims to obtain a scheme, consistent with public policies. The Experimentation confirmed consumer interest for environmental labelling of food, broad interest of stakeholders and also raised strong debates on methods and implementation scenarios.

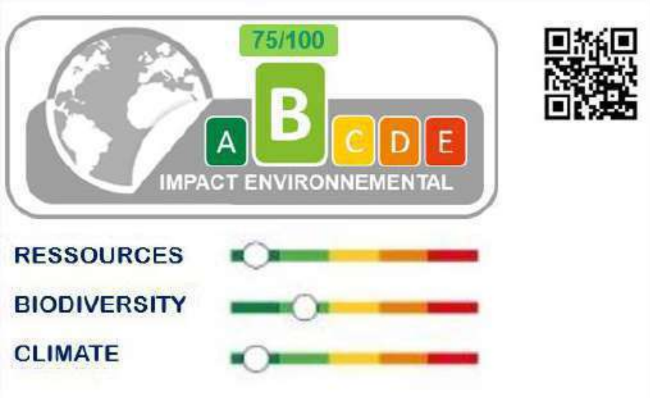

Figure 4: Example of a suitable environmental display for consumer understanding (official format remains to be set)

Outcomes and way forward

The Experimentation has not yet produced a consensual and operational labelling scheme. However, inspired by the different projects and based on the conclusions and recommendations it has yielded, a roadmap for the operationalization of the scheme has been defined, aiming for an implementation by 2023.

Next steps for the implementation of the scheme are finalizing the official algorithm for the overall rating, testing the label on a large real-life set of 550 products (food and beverages), providing a calculation tool, validating the format, defining the review process, validating and promoting the scheme in a regulation. Those tasks are ongoing during 2022.

France aims at implementing a large-scale official eco-labelling scheme in 2023, to support the ecological transition of the food system. This experience is intended to be shared and to contribute to the European and international discussions on information to consumers on the environmental impacts of products.

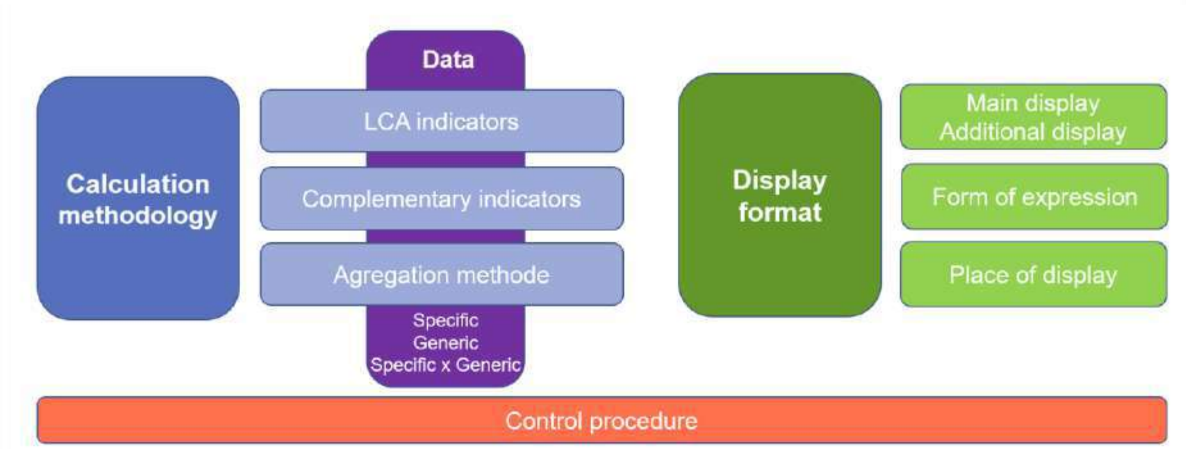

Figure 5 : Global scheme to be set for labelling operationalisation

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The contribution of Life Cycle Sustainability Assessment to the development of sustainable food labelling framework – Insights from the tomato industry in Italy

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Keywords: *LCSA; Product Environmental Footprint; Life Cycle Assessment; farm to fork; sustainability footprinting*

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Within the framework of the Green Deal the European Commission developed the so called "Farm to Fork Strategy" [1]. It aims to improve the availability and price of sustainable food and to promote adoption of healthy and sustainable diets by consumers. Key elements include – among others - improving consumer information through a proposal for a harmonized mandatory front-of-pack nutrition labelling, and a proposal for a sustainable food labelling framework to empower consumers to make sustainable food choices. The sustainable labelling framework aims at covering, in synergy with other initiatives, the nutritional, climate, environmental and social aspects of food products.

As one method to assess the sustainability of products and services Life Cycle Assessment (LCA) considers all life cycle stages and thus is an adequate approach to evaluate potential impacts of the food sector from raw material production, farming, processing, packaging and transports to use and disposal by the costumer. This is already reflected in the Environmental Footprint and the strong support it receives from the European Commission [3].

To address all sustainability pillars in accordance to the farm to fork strategy a life cycle sustainability assessment (LCSA) could be used and build the basis for a Product Sustainability Footprint (PSF). To make a PSF applicable to different product systems and sectors there are still some obstacles to overcome. Main challenges are to develop a broadly applicable methodology, the interpretation and communication of results and the availability of PSFCRs, verification procedures, data and benchmarks. [4]

In the EU funded project ORIENTING [2] the consortium develops a robust and operational methodology for the life cycle sustainability assessment (LCSA) of products and services in close contact with relevant stakeholders. The novelty value of the project lies in a consistent approach that considers environmental, social and economic impacts in an integrated way. The ambition is to develop a methodology that can assess goods produced under linear as well as circular business models, allowing practitioners to understand and manage possible trade-offs. Also ORIENTING contributes to the development of a future Product Sustainability Footprint at European level, evolving the existing PEF framework and designing new indicators for the evaluation of material criticality and product circularity. To make LCSA suitable for supporting the implementation of the sustainable labelling framework a twofold approach is chosen in ORIENTING: first to improve PEF with contributions to biodiversity and land use impact and improve S-LCA. Second to make current methodologies applicable, integrate circularity and criticality, provide guidance to users on how to carry out LCSA and on how to integrate and interpret results. Within the project five industry case studies from different sectors are conducted to test the methodology developed and thus to assure a user oriented approach. As part of the food sector tomato industry in Northern Italy was chosen.

In this contribution we present the Orienting approach, give first insights on its application to agricultural production systems, and discuss how it can contribute to the implementation of the sustainable labelling framework. We will present the demonstration status focusing on the goal and scope, the data collection phase. Furthermore, first interim results are presented and discussed looking at the joint investigation of all dimensions under investigation (environmental, social and economic life cycle assessment as well as circularity and criticality). Based on this, we will discuss the suitability of the ORIENTING framework for application in companies with different levels of experience in LCSA. Furthermore, the overall contribution of LCSA to support the farm to fork strategy is discussed under the consideration of different labeling and result visualization options.

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First insight of pesticide residues consideration for environmental labelling of food product using LCA, a French experiment

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Introduction

Environmental labelling of food product is nowaday a key subject for policies and consumers in Europe, LCA is the methodological basis. In France in 2020-2021, Agency and Ministry for Ecological Transition (Ademe and MTE) launched a call for proposals of an environmental labelling method for food products. 18 proposals were received and analysed by the scientific council which indicated (Soler et al. 2021) that food labelling must be based on LCA and on the "Product Environmental Footprint" (PEF) reference framework, with the need to assume a system compatible with European work. Moreover, the inclusion of pesticide residues was questioned, pointing that regulation already ensures the sanitary quality of food products through the application and control of maximum residue limits (MRLs), nevertheless they recommand a targeted debate notably on the fact that residues in food products do not come from environmental exposure but from direct ingestion. Indeed, nutritional aspects are already considered in a nutri-score in France (Julia and Hercberg 2017) and other countries (e.g. Spain, Germany) ; however, the indicator does not cover the presence of additives nor pesticide residues, which can have human health impacts for consumers. Currently, no indicator presents the potential health risks of food other than nutritional.

In LCA of food products, (eco-)toxicity is dominated by pesticides (Bessou et al. 2013; van der Werf et al. 2020) and in particular by ingestion of residues, which is the main route of exposure (Fantke and Jolliet 2016; Gentil et al. 2020). The international working group on Operationalising LCA for pesticides, OLCA-Pest, recently recommended to account for pesticide residues in LCA (Fantke et al. 2020). Although there are regulations on sanitary quality of food products regarding pesticides, and related risks are hence considered "acceptable", potential impacts on humans still exist (Gentil et al. 2020). Moreover, as the planetary boundary for chemicals including pesticides is exceeded (Persson et al. 2022), consumers should know the risk of their food and act accordingly. The aim of our research is to highlight the feasibility and urgent need to consider within LCA, the pesticide impacts from residues, on top of environmental exposure, for food environmental labelling purposes.

Materials and methods

For the inventory phase, a selection of 8 crops (i.e. tomato, apple, carrot/potato, chicory/salad, soybean, sunflower, vine, sugar beet) representing the main crop families (e.g. cereals, tubers…) was realised using Agribalyse 3.0 (French LCA inventory for agri-products) and distinguishing farming pratices (e.g. organic, conventional). Open-field production was preferred to apply pesticide emission modelling. In Agribalyse, only so called 'specific' scenarios contain detailed pesticide inventory data, those specific scenarios are aggregated to compose generic scenarios leading to representative French crop production datasets. For each selected conventional crop scenario, the dominant specific scenario in the generic one was chosen (e.g. the specific scenario "lettuce, open field, conventional, at farm gate" was selected and represents 43.2% of the "lettuce, conventional, national average, at farm gate"). No generic scenarios are available for organic productions, so only specific scenarios were selected. A total of 22 scenarios were analysed, of wich 9 in organic agriculture.

Then, according to OLCA-Pest recommandations on PestLCI (Nemecek et al. 2022), pesticide emission fractions to the environment and crop (i.e. to air, off-field surface, field soil surface, crop leaf surface) were used (Figure 1), with a differenciation by type of pesticide (e.g. fungicide, insecticide) and crop families and according to French national soil occupation average for off-field emissions (i.e. 59% agricultural soil, 40% natural soil and 1% surface water). These emission fractions are now fully available in Nemecek et al. (2022) and were recently implemented in Agribalyse (the PestLCI model is freely available on https://pestlciweb.man.dtu.dk/).

Emissions were then allocated to the corresponding USEtox_LC-Impact and dynamiCROP impact compartments, respectively, to assess environmental and residues' potential human impacts. An intermediate approach of LC-Impact with the dynamic version of USEtox 2.12 was developed to obtain characterisation factors (CFs) at mid-point with a 100 years time horizon. Only human non-cancer (HNC) toxicity was assessed due to too many missing CFs for human cancer toxicity (85% of the active susbtances used in our case studies are not characterized). Those results were compared with the current modelling approach, using impact method EF3.0 (Product Environmental Footprint) and considering 100% of pesticides emitted to soil. Freshwater, marine and terrestrial ecotoxicity were also studied but are not presented here.

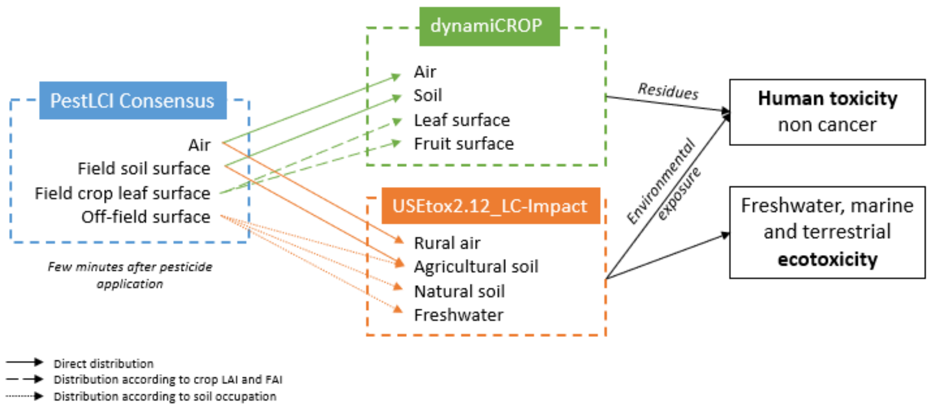

Figure 1: Connection of emission compartments of PestLCI with USEtox_LC-Impact for environmental exposure and dynamiCROP for residues (LAI: leaf area index, FAI: fruit area index)

Results and discussion

Importance of residues in human non-cancer toxicity (HNC) for conventional products

Our method allows us to take into account the impacts of pesticides including residues on human health in LCA and to compare different types of farming e.g. organic versus conventional. Table 1 presents the impact score for HNC toxicity from environmental exposure and from residues (without processing factor from Fantke et al. (2012), for e.g. baked potatoes). Impacts from residues are mostly dominating total impact of pesticides for conventional productions, except for tubers (potato: 2%). Results for both environmental exposure and residues are often dominated by one substance, e.g. for environmental exposure, in 16 of 19 scenarios, impact is explained by one substance representing more than 50% of total impact. Copper substances are dominating environmental exposure impacts for organic crops, while pesticides from the triazoles and organochlorines family are mostly dominating impacts for conventional crops. These results highlight the possibility to reduce HNC toxicity by substituting or reducing the one substance dominating total impact. Within our 22 scenarios, pesticide residues account for up to 99.5% of all pesticide-related impacts (conventional lettuce) and are generally dominating the total HNC toxicity impact. In Figure 2, residues represent 53% of human impacts from pesticides for conventional apple, and 96% for conventional tomato. Residue-related toxicity for organic products is usually zero, except for some case studies such as tomato, due to spinosad pesticide residues (homologated in organic agriculture).

Table 1: Impact scores in CTUh/kg of crop for human non-cancer toxicity from environmental exposure and residues (without processing factor) with the percentage of the total human non-cancer toxicity and the main substance responsible of the impact (CTUh: Human Comparative Toxic Unit, n/a: calculation not available due to missing characterization factors, BR: Brazil, FR: France, AOC: Controlled Designation of Origin) Green lines represent organic crops.

Human non-cancer toxicity	From environmental exposure			From residues (Without processing factor)		
Crop and type of farming	Impact score (CTUh/kg crop)	% / total	Main substance	Impact score (CTUh/kg crop)	% / total	Main substance
Apple, conventional	1,2E-07	47%	Emamectin benzoate	1,4E-07	53%	Amitrole
Apple, organic	1,0E-09	100%	Copper oxychloride	n/a	n/a	n/a
Tomato, conventional	1,4E-10	4%	Copper sulfate	3,4E-09	96%	Acetamiprid
Tomato, organic	1,4E-10	98%	Copper sulfate	2,4E-12	2%	Spinosad
Lettuce, conventional	5,8E-11	0,5%	Abamectin	1,2E-08	99,5%	Pronamide
Chicory witloof, organic	1,4E-09	100%	Copper oxide	n/a	n/a	n/a
Chicory witloof, conventional	8,6E-10	2%	Difenoconazole	3,6E-08	98%	Difenoconazole
Carrot, organic	1,5E-10	100%	Copper sulfate	n/a	n/a	n/a
Carrot, conventional	7,7E-11	29%	Linuron	1,9E-10	71%	Metam-sodium
Ware potato, conventional	1,8E-10	98%	Diquat	4,0E-12	2%	Diquat
Soft wheat grain, conventional	1,0E-10	6%	Epoxiconazole	1,6E-09	94%	Picoxystrobin
Winter wheat, organic	0	-	-	0	-	-
Sugar beet, conventional	8,2E-12	100%	Cyproconazole	n/a	n/a	n/a
Soybean, animal feed, BR	3,7E-10	100%	2,4-D	n/a	n/a	n/a
Soybean, animal feed, FR	6,4E-11	100%	Metolachlor, (S)	n/a	n/a	n/a
Soybean grain, organic	0	-	-	0	-	-
Sunflower grain, conventional	2,4E-11	100%	Metolachlor, (S)	n/a	n/a	n/a
Sunflower grain, organic,	0	-	-	0	-	-
Grape, conventional, AOC	2,8E-09	100%	Difenoconazole	n/a	n/a	n/a
Grape, conventional	6,6E-09	100%	Copper	n/a	n/a	n/a
Grape, organic, AOC	1,1E-08	100%	Copper	n/a	n/a	n/a
Grape, organic	8,7E-09	100%	Copper	n/a	n/a	n/a

Figure 2 compares HNC toxicity calculated with EF3.0 method (PEF) and with our approach (USEtox_LC-Impact and dynamiCROP) for apple and tomato productions in conventional and organic farming. Some organic crops have no impact due to the absence of substances used, and some residues impacts could not be assessed for inorganic substances used. HNC toxicity is in general 3 orders of magnitude higher than with PEF method (EF3.0), due to the inclusion of residues.

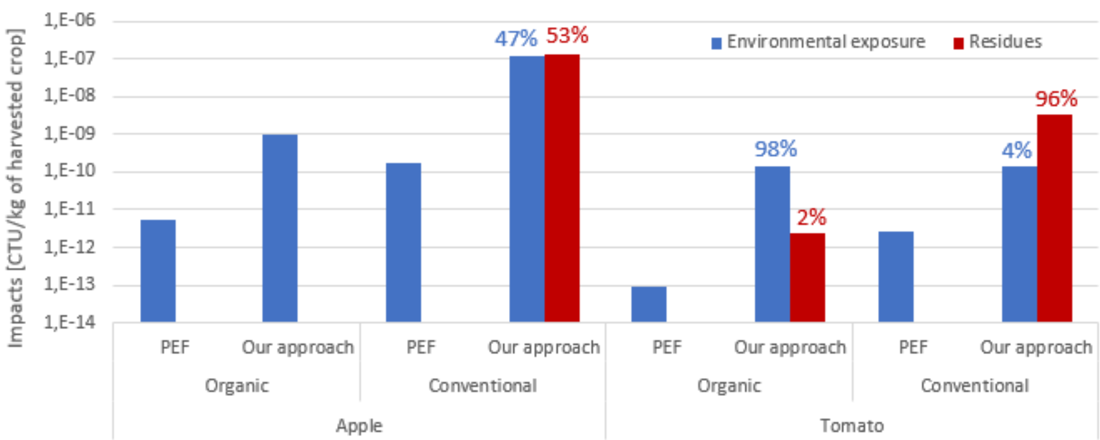

Figure 2: Comparison of human non-cancer (HNC) toxicity calculated with EF3.0 method (PEF) and with our approach (USEtox_LC-Impact and dynamiCROP) for apple and tomato productions in conventional and organic farming. Percentages

indicate the environmental (blue) and residues (red) shares of total HNC toxicity. sScale is logarithmic and unit is Comparative Toxic Unit (CTU)/kg of harvested crop).

MRLs respected and potential human health impacts

DynamiCROP model allows to estimate amounts of pesticide on food crops according to pesticide application and to check if MRLs are respected. In the 22 case studies, the amounts of pesticides in food products were estimated to be below MRLs; however potential health impact could be assessed and is not equal to zero.

Some limitations

Currently, the full impacts of pesticides cannot be assessed. Only human non-cancer toxicity could be assessed due to too many substances not characterized for cancer impacts. Indeed out of 138 pesticides applied in our case studies, 85% were not characterized for cancer impacts; also 28% of substances were not characterized for human non-cancer toxicity for residues and 26% for environmental exposure. Plant uptake of copper substances could not be assessed with the current version of dynamiCROP model, as it is not yet developed for inorganic substances; it was therefore not possible to reach any conclusions on their residues in food. At inventory level, out of our 138 substances, 26% are not homologated in France anymore, hence update of Agribalyse is required and should be carried out in the upcoming release. Thus, potential over- and under-estimation of impacts exists due to these current limitations.

Outlook and conclusions

Using Agribalyse and the most up-to-date LCIA pesticide models, a methodology to assess human toxicity due to pesticides was proposed for food environmental labelling purposes. Thus, a pesticide-LCA study of 22 representative crops, including food residues with metal substances at 100 years for 8 crop types was assessed, comparing impacts for organic and conventional pratices. First results show that human non-cancer toxicity of residues reached up to 99,5% of total impacts from pesticides for conventional products. Human non-cancer toxicity is always higher for conventional than organic crops, mainly from residues.

Nevertheless, to fully assess the impacts of pesticides, CFs for cancer toxicity need to be developed as well as CFs for new substances, notably the ones used in organic farming. Further research is also required for inorganic substances, metabolites, adjuvants and cocktail effects.

Overall, in the context of consumer information, we are challenging the statement that MRLs are already wholly addressing human health due to pesticides. Indeed, our study shows that doses of ingested chemicals below MRLs can still have potential impacts on humans. Thus, environmental labelling of food products (using LCA methodology) should consider impact of pesticides on human health, from both environmental exposures and residues in food, as recommended by the international scientific community, in order to compare crops with each other.

This approach could be extensively extrapolated to other food crops to cover environmental labelling requirements and pave the way toward general consideration of pesticide and their residues for environmental labelling of food products. Consideration on processed food products must also be carried out. As per now, priority is to operationalize current tools for practitioners and for this environmental labelling purposes including in LCA software tools.

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Milk alternatives from an environmental and nutritional point of view

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Keywords: *Plant-based beverages; Milk alternatives; Milk, Life Cycle Assessment; Environmental impact; Nutritional profile.*

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Objective

Milk consumption in humans goes on for longer than in other mammals' species (Pereira, 2014). Nowadays the consumers are becoming more aware of the environmental burden that some products, such as milk, carry (Grunert et al., 2018). Because of this, they are looking for alternatives that are more environmentally friendly and well as nutritionally similar. This study explores the data available in the literature and compares the nutritional profile of several milk alternatives with the profile of milk from different mammals, as well as their environmental impact.

Approach and methodology

This work explores the data available in the literature and compares the nutritional profile of several milk alternatives with the profile of milk from different mammals, as well as their environmental impact. For this, the Google Scholar search engine was used, and the search was structured into two phases using two sets of keywords. The first was aimed at LCA using the keywords: "xxx milk LCA", "mylk vs milk LCA", "milk vs plant-based milk LCA", "plant-based milk LCA", "xxx beverage LCA", "milk substitutes LCA" and "environmental impact of milk substitutes". And the second was for the nutritional properties of the beverages, with the keywords: "xxx milk", "xxx mylk", "plant beverages", "nutritional profile of plant beverages". In these, the "xxx" term was substituted by different terms depending on the source of the beverage: bovine/cow, goat, human, sheep, or buffalo (for animal milk) and almond, cashew, coconut, hazelnut, hemp, oat, peanut, quinoa, rice, sesame, soy, tiger nut or walnut (for plant-based beverages). The research was limited to studies published in scientific journals from the last 10 years and available in English. The initial search yielded more than 231 articles. Further title, abstract and results' sections of the articles were analysed for the availability of quantified data on nutrients and environmental impact. The analysis narrowed down the articles used in this review to 66. The information was then retrieved and for further analysis in the review.

Main results and discussion

The values for the analysed macronutrients are higher (in g / 100 g of product) in plant-based products than in animal-based – 8.71 g of protein in soy milk, 35g of fat in coconut milk, 7.5 g of fibres in tiger nut milk and 80g of carbohydrates in rice milk. The same is true for most micronutrients, both in the analysed minerals (mg / 100 g of product) and vitamins (mg or µg / 100 g of product) – 6.5 mg of iron in hemp milk, 70 mg of magnesium in soy milk, 256 mg of phosphorus in coconut milk, 639 mg of potassium in coconut milk, 203 mg of sodium in tiger nut milk, 0.06 mg of vit. B1 in soy milk, 0.637 mg of vit. B3 in coconut milk, 3.84 mg of vit. B6 on almond milk, 48 µg of vit. B9 in soy milk, 77.14 µg of vit. B12 in almond milk, 19.2 mg of vit. E in almond milk and 3.33 µg of vit. D in both coconut and rice milk. When comparing the nutritional profile of these alternative beverages, these appear to have been fortified in some nutrients, which is a normal practice during the processing step of these products.

The environmental damage of the food system is shown in several recent studies: (Poore & Nemecek, 2018) show that this industry, in particular, has big greenhouse gas, land and water footprints. The environmental footprint of the production of these products can vary very easily with the number of animals on the farm, the conditions where they are kept, and the milk production level (Rotz et al., 2010). On the environmental impact of these products, data for most of the categories presented in the article is not available – and even with data available, sometimes a full comparison is not possible due to missing values.
The production of one litre of milk can release to the environment 0.089-51.60 kg CO_2 eq. for for animal-based milk and between 0.021-3.85 kg CO_2 eq. for plant-based beverages, almost 13 times less CO_2 than the same volume of animal-based milk. The highest and lowest energy consumption (both renewable and non-renewable energy consumption) comes from rice milk production (1.04-47.60 MJ / L of milk). Water consumption reaches very high volumes with almond milk production (59-6100 L / L of milk), followed by cow milk production (11.7-1030 L / L of milk). The highest impact on ozone layer depletion is associated with goat milk (8.78E-8 to 9.82E-7 kg CFC11 eq.), while plant-based beverages have 10 times lower impact in this category. Water eutrophication is divided into marine eutrophication (animal milk has the highest impact on this category, 0.001-0.346 kg N eq., whilst plant-based milk varies between 0.000267-0.0062 kg N eq.) and freshwater eutrophication (no data was available for plant-based products and the highest impact comes from buffalo milk with 0.033 kg P eq. / L of milk). The highest acidification potential comes again from animal milk production, most precisely buffalo milk (0.065kg SO_2 eq.).

Conclusions

Overall plant-based beverages analysed by the studies and available on the market appear to be nutritionally richer than animal millk, and the environmental impact of these beverages is lower than bovine milk (on the categories of global warming potential, ozone layer depletion, marine water eutrophication and acidification potential). At the same the water footprint for some of these alternative beverages is much higher (e.g.: almond milk production consumes 6100 L of water per litre of product). This study has many limitations since the available data for the different products is limited, for both nutritional profile and environmental impact. This is especially noticeable in data related to plant-based beverages.

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Human health impacts of particulate matter emitted from different milk production systems in Brazil: LCA sensitivity analysis

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Rationale and objective of the work

Brazilian milk production reached a record 25.53 billion liters in 2020 (IBGE, 2021). According to Embrapa (2021), the supply of milk grew by 2.8% in the country, which keeps Brazil the third-largest producer of milk in the world, behind the United States and India (FAOSTAT, 2021). However, the Brazilian raising of ruminant animals management showed an increase of 107% in air pollution from 1990 (1 kilo-DALY) to 2018 (2 kilo-DALY) due to particulate matter (PM) related emissions (UN, 2022). PM is an atmospheric pollutant composed of a complex mix of solid and liquid particles suspended in the air (WHO, 2018). PM is graded according to its aerodynamic diameter and can reach less than 2.5 micrometers ($PM_{2.5}$), standing as the fifth largest risk factor for human mortality in 2015 (Cohen et al., 2017).

Life Cycle Assessment (LCA) is an important technique (ISO, 2006) to account for the health impacts due to PM emitted by milk production in Brazil. However, most characterization models for the PM formation category were developed for different geographical scopes, such as Europe, the United States, and Japan. Some recent models covered the Brazilian context, for example, Fantke et al. (2017, 2019), Van Zelm et al. (2016), and Oberschelp et al. (2020). Nevertheless, there is a methodological gap due to the existence of few studies in the literature evaluating the sensitivity of methods that include the Brazilian context concerning the PM category (Giusti et al., 2022).

Based on an LCA study, this research aims to evaluate the human health damages of PM emitted from two confined milk production systems in Brazil; and to analyze the LCA sensitivity of results in face of different characterization models application.

Methodology

Goal and Scope Definitions

Two systems of confined milk production were evaluated in Brazil. The first one was the compost barn system located at Angatuba city of São Paulo state. In this system, the cows are confined, and sawdust is constantly inserted as bedding (bulky material) for the cows and mixed with manure to produce biofertilizer. The second one was the confined system located at Campos Gerais of Paraná state, with biogas and/or biofertilizer generation in the manure treatment.

Both systems were analyzed in a cradle-to-farm production for 1 kg of Fat and Protein Corrected Milk (FPCM) as the functional unit (UF). The physical allocation was used to address the multifunctionality of the milk production systems due to the generation of two by-products: meat and manure.

Life Cycle Inventory Analysis

Life Cycle Inventory (LCI) for the confined milk production in Campos Gerais region was extracted from the National Life Cycle Inventory Database (SICV Brasil) and imported into the OpenLCA 1.10.2 software tool. For the LCI of the Compost Barn production system in the southwestern region of São Paulo state, the necessary data from Silva (2022) were used. The background processes to complete the cradle-to-farm compared systems were obtained from the ecoinvent 3.7 databases.

Life Cycle Impact Assessment

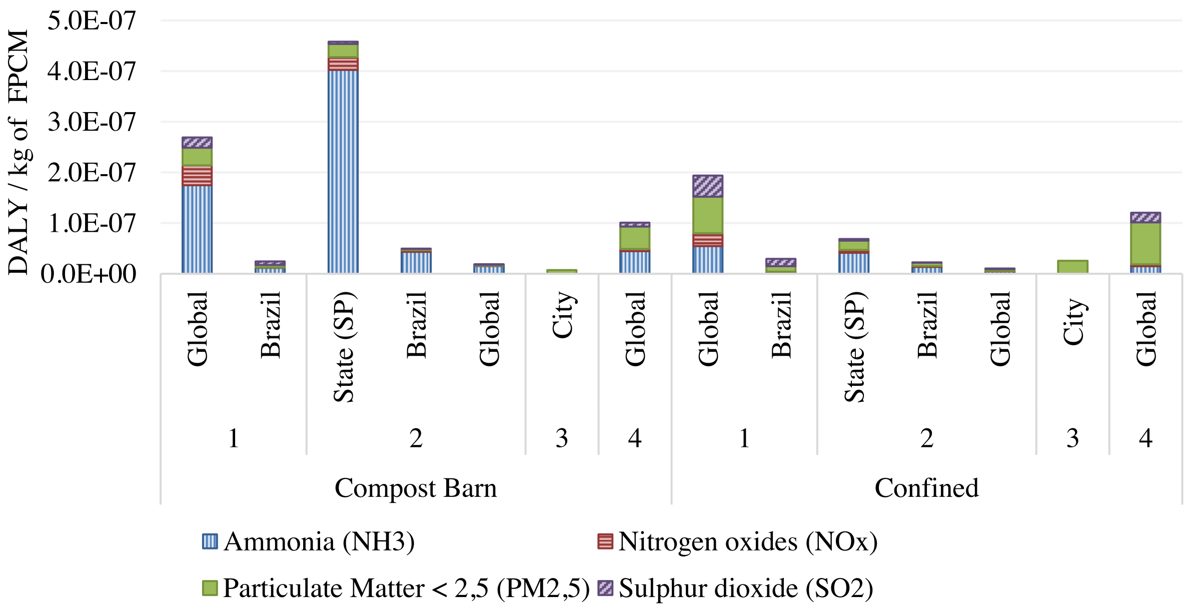
Life Cycle Impact Assessment (LCIA) was developed exclusively for the PM formation category using four characterization models with Brazilian coverage: (1) Van Zelm et al. (2016), which provided Characterization Factors (CF) to the world and only one CF for Brazil as a whole; (2) Oberschelp et al. (2020), with CF to the world, to Brazil as a whole, and regionalized CF to Brazilian states; (3) Fantke et al. (2017, 2019), which provided regionalized CF for 126 Brazilian cities, and; (4) UNEP and SETAC (2016), which is the global recommendation from the Life Cycle Initiative. Giusti et al. (2022) recently recommended using at least one of the cited models (1), (2), or (3) for LCA studies in the Brazilian context.

Considering the models developed by Van Zelm et al. (2016) and Oberschelp et al. (2020), which did not divide the factors into archetypes, the same elementary flow emitted in different archetypes received the same CF. On the other hand, Fantke et al. (2017, 2019) and UNEP and SETAC (2016) provided CFs varying with the emission archetype; thus, the models' archetypes were connected to the inventories' archetypes as follows: emissions to air in high population density archetype received the CF for outdoor urban archetype; emission in low population density was connected to CF for outdoor rural archetype and; emission to unspecified archetype received the higher CF.

Results and discussion

Regarding the inventory data, the confined system showed lower emissions of NH_3 (69%) and NO_x (35%) concerning the compost barn and higher emissions of $PM_{2.5}$ (109%) and SO_2 (106%). These differences led to different impact results when changed the characterization model, as shown in Figure 1.

Figure 1 - Life cycle impacts of particulate matter formation for the compost barn and confined systems. Legend: 1) Van Zelm et al. (2016); 2) Oberschelp et al. (2020); 3) Fantke et al. (2017, 2019); 4) UNEP and SETAC (2016)



Using the CF provided by Van Zelm et al. (2016) to the global average, the compost barn showed an impact of 2.7×10^{-7} DALY/kg FPCM, and the confined system was 28% lower. Using the Brazilian CF of Van Zelm et al. (2016), the compost barn impact was 2.4×10^{-8} DALY/kg FPCM, and the confined system resulted in 20% higher damages. The NH_3 emissions were the primary hotspot in the compost barn for global and national CF. However, the hotspot varied with the LCIA regionalization level in the confined system. Results indicated that $PM_{2.5}$ is the hotspot for the global approach and the SO_2 for the national one.

Using the Oberschelp et al. (2020)'s CF, the compost barn resulted in 1.8×10^{-8}, 4.9×10^{-8}, and 4.6×10^{-7} DALY/ kg FPCM for global, national, and state levels, respectively. These results were 45%, 54%, and 85% lower for the confined system. These three geographical coverages indicated the NH_3 as the main hotspot for the compost barn and confined systems.

Fantke et al. (2017, 2019)'s CF values showed that the compost barn impact was 7.5×10^{-9} DALY/kg FPCM, and the confined system presented an impact 242% higher. To this model, the NH_3, SO_2, and NO_x emissions did not account for effects due to the lack of specific CF. Thus, the hotspots analysis was not a viable step in this model use.

Finally, the CF recommended by UNEP and SETAC (2016) resulted in 1×10^{-7} DALY/kg FPCM for the compost barn, which was 16% lower than the confined impact. The confined system presented higher emissions of NO_x for the high population density archetype, mainly due to the background processes and higher emissions of $PM_{2.5}$ and SO_2 compared to the compost barn. NH_3 and $PM_{2.5}$ were found as the hotspots in the compost barn, while only $PM_{2.5}$ was highlighted in the confined system.

It is worth mentioning that the analyzed milk production systems are not directly comparable, given the need for more harmonization in the inventory data quality. However, it is interesting to note that the variation in the characterization models significantly changed the impact results of both systems, also changing the hotspot analysis.

Owsianiak et al. (2014) evaluated the environmental impacts of four window design options for residential buildings comparing the ILCD 2009 with IMPACT 2002+ and ReCiPe 2008. The PM formation impacts showed a difference of only one order of magnitude by varying the LCIA method. However, the authors identify that the hotspots varied according to the method due to the different characterization models used. Nevertheless, the methods used by Owsianiak et al. (2014) were developed for a geographical scope divergent from the Brazilian one. Moreover, Giusti et al. (2022) also found a high variance of LCIA results for the Brazilian production of particleboards when they varied the characterization models, suggesting that the CF covering the Brazilian context needs further refinement to reduce their uncertainties.

Conclusion

For the PM formation category, regionalized CF values are recommended. Fantke et al. (2017, 2019) provided the most refined territorial scope among the used models and CF for the different archetypes. However, this model showed a limitation due to the lack of factors for PM precursor emissions.

Thus, regarding the total PM impacts of the analyzed systems and geographic scope, the state-level model provided by Oberschelp et al. (2020) showed more consistency for the LCA application. The selection of the LCIA method should be made with caution, considering the LCA scope and the level of regionalization for the models available and required to attend to the LCA goal.

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Environmental implications of soybean reduction in dairy cattle diet in Luxembourg: results from the combination of detailed CH_4 emission and agent-based model

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Abstract
Soybeans (*Glycine max.* (L.) Merr.) are an important high-quality protein source in animal feed and currently cover 70% of the animal protein requirement in Europe, while just as little as about 3.5% is grown in Europe. Luxembourg currently imports 100% of its soybeans used for feed consumption from overseas, thus causing important indirect emissions. To increase the independency of the country from soybean importations, the current managing practices of Luxembourgish farmers would need to change. However, agricultural systems can be overly complex and modelling such systems in a way that the decision makers can benefit from resulting tools is a difficult task. Agent-based models (ABM) have been used by modelers to simulate complex human-natural systems (CHANS) due to their ability to incorporate human behavioral aspects into the models. In this paper, we use an ABM that is built to simulate dairy farms in Luxembourg to explore two scenarios oriented towards the achievement of a partial soybean autarky in Luxembourg that are inspired by (Zimmer *et al.*, 2021a). The results of our simulations show that achieving partial soybean autarky in Luxembourg is possible but requires systematic changes in dairy and suckler production system. The economic cost of producing soybean locally and/or slowdown of animal growth should also be analysed along with the environmental impacts. However, there could be significant reduction in environmental impacts generated in the soybean importing countries.

Introduction
Livestock systems account for 44% of all anthropogenic CH_4 emissions and 53% of N_2O emissions (Gerber *et al.*, 2013). Considering the contribution of global supply-chains, Gerber *et al.* (2013) estimates that the total contribution of the livestock sector to the global anthropogenic greenhouse gases (GHG) emissions is 14.5%. This includes enteric fermentation, excretions and respiration. The amount of CH_4 generated in the enteric fermentation process can significantly vary based on the genetic characteristics of an animal and the type of feed it consumes. In particular, soybeans (*Glycine max.* (L.) Merr.) are an important high-quality protein source in animal feed and currently cover 70% of the animal protein requirement in Europe (Bernet *et al.*, 2016), while just as little as about 3.5% is grown in Europe, being South America its main global producer (Pannecoucque *et al.*, 2018). Luxembourg currently imports 100% of its soybeans used for feed consumption from overseas, thus causing important indirect emissions (Zimmer *et al.*, 2021a).

Soybean is considered as a great source of protein for monogastric animals not only because of its high protein content but also because of the ideal amino acid composition (Montoya *et al.*, 2017). A share as high as 92% of its world production happens in five countries (USA, China, Argentina, India and Brazil) (Pagano and Miransari, 2016) and its global trade volume has surpassed some other commodities in the recent years (Sun *et al.*, 2018). Although complete soybean autarky requires 9 – 12% of the arable land in Europe (Guilpart, Iizumi and Makowski, 2020) and it seems to be an unrealistic goal, expansion of soybean cultivation area in EU is possible. The soybean cultivation in EU was 2.8 million tons in the year of 2021 (Eurostat, 2022), and more than a million of this was in Italy. The second largest soybean producer in Europe is Serbia in the same year with 700 kt, which shows the trade potential within the continent as well as the potential of soybean cropping in similar latitudes. (Toleikiene *et al.*, 2021) tries to find the potential of soybean cultivation beyond its current northern limit in Europe, whereas (Klaiss *et al.*, 2020) shows the challenges of organic soybean production in Switzerland. The study of (Karges *et al.*, 2022) has three main objectives: (1) identification of soybean cultivars that are most suitable for central Europe, (2) exploration of effect of irrigation on different soybean cultivars and (3) determining the agro-economic potential of soybean cultivation in food and feed markets.

In this paper, we aim at simulating two possible scenarios oriented towards the achievement of a partial soybean autarky in Luxembourg, that are inspired by (Zimmer *et al.*, 2021a). The first one (scenario A) consists of a decrease in the soybean ratio in the dairy cows' diet based on the minimum and maximum amounts of soybean in different feed rations, and the second one (scenario B) consists of an increase of local soybean production. This change, however, would necessitate a modification of the current managing practices of Luxembourgish farmers and their interactions they have with customers, other farmers, and possible intermediaries. To understand and model the interactions that may occur during agricultural activities, it is therefore essential to understand the decision-making process of farmers. As every human being, farmers can also be influenced by the opinions of others and they can make decisions based on external advice (Rose *et al.*, 2018). To this end, agent-based models (ABM) are a reliable tool to capture the behavioral aspect of human complex systems and therefore gained attraction in agricultural business modeling. The two scenarios dealt with in this paper are therefore simulated using an ABM, which is coupled with life cycle assessment (LCA) to assess the environmental implications of the decisions taken by the farmers in a lifecycle perspective. The simulator is more extensively described in (Marvuglia *et al.*, 2017) and (Marvuglia *et al.*, 2022).

Materials and methods

ABM-LCA Coupling

In (Marvuglia *et al.*, 2022) we simulated the information diffusion (green consciousness (GC) attitude) in the network of farmer agents. The model now developed into a state where we can simulate dairy farming activities along with the cropping activities. This is especially important for agricultural sector in Luxembourg since most farms in the country are of a mixed type (producing crops, meat and milk in the same holding). The LCA model and the ABM are "tightly" coupled, in the meaning discussed in (Baustert and Benetto, 2017). The outputs of the ABM are directly fed into the LCA framework Brightway2 for impact assessment calculations.

The modelling of livestock production system

In our model, one single animal is the main physical unit for the animal management. Several phenotypical attributes are assigned to an animal which can be static (e.g., gender) or dynamic (e.g., weight). In addition to the individual animal attributes, there are also farm properties that affect the growth and feeding of the animals. One assumption we made is modelling the dairy cows as Holstein-Friesian and suckler cows as Belgian Blues which are the prevalent breeds of corresponding farming practices. Together with these properties and assumptions, the choices made by the farmer determine the resulting production as well as animal's lifetime. After each calving, the calf is assigned to the farm with a certain gender, bodyweight, and birth date.

The feed rations

The animal diet is a major determinant for maximizing the productivity of the herd and farmers choose different feeding strategies based on the farm's operation type (dairy or suckler). Using the rations calculated in (Zimmer *et al.*, 2021b) (Table 1) for an adult Holstein cow, the farms are initialized with mixtures of these rations. The energy intake of each animal is calculated using the IPCC equation for gross energy (GE) intake (H. Dong *et al.*, 2006) for each timestep of the simulation, and then the total daily dry matter intake (DMI) of an animal is calculated with respect to an adult Holstein cow. Based on their strategy (organic, conventional, GMO, non-GMO, etc.) farmers choose different mixture of feed rations to maximize their animals' capacity, and at the same time keep the animals healthy and optimize their profits (Table 2).

Table 1: The mixture of feed rations in different seasons for each type of farm. (Zimmer et al.*, 2021b). (SoyaMax: The current level of soybean extraction in feed rations of Luxembourgish dairy, SoyaMin: Targeted extraction level that is feasible for farms; P= pasture).*

Ration	Grass Silage (%)	Maize Silage (%)	Soya (kg/day)	Maize Silage (kg/day)	Grass Silage (kg/day)	Barley (kg/day)	Triticale (kg/day)	Maize (kg/day)	Rapeseed (kg/day)	SoyaMax (kg/day)	SoyaMin (kg/day)
R_1	70	30	0.7	16	29.7	1	1	1.2	0.7	1	0.7
R_2	40	60	1.1	28	17	0.8	0.8	1	1.1	1.5	1.1
R_3	70	30	1	16	29.7	0	0	2.5	1	0.33	0.23
R_4	40	60	1.5	28.8	17.1	0.5	0.5	0.5	1.5	0.5	0.36
R_5	100	0	0	0	34	1	0.6	0.15	0.3	0	0
P	0	0	0	0	0	0	0	0	0	0	0

Table 2: The feed rations of different types of farms as they are implemented in the simulator (Zimmer et al.*, 2021b).*

Farm type	Winter	Summer
Conventional	50% R_1, 50% R_2	33% R_1, 33% R_2, 33% P
Conventional-GMO	50% R_3, 50% R_4	33% R_3, 33% R_4, 33% P
Organic	33% R_1, 67% R_5	100% P

Methane (CH_4) emissions

The CH_4 emission of each cow is calculated as a function of GE intake, which depends on different animal traits, such as body weight, parity, age, etc. To calculate it, the energy requirement equations from (Hongmin Dong *et al.*, 2006) are used. CH_4 emission per cow is then calculated using the equation developed by IPCC (Hongmin Dong *et al.*, 2006):

$$EF\left(\frac{kg\ CH_4}{head \times year}\right) = \frac{GE\left(\frac{MJ}{head \times day}\right) \times \frac{Ym}{100} \times 365}{55.65} \tag{1}$$

where EF is the emission factor and Y_m is the methane conversion factor (i.e. the percentage of gross energy in feed converted to methane) for distinct types of animals. Our approach considers the properties of individual animals and is therefore more detailed than the conventional approaches.

Scenarios to improve soybean autarky in Luxembourg

After careful discussions with local stakeholders, we implemented two scenarios that would potentially improve the soybean autarky of Luxembourg. The objective is to simulate these scenarios and assess the financial and environmental outcomes. In (Zimmer et al., 2021b) the potential of reduction in soybean rate in feed rations for Luxembourgish dairies was assessed. If the amount of soybean extraction in supplementary feed can be minimized, it may lead to reduction in soybean imports as much as 42%. Therefore, in our Scenario A the farmers reduce the level of soybean extraction gradually from SoyaMax to SoyaMin over ten years. The soybean extraction required by each farm is monitored and the consequent change in soybean imports reflects the mitigated environmental impacts.

A survey conducted by IBLA, the institute for organic agriculture in Luxembourg, shows that most farmers are open to adapt soybean into their crop rotations (Zimmer et al., 2015). The assumption is that each year 3200ha of agricultural area can be cultivated considering the climatic conditions and crop rotation constraints. In our simulations for Scenario B, a farmer may choose to add soybean into the crop rotation if his or her GC value is above a pre-set threshold ß (which is set as 0.5 for this work). Although we cannot avoid the global impact due to cultivation of soybean in this scenario, we mitigate the impact due to transportation from overseas.

Results and discussion

The progression of soybean autarky of Luxembourg is given for both scenarios in Figure 2(a). The methane emissions due to change in feed composition of animals are given in Figure 2(b). In scenario A we end up with less carbon emissions and more autarky since the consumption and thus production of soybean is reduced, whereas in scenario B the import continues but it is partially compensated by local production. The yield in Luxembourg is lower compared to traditional soybean exporting countries, thus greater agricultural land is required for the same amount of produce. However, since the emissions due to transportation is still lower than in the case of imported soybeans, the emissions can be reduced if scenario B is applied as well.

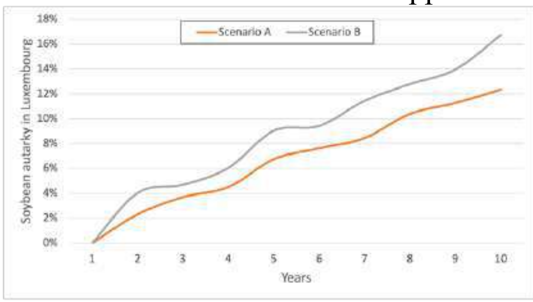

Figure 2(a): The soybean autarky evolution for scenarios A and B.

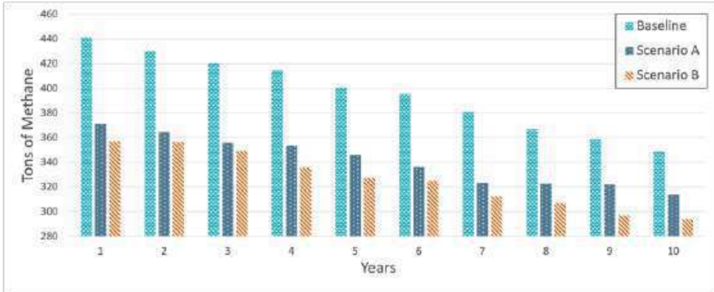

Figure 2(b): Methane emissions in case of business-as-usual scenario vs scenarios A and B.

The midpoint and endpoint impacts, calculated with the ReCiPe (Huijbregts *et al.*, 2016) method, show improvements for both scenarios. Figure 3 shows the results for the midpoint impacts. Natural land transformation and urban land occupation impacts decrease due to a lower soybean consumption by animals (Figure 4). It is important to note that the change in animal diet brings reduction in animal feed costs. In scenario B, the local soybean production brings additional costs, like seeds and fertilizer, but the animal feed purchases due to local soybean production.

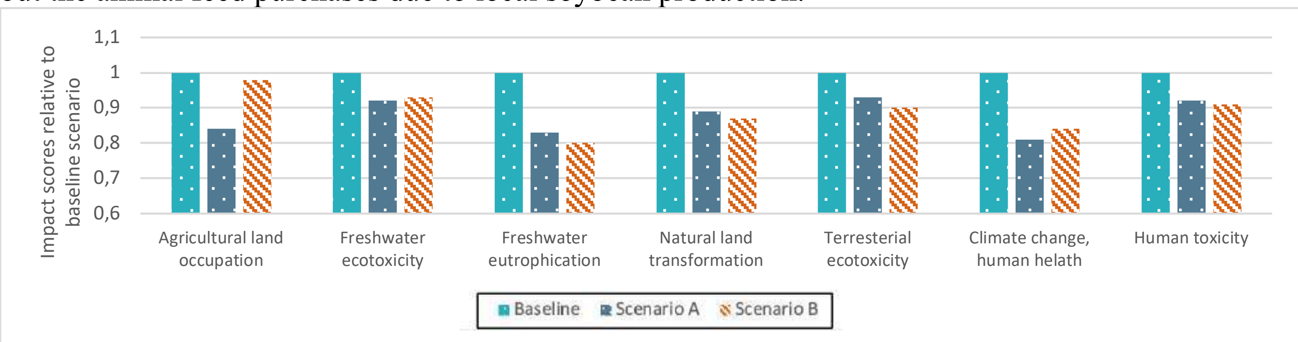

Figure 3: Comparison of different midpoint impact scores in each scenario.

Conclusion

In this paper we simulated scenarios that explore the possibility of establishing soybean autarky in Luxembourg using our ABM-LCA model. Since the cultivation of soybean in some regions of Luxembourg is possible, the current imported soybean may be partially replaced with local production. Otherwise, the current amount of soybean in feed rations is more than enough to ensure required protein intake for animal growth; therefore, having less soybean in animal diet is also possible, which would lead to a higher national soybean autarky. The results show that mitigation of several life-cycle impacts is possible and partial soybean autarky can be achieved if the farmers and other stakeholders can adapt soybean cultivation within the region.

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Toolbox for modelling climate change impacts on the environmental sustainability of the European dairy sector by 2050

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Keywords: Risk Assessment; GIS; Mathematical modelling; LCA; LCI; climate hazards; Milk.

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Rationale and objective: The European Union (EU) has adopted a net-zero emission target for 2050. In line with this flagship initiative, the EU dairy sector aims to supply the future demand for dairy products, which is projected to double, by moving towards an environmentally sustainable production by 2050 thanks to the development of mitigation strategies (IPCC, 2018). However, the environmental sustainability of the EU dairy sector is subject to climatic conditions, and thus, this transition can be challenged as climate change will modify ecosystems unevenly across regions. In this context, climate change hazards have an effect on the dairy sector's environmental sustainability due to changes in the foreground and background data of the Life Cycle Inventory (LCI). On the one hand, climate hazards lead to biophysical impacts on the dairy products value chains, mainly at the production stage (i.e. feed and raw milk production), leading to changes in the environmental impact per unit of raw milk. Raw milk losses, caused by cow's milk yield reduction due to heat stress, is one of the identified biophysical impacts that is expected to change. In addition to heat stress, raw milk losses can be caused by cow's diseases as well that alter the raw milk quality and reduce cow's milk yield. Other biophysical impacts at this stage also include changes in the crop yields and their geographical distribution caused by climate variability, crop pest infestation, and floods. Moreover, changes in on-site freshwater available for herds and crops are caused by water stress. On the other hand, the environmental sustainability of the dairy sector can also be affected by adaptation strategies to cope with the aforementioned biophysical impacts since given strategies require resources to operate.

Nevertheless, the quantification of the changes in the foreground and background data is quite complex, considering the significant number of internal and external factors involved, and the high degree of uncertainty associated with them (Guzmán-Luna et al. 2021). In this instance, PROTECT (www.protect-itn.eu), which is a Marie Skłodowska-Curie Action ITN funded under the Horizon 2020 programme, uses predictive modelling tools to evaluate the climate change effects on the dairy sector from different perspectives. Within PROTECT, the present contribution looks at defining the challenges that climate change poses to the transition of the dairy sector towards environmental sustainability by 2050. Despite the present degree of complexity and climate change uncertainty, this research presents a toolbox to model the effects of climate change on the EU dairy sector's environmental sustainability by quantifying changes in the foreground and background data caused by biophysical impacts from climate change and proposed adaptation strategies.

Approach and methodology: Based on previous work on how climate change affects the environmental sustainability of the dairy sector (Guzmán-Luna et al., 2021), it was possible to qualitatively capture all the elementary flows and links involved in that complexity (Module 3 and 4 of Fig. 1, with focus on the production stage). Around it, several modules have been constructed as depicted in Fig. 1 and detailed below.

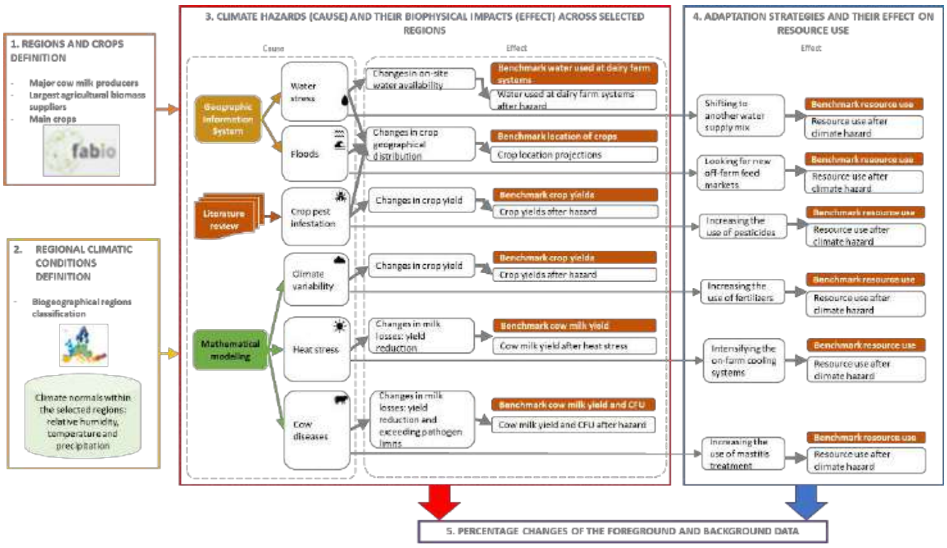

Fig 1. Framework of the toolbox to estimate changes on the LCI due to climate change at the production stage.

The first module identifies and selects the countries and the crops used in the cows' feed. First, the 10 cow milk producing countries in the European dairy sector are defined by using FABIO (Food and Agriculture Biomass Input-Output), which is a set of global multiregional supply and use tables that covers 130 commodities and 191 countries (Bruckner et al., 2019). Then, the crops supplied to those 10 cow milk producing countries are identified together with the largest supplying countries for those crops. To do so, several filters are run in Matlab (2021) to reduce the size of the FABIO database to the countries and commodities of interest. Also, at this module, the identified crops are categorized in five crop groups (i.e. cereals, oilseeds, sugar crops, grain legumes, and roots) for the sake of simplicity.

The second module defines the climatic conditions of the selected countries. Four biogeographical regions across Europe are selected: i) Atlantic (i.e. Western Europe), ii) Mediterranean (i.e. southern Europe), Continental (i.e. central, and eastern Europe), and iv) Northern, as proposed by European Environment Agency (2017). Later, open databases are used to obtain monthly climatic data on the temperature, relative humidity, and precipitation of these four regions under different climate scenarios (NASA, 2021; World Bank Group, 2021). The Representative Concentration Pathways (RCPs) are climate scenarios developed by the Intergovernmental Panel on Climate Change and they are characterized by their total radiative forcing ranging from very low (RCP2.6) to very high (RCP8.5) (IPCC, 2014). The RCP 4.5 and 8.5 are the climate scenarios used in the present contribution.

Then, the third module estimates the magnitude of climate hazards across the selected regions and estimates the corresponding biophysical impacts, whereas the fourth module estimates the effects of adaptation strategies to compensate biophysical impacts on the resource use. As shown in Fig. 1, different tools, and a combination of them, are used in these two modules depending on the climate hazard present.

Starting with the first two climate hazards, Geographical Information Systems (GIS) allows to visualize and analyse complex environmental challenges around the globe due to its robust geographical data (Eccles et al., 2019). Thus, projected georeferenced data under the RCPs scenarios from the Aqueduct project is used to define the magnitude of water stress, and riverine and coastal floods (World Resources Institute, 2022). Across regions under water stress, adaptation strategies, such as changing the water supply mix, are required to guarantee on-site water. The P-WSmix (Prospective Water Supply mix) model from Leão et al. (2018) is implemented. It is built on Aqueduct data, and it allows to project the water sources under future climate scenarios depending on the geographical location and water user.

Crop pest infestation is the next identified climate hazard. Literature (i.e. scientific papers, national and EU reports) is needed to obtain data on the crop pest infestation prevalence and the corresponding changes in yields in the five crop groups under different climate scenarios. Adaptation strategies, such as the use of pesticides, are necessary to avoid crop pests. Data from literature is used to estimate the extra amount of pesticide required based on the pest prevalence.

Moving to the next climate hazard, mathematical modelling is used to estimate changes in the yield of the five crop groups due to climate variability. The FAO's AquaCrop model, which models crop growth considering environment and management conditions, is used (FAO, 2022), and monthly climatic data from Module 2 is required. Then, adaptation strategies, such as fertilizer use, are required to compensate for yield reductions on affected crop groups. Data from literature is used to estimate extra fertilizer needs.

Following the next climate hazard, mathematical modelling is also used to estimate the number of months under heat stress and the corresponding milk losses in different climate scenarios. The Temperature Humidity Index (THI) is a common indicator used to determine when cows are under heat stress once the THI threshold (i.e. 68) is exceeded (Hempel et al., 2019). Monthly temperature and relative humidity data from Module 2 are required here. Later, available models are used to estimate the extra water and energy required by the heat abatement system (i.e. adaptation strategy) during the identified heat stress months.

Regarding the last climate hazard, mathematical modelling is used to estimate changes in milk losses due to cow diseases (i.e., bovine mastitis). The predictive model from Guzmán-Luna et al. (2022), which is based on a risk assessment approach, is used to estimate raw milk losses as a result of a reduction of milk yield and exceeding the mastitis pathogen concentration in the bulk tank milk (CFU/mL). Then, data from the literature is used to estimate the amount of mastitis treatment (µg/mL) required based on the pathogen concentration in the tank.

In the fifth module, the estimated percentage changes in the foreground and background data due to biophysical impacts (Module 3) and adaptation strategies (Module 4) can be included in the LCI, so later, it is transferred to the impact assessment stage.

Main results: To demonstrate the expected results from the toolbox, this section only shows results from the Spanish Mediterranean region, and only presents changes in the LCI due to the biophysical impacts of one climate hazard (i.e. heat stress), and the corresponding adaptation strategies. As defined in Module 1, Spain is one of the largest milk producers in Europe (Fig. 2a). To model how imported feed will be affected, the largest crops suppliers to the Spanish dairy farms are identified (Fig. 2b).

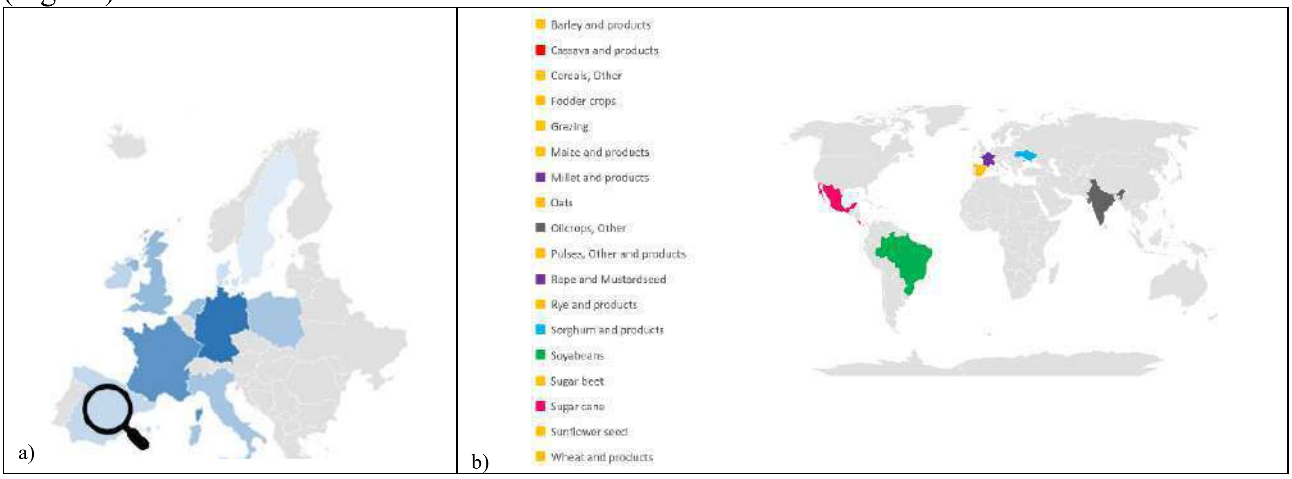

Figure 2. Largest milk producers across Europe (a) and the crops imported together with their country of origin (b).

As a result from Module 2, the temperature and relative humidity for the Mediterranean region projected by 2050 under RCP4.5 (a) and RCP8.5 (b) are displayed in Fig. 3.

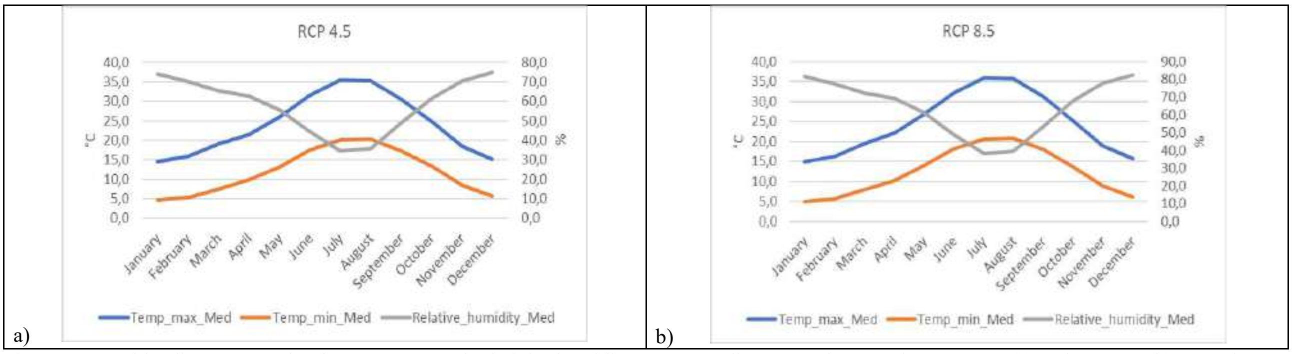

Figure 3. Monthly climate normals of temperature and relativity humidity across Mediterranean by 2050 in a RCP4.5 (a) and RCP8.5 (b) scenario.

Then, from Module 3 on biophysical impacts, Fig. 4 shows that cows will experience 6 heat stress months in a RCP4.5 (a), and 7 months in a RCP8.5 (b). It leads to an increase on the annual raw milk losses of 7% and 9%, respectively, when no improvements are considered (e.g. accounting for increase in milk yield over time or improving cows' genetic to be more resistant to heat stress).

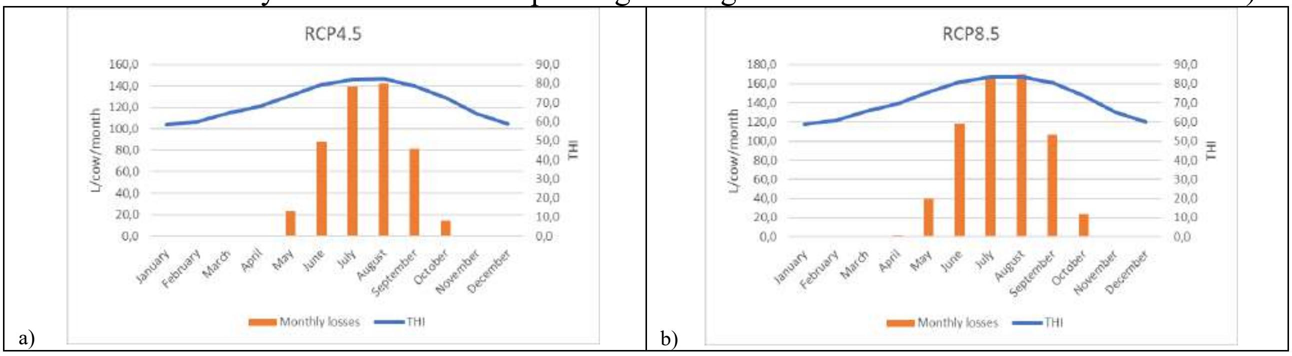

Figure 4. Number of months under heat stress (i.e., THI>68) and the subsequent monthly raw milk losses in two scenarios: RCP 4.5 (a) and RCP8.5 (b).

Lastly, as a result of Module 4, adaptation strategies (i.e. heat abatement systems) are required to relieve heat stress during those heat stress months and avoid raw milk losses. However, heat abatement systems lead to an annual increase of 23% in water and 12% in energy in an RCP4.5 scenario, and an annual increase of 24% and 13% in an RCP8.5. At this point, the future energy and water supply mix need to be considered as they affect the background data of the water and energy required.

Conclusion

A combined set of tools, such as the proposed in the present toolbox, are necessary to handle and address complex environmental issues where many interconnected factors are involved. By using the toolbox, it is possible to quantify the different variations that the dairy sector is expected to experience, both at a foreground and background level due to climate change impacts.

However, uncertainty can be present in the toolbox due to the projected data used (e.g., climatic data) as well as in the models and data extracted, both from literature and GIS. Thus, an uncertainty analysis is the next step of this research. In addition, the present toolbox only aims to estimate changes in the LCI as a consequence of climate change. Variations at the impact assessment stage might also occur as several impact categories are climate dependent, but those are left out of the scope of this research. This contribution looks at supporting the dairy sector in its transition to environmental sustainability by defining potential pathways that this sector could face by 2050.

Acknowledgment

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Environmental impact of insect-based milk alternative

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Keywords: *Insect milk; Life cycle assessment; Product development; Pulse electric fields; Tenebrio molitor.*

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Objective

The world's population will drastically increase by 2050, thus the food demand and the environmental impact of food systems will increase. It is urgent to define alternatives for high impacting foods like animal-derived products. Dairy products are in the top animal protein sources; they provide important nutrients such as fats, calcium, vitamin D and B12. Besides being a complex and unique product, bovine milk has a high environmental burden, which is accounted to the direct emissions of cows and feed production. Insect biomass, and specifically *Tenebrio molitor* larvae, has a potential to be more sustainable than animal-derived products (Oonincx and de Boer, 2012; Smetana et al., 2015; Miglietta et al., 2015; Joensuu and Silvenius, 2017; Thévenot et al., 2018). However, the environmental impact of insect as farmed animals depends on the production, preparation and transport of feed. The comparability of insect studies is highly dependable on the method and functional unit selected (Smetana et al., 2021). Therefore, current study aims to develop an alternative to bovine milk from *T. molitor* larvae and further define its environmental impact. The developed of a product is done to assure the establishment of a comparative functional unit with protein and fat correction to assure similarities in nutritional profile.

Approach and methodology

The hypothesis stated: if it is possible to develop an alternative to bovine milk from *T. molitor* larvae, it will be more sustainable than bovine milk. A preliminary literature review was performed to collect data and adapt it for experimentation. Only one experimental sample was selected as prototype due to its characteristics specially color, consistency, and stability. During product development much experimental data was gathered by controlling and manipulating variables. The data was used for the LCA which was modelled in a similar way as other studies on the environmental impact of *T. molitor* and bovine milk.

The aim of the performed LCA was to examine the life cycle stages of an insect milk prototype production from cradle to factory gate, and to identify the processes with the highest environmental impacts within the system. Due to the attributional nature of the LCA, the results were compared to standardized bovine milk from the Agri-footprint database (Blonk Consultants, Gouda, The Netherlands).

The functional unit (FU) was 1 kg of fat and protein corrected milk (FPCM). System boundaries included the stages of resource production, insect farming (including primary processing by killing through freezing at -18°C), and insect milk production (formulation, processing, and storage). The life cycle inventory (LCI) relied on different data sources: background data from ecoinvent 3.1 (ecoinvent, Zurich, Switzerland) and Agri-footprint (Blonk Consultants, Gouda, the Netherlands); insect production is modelled according to the production data from local insect supplier (Hermetia Alstätte GmbH, Ahaus, Germany) with processing data upscaled according to the industrial studies and machinery data. The results were calculated with the software SimaPro v8.5.2.0 (PRé Consultants B.V., Amsterfort, the Netherlands). The method selected for the assessment was IMPACT 2002+ (Jolliet et al., 2003). A Monte Carlo analysis was performed to estimate the uncertainty ranges of the results and draw accurate conclusions.

Main results and discussion

Pilot scale trials identified a potential recipe and process to develop an insect-based milk alternative. The insect milk prototype was composed by *T. molitor* larvae, water, ascorbic acid, *T. molitor* extracted fat, and sunflower lecithin. The nutritional composition of the obtained insect milk was 1.19 % crude protein, 5.76 % lipids, < 1 % carbohydrates and 0.30 % ash. The insect milk showed no phase separation after two weeks of storage at 4°C. The production yield was 50 %, meaning half of the initial mixture was an exoskeleton puree, and can be considered as a side product useable for feed. It should be noted that majority of proteins remained in the press cake. To reduce the losses of proteins in the press cake, a Pulsed Electric Field (PEF) pre-treatment as a gentle physical electroporation method has been used, which increased the protein content in the prototype milk from 1.2% to 2.8%.

The results of the LCA presented that the ingredient *T. molitor* frozen larvae was responsible for 73.8 % of the impact of 1 kg FPC insect milk (more than 70 % of the impact was allocated to the insect diet composed of carrots and oats. 1 kg of FPC insect milk had an impact on climate change of 0.764 kg CO_2eq. and demanded 10.55 MJ primary energy. The comparison between standardized bovine milk, showed that insect milk had overall significantly lower environmental impact (307.62 μPt lower than bovine milk). However, insect milk presented higher or similar burden in the categories of non-renewable energy, mineral extraction, land occupation and global warming. It is necessary to point out that literature sources indicate higher impact for these categories for bovine milk (e.g., for Global Warming Potential in the range of 1.09-2.4 kg CO_2eq. kg^{-1} FPCM).

Conclusion

This study tested the feasibility of an insect-based milk alternative production and its environmental impact. Development trials identified a successful method and recipe for the development of the elementary prototype of "insect milk", further improved with the application of PEF technology. The Life Cycle Assessment served as guidance for further product development and improvement by identifying the current hotspots of the life cycle. The impact of insect milk prototype was 0.76 kg CO_2 eq. kg^{-1} FPCM in global warming potential, the land use was 0.93 m^2a and the primary energy required 10.55 MJ; most of the burden was caused by feed production. The environmental analysis performed in this study determined that insect-based milk had a potential to become a product with low environmental impact. The results could further be improved by selecting a low impact diet and energy sources with lower environmental burden.

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Lowering the carbon footprint of milk production: a life cycle assessment of European dairy farms

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Keywords: *Life cycle assessment modelling; carbon footprint; dairy production*

Abstract:
The objective of this study was to compare carbon footprints (CF) of European dairy farms using life cycle assessment (LCA). Data was collected on a monthly basis over two years from 71 commercial dairy farms in Ireland, Northern Ireland, England, Spain (Galicia and Basque regions), Portugal and France. The emissions up to the point of sale of milk from the farm were calculated within a global boundary. The functional units were: (i) per kg fat and protein corrected milk (FPCM); (ii) per hectare of the farm exporting milk; (iii) per hectare of global land use. Farms were categorized based on the proportion of time that cows spent grazing and mean carbon footprints (CF) were 1.13, 1.23 and 1.50 kg CO_2-eq./kg FPCM for GRAZING (>60% grazing; n = 16), MIXED (up to 60% grazing; n = 17) and HOUSED systems (0% grazing; n = 38), respectively. HOUSED had the largest range; between 0.88 and 2.49 kg CO_2-eq./kg FPCM and included the farm with the overall lowest CF. HOUSED had the highest mean CF per ha of the farm exporting milk: 43.33 t , followed by MIXED (15.06 t) and GRAZING (11.62 t). There was the same ranking per ha of global land use; for HOUSED (14.87 t), MIXED (9.74 t) and GRAZING (9.25 t). A sensitivity analysis comparing the use of higher tier emission factors (HTEF) compared to default values (DEF) showed the HTEF method resulted in a 2.0-7.9% lower CF than DEF method. There was large variation in the CFs of these farms indicating considerable potential to identify best practices for lowering emissions per product and area-based functional units.

Introduction
The dairy sector faces a major challenge to reduce greenhouse gas emissions to meet national targets in light of EU commitment to net zero emissions by 2050 (European Commission, 2019). The dairy sector is also a major source of social and economic stability, which is why

we need suitable mitigation strategies for the different systems of dairy production in Europe. Life Cycle Assessment (LCA) is a method used to account for the emissions for the life cycle of a product, e.g. milk. The International Standards Organisation have outlined the procedures for LCA (ISO, 2006a, b). However, there remains ambiguity around methodology and assumptions used for LCA of milk production (Yan et al., 2011, Baldini et al., 2017, Lorenz et al., 2019). Choices made by the LCA practitioner about allocation method, boundary, and functional unit for example, will affect the final carbon footprint value (O'Brien et al., 2014, Zehetmeier et al., 2014, Salou et al., 2017, Herron et al., 2019). Consequently, comparing LCA studies, especially across different countries, can be difficult.

When compiling the inventory component of an LCA study, emission factors (EF) or algorithms are described by a tier system. Higher tiers are associated with lower levels of uncertainty (IPCC, 2019). Governments are encouraged to carry out national research to identify EFs that are more appropriate for a country's climatic conditions. Hence, they can better predict emissions especially for activities that make up a large proportion of the emissions from a farm. For example enteric methane from livestock typically accounts for more than half of total emissions from a dairy farm (FAO, 2022). In this study, we have used detailed farm data to assess GHG emissions from different systems of dairy farming using one LCA model. The model has been adapted to incorporate higher tier EFs, where possible, to be able to detect farm practices that lower emissions on different systems of dairy production. A sensitivity analysis was also conducted to identify the effect of using default emission factors from the IPCC guidelines (2019) compared to the higher tier EFs provided by literature.

Material and Methods

A total of 71 dairy farms were selected from nine regions across Europe (The republic of Ireland, Northern Ireland, England, Galicia (Spain), Basque country (Spain), Normandy, Pays de Loire, Brittany, Portugal) as part of the Interreg Dairy-4-Future project. Farm data covering monthly animal numbers, diet composition, land use, manure management, grazing status, milk production, fertiliser, lime, forage and concentrate stocks, contractor, chemical and energy use was collected over a period of two years (2018, 2019) via interview, online survey and telephone communication. Regional data regarding monthly temperatures and average crop yields were also collected from region. Data was validated with the farmers, their advisors, and national livestock databases to achieve a high standard of accuracy. The farms were grouped according to the proportion of time that cows were outside grazing (with grazed pasture making up the majority of intake) during a calendar year: GRAZING = >60% of time spent grazing, MIXED = ≤60% of time spent grazing, HOUSED = 100% time housed (Table 1).

The carbon footprint was assessed using a life cycle assessment (LCA) model used by O'Brien et al. (2010) and adapted for use in this study to account for the different climatic conditions and dairy systems operated in the Atlantic Area regions. The model was created in Microsoft Excel, which allowed greater resolution modelling compared with generic LCA softwares with the detailed data collected. The study quantified emissions using a cradle to farm-gate boundary, excluding emissions from infrastructure and medicines. Higher tier emission factors/algorithms were used, if available. A sensitivity analysis was done to compare the CF results with higher tier EFs, 'HTEF', compared to default EFs from the IPCC (2019) and EEA (2019), 'DEF', guidelines. The results were compared according to countries (Ireland, UK, Spain & Portugal, France). The EFs for Spain and Portugal were the same and, hence, were grouped together for these assessments.

The emissions from meat from cull cows and surplus calves were allocated using the biophysical approach specified in the International Dairy Federation guidelines (IDF, 2015). Emissions (kg CO_2-equivalents) were expressed using the two functional units: 1 t of fat and protein corrected milk (FPCM), 1 ha of on-farm land (land on which the milk was produced) and 1 ha of global land (including land used to produce feed imported onto farms). The choice of FUs represent the efficiency of the dairy operation and the impact on land use. Using emissions per ha of global land use allows consideration of the land used in milk production.

The Statistical Analysis Systems (SAS) Institute software package (SAS institute Inc., 2013) was used to evaluate the relationships between CF and farm parameters of the different systems. Normality and equality of variance was assessed visually and a one-way ANOVA analysis performed to determine the effect of system type on CF, followed by Tukey's post-hoc test for significance in pairwise comparisons. The stepwise multiple regression procedure was used to determine parameters of significance in relation to the CF. Variance inflation factors were used to check for multicollinearity.

Table 1. Overview of the mean key farm characteristics and the CF from the three dairy systems

Item	Unit	System			SEM	P-value[a]
		Grazing	Mixed	Housed		
Number of farms	#	16	17	38		
On-farm land area	ha	113.3	127.8	63.6	9.17	**
Arable land	ha	4.0	16.5	21.9	2.26	**
Stocking rate	LU/ha	2.04	1.99	4.20	0.215	***
Dairy cow replacement rate	%	26	31	35	1.2	**
Average cow liveweight	kg	554	625	658	7.3	***
Mean time spent grazing	%	68	42	0	3.5	***
Annual milk production	kg FPCM/cow	5,889	8,371	9,793	243.5	***
Milk fat	%	4.34	4.14	3.74	4.512	***
Milk protein	%	3.56	3.32	3.27	2.212	***
Concentrates imported onto the farm	t/LU	0.93	2.24	3.29	0.169	***
Forages imported onto the farm	t/LU	0.37	0.31	1.21	0.137	**
Fertiliser N	kg N/ha	202	132	124	11.9	**
Nitrogen use efficiency	#	0.48	0.37	0.33	0.042	ns
Phosphorus use efficiency	#	1.24	0.72	0.52	0.132	**
Electricity usage	kWh/cow	371	365	509	26.7	**
Diesel consumption	L/cow	80.7	115.2	141.6	6.2	***
Carbon Footprint	kg CO_2 eq./kg FPCM	1.13	1.23	1.50	0.039	***
	t CO_2 eq./on-farm ha	11.62	15.06	43.33	2.663	***
	t CO_2 eq./global ha	9.25	9.74	14.87	0.526	***

[a] Significance levels derived from an F-test comparison are *** = P<0.001, ** = P<0.01, * = 0.05, and ns = non-significance (P>0.05).

Results & discussion

The housed system had a higher (P<0.001) CF per kg FPCM, per ha of on-farm land and per ha of global land than MIXED and GRAZING respectively (Table 2). HOUSED had a different emissions source profile compared to GRAZING and MIXED. A stepwise regression of HOUSED showed that the proportion of uncovered slurry storage, feed efficiency, concentrate use and milk yield per cow explained 72% of the variation in carbon footprint on these farms.

A decrease in emissions intensity with an increase in milk yield in the HOUSED system is in line with previous studies (Gerber et al., 2011, Lorenz et al., 2019). However, there were no similar relationships for GRAZING and MIXED (Figure 1).

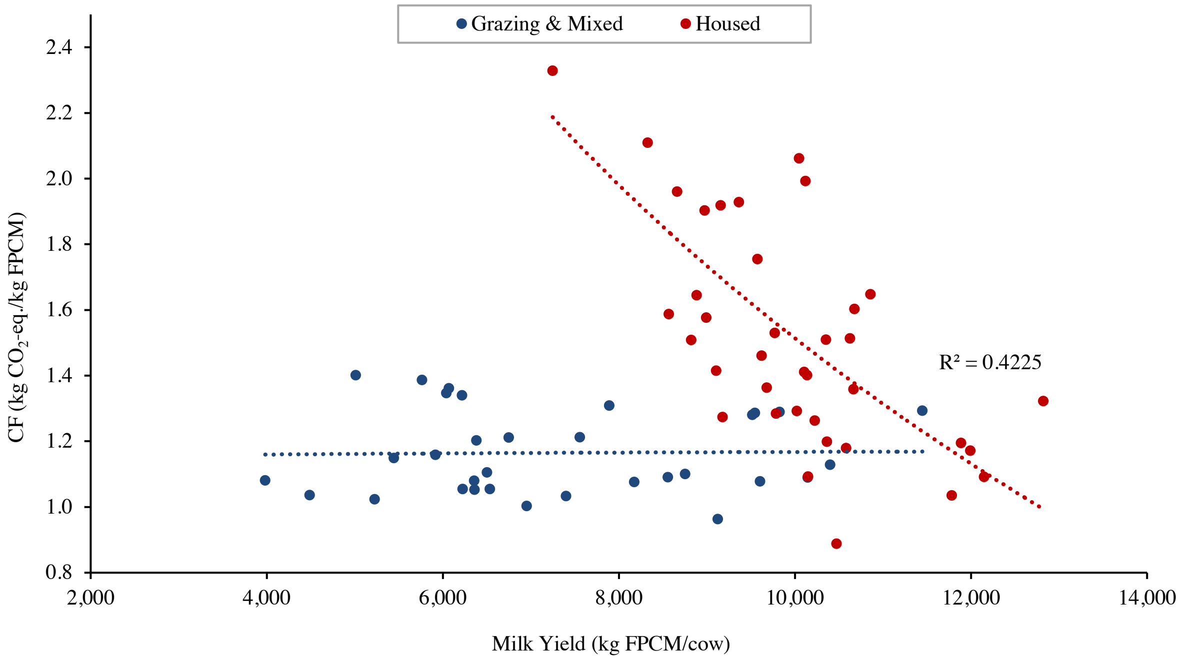

Figure 1. Relationship between annual milk output per cow (kg FPCM/cow) and the carbon footprint (kg CO_2eq./kg FPCM) on three different systems of milk production in the Atlantic Area of Europe. See text for a description of the systems

In this study, the emissions from manure management and concentrate use in HOUSED meant a significantly higher carbon footprint despite higher milk yields than GRAZING and MIXED. However, CFs in line with GRAZING and MIXED were achievable when milk yields were greater than 10,000 kg FPCM/cow. The results of the stepwise regression from GRAZING and MIXED showed that age of first calving, nitrogen surplus and feed efficiency were significant factors in determining the CF per kg FPCM. Stocking rate was the common factor for determining CF using the area FUs for all systems.

The sensitivity analysis showed that carbon footprint decreased by 2.0 - 7.9% using the HTEF compared with DEF. The magnitude of the difference depended on the HTEF available for the different regions. Some HTEF emission algorithms used farm-specific data to determine methane from enteric fermentation (dairy cow diet composition and intake) and from liquid slurry storage (slurry removal timing, regional temperature), which also affected the differences in the two methods.

Conclusion

Previous studies have compared the carbon footprint from housed and grazing systems but have been limited in sample size, comparability and resolution of the modelling. Grazing and mixed systems did have lower footprints on average, however the greater variation in the housed system shows great mitigation potential. The HOUSED regression model showed that mitigation strategies such as covering manure storage and reducing concentrate input have the capacity to greatly reduce CF, and indeed the lowest CF of all farms was a housed system. The sensitivity analysis showed that great disparities can arise between CFs depending on the emission factor or algorithm used. Using detailed data allows for high-resolution carbon footprinting and determination of effective, farm-specific mitigation strategies.

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Regionalized life cycle assessment of renewable energy and waste valorization technologies for the Canadian egg industry

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Rationale:
Due to being the fastest growing market among livestock products along with increasing scrutiny regarding the sustainability impacts of livestock production, the Canadian egg industry is striving towards reducing its net emissions and overall environmental footprint (Pelletier et al. 2018). Direct energy use contributes between 1-9% of total life cycle emissions in the egg industry, depending on province, while manure management is the largest contributor to life cycle acidifying (45%) and eutrophying (46%) emissions as well as being a large contributor (i.e. 17-46%) to GHG emissions (Pelletier 2017; Turner et al. 2022). Green technologies for renewable energy generation and waste valorization offer potential opportunities for mitigating resource use and emissions in the egg industry. However, to date, there has been no systematic accounting of the distribution, scale, feasibility, mitigation potential and scalability of these technologies specifically for the Canadian egg industry (Kanani et al. 2020).

Objective:
The purpose of this research was to identify a subset and assess the mitigation potential of renewable energy and manure valorization technology options and deployment scenarios that are potentially most suitable for Canadian egg farms on a regional basis, taking into account available renewable energy resources, environmental payback times for the technology systems, and potentially displaced conventional energy sources.

Methods:
GIS was used to map the coincidence of Canadian egg farms with location-specific renewable energy resource availability. Farms located in zones exceeding minimum thresholds for wind and solar energy generation were identified for further analysis, and all farms were considered for potential manure valorization via gasification and biodigestion. Environmental payback times were calculated for each technology/region, taking into account displaced conventional energy resources in order to identify those farms for which an environmental payback would be achieved within the anticipated lifespan of a renewable energy generation system. Regionalized life cycle assessments were then utilized to understand and compare the relative efficacy (% reduction in impacts per tonne of eggs produced) of these technologies for environmental impact mitigation potential in the Canadian egg industry.

Results:
The results of these analyses demonstrate the potential to substantially reduce resource use and

emissions per tonne of eggs produced in four key provinces (Alberta, Saskatchewan, Nova Scotia, New Brunswick) that operate predominantly on fossil-fuel based electricity grids. Both solar and wind energy (wind speeds > 4 m/s) technologies are suitable in these provinces, with reasonable environmental impact payback times (eIPBTs). In provinces with greener electricity grid mixes (British Columbia, Ontario, Newfoundland and Labrador), long eIPBTs preclude consideration of on-farm solar PV systems and a minimal emissions reductions potential associated with on-farm wind turbine installations. Results for Prince Edward Island were mixed. This was the same case for two principal waste valorization technologies identified as potential options for the egg industry (anaerobic co-digestion and gasification). Based on an LCA study, both technologies were found to be more beneficial than direct land application of manure, with the exception of land occupation impacts. Anaerobic co-digestion has the greatest resource use/emissions reduction potential. Specifically, resource/environmental impact mitigation potential per tonne of eggs ranged from 10-15% for climate change impacts and 22-41% for cumulative energy use for both wind and solar technologies in provinces with "dirty" electricity grids. The emissions reductions potential for gasification ranged between -2-21% for climate change emissions and -5-56% for cumulative energy use, depending on province of deployment. For biodigestion, which produces methane in substitution of conventional natural gas and whose mitigation potential is hence not province-specific, the estimated environmental impact payback time for the digester was 6 years for climate change and <1 year for cumulative energy use, and life cycle resource/environmental impact mitigation potential was 21-23%/tonne of eggs for climate change impacts and 94-119%/tonne of eggs for cumulative energy use) for an average sized egg farm across provinces.

Conclusions:

This study emphasizes the importance of regionalization in LCA in order to accurately characterize potential life cycle impacts in agricultural systems and candidate mitigation technologies, which are highly variable in time and space. It also shows that adoption of specific renewable energy or manure valorization systems on farms in some regions can substantially reduce the net life cycle impacts of egg production on Canadian egg farms.

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The effect of emission reduction strategies on other environmental impacts in Australian egg and chicken meat production

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Rationale and objectives

Under pressure to develop and implement pathways to greenhouse gas (GHG) emission reduction or net zero emissions, agri-food producers need to identify viable mitigation strategies. However, environmental burden shifting is not commonly considered. The objective of the study was to use attributional life cycle assessment (aLCA) to screen GHG mitigation strategies and evaluate the effect on other environmental indicators, especially fresh water and land availability. These indicators were selected based on relevance to economy-wide and industry research priorities.

Approach and methodology

Scenario analyses were completed using a standard model of Australian chicken meat and egg production supply chains. Inventory data were collected from Australian egg producers and vertically integrated chicken meat processors as part of a baseline study (see Copley & Wiedemann, *in preparation* and Copley & Wiedemann, *in press*). Industry coverage was 40 % of the industry for eggs and 50 % for chicken meat.

The egg supply chain included breeding and hatchery processes, pullet rearing, and layer farms through to grading floors, with all associated inputs. The endpoint of the supply chain was the cold storage unit where eggs are stored prior to wholesale distribution, which was located at the grading site. The functional unit (FU) was 1kg of eggs ready for wholesale distribution. Results are presented for cage, cage-free (barn) and free-range production. The chicken meat supply chain included breeding (rearing of parent birds, fertile egg production and hatchery processes), grow-out and meat processing, with all associated inputs. The endpoint of the chicken meat supply chain was the cold storage unit where chicken meat is stored prior to wholesale distribution. The FU of 1kg of chicken meat product ready for distribution to retail reflects the retail product mix: whole birds, bone-in and boneless portions. Results are presented for conventional and free-range production.

All modelling was performed using SimaPro™ 9.3 (Pré-Consultants, 2021). In accordance with ISO 14067 (ISO 2018), GHG emissions associated with land use (LU) and direct land use change (dLUC) were included and reported separately. GHG emissions were assessed using IPCC AR5 global warming potentials (GWPs). Fossil fuel energy demand was assessed by aggregating fossil energy inputs throughout the system and reporting these per megajoule (MJ) of energy, using Lower Heating Values. Fresh water consumption (L) was assessed using methods consistent with ISO 14046 (ISO, 2014). Stress-weighted water use was assessed using two methods: the Water Stress Index (WSI) of Pfister et al. (2009) and the Available Water Remaining Method (AWARE) method (Boulay et al., 2018) for comparison. Land occupation, reported in square metres (m^2) was assessed by aggregating impacts throughout the supply chain.

A literature review was completed identifying a wide range of potential GHG mitigation options (n = 18) that could be suitable for the Australian egg and chicken meat industries. Screening was performed by identifying the GHG emission source to be reduced (e.g. on-farm energy use), the mitigation strategy (e.g. solar) and the mitigation potential (assessed using the standard industry models). An adoption rate was then considered, based on the likely uptake of the strategy or technology. Based on these criteria, options were either screened 'in' or 'out'. Multi-indicator analysis was then conducted on each of the viable strategies and technologies.

The following dietary and technology modules were modelled: M1 (a. substitution of 30 % of soybean meal with canola meal; b. substitution of 30 % of soybean meal with cottonseed meal), M2 (adoption of solar on layer and grow-out, breeder and rearer farms offsetting 30 % of grid electricity demand at each site), M3 (10 % reduction in dietary crude protein for free range birds), M4 (energy efficiency measures), and M5 (anaerobic digestion (AD) on layer farm; covered anaerobic ponds at meat processing plants).

Results and discussion

Baseline results for Australian egg and chicken meat production are reported in Copley & Wiedemann (*in preparation*) and Copley & Wiedemann (*in press*).

Substituting soymeal with alternative proteins resulted in elevated water consumption and water stress (alternative: cottonseed meal) and higher land occupation (alternative: canola meal). Because crop systems vary widely in land management, yield and irrigation usage, this was seen as the least consistent strategy for mitigation of multiple impacts concurrently when using a substitution strategy, suggesting care should be taken with this approach. Alternatively, improving feed efficiency could uniformly reduce impacts and would be a more reliable strategy.

M2 and M4 reduced GHG emissions and fossil energy, without increasing impacts across other categories. M3, only significant in free range systems, reduced GHG emissions slightly without affecting other impact categories. For chicken meat, M5 resulted in slightly lower GHG emissions (driven by reduction in GHG emissions at the meat processing plant) and did not have perverse effects on other indicators.

The impact assessment results for M5 (reported for chicken meat only) revealed the sensitivity of the results to production location and system design. AD did not affect freshwater consumption, water stress, water scarcity or land occupation impacts per kilogram of eggs. Integration of the digester with a combined heat and power (CHP) unit, for example, could also result in reduced fossil energy consumption. Depending on where production occurs (e.g., which state), methane leakage from the AD could increase GHG emissions more than they were offset by the reduction in fossil energy consumption. In the Australian state of Tasmania, for example, which has Australia's lowest emission intensity energy grid, methane leakage from an AD on a layer farm resulted in GHG emissions 10% higher than baseline emissions whilst in Victoria (Australia's highest emission intensity energy grid) an identical farm reduced GHG emissions 10% lower than baseline emissions.

The results demonstrate the importance of not only multi-indicator analysis of GHG mitigation strategies but of the need for appropriate consideration of geographic factors, e.g., the viability of a technology in one jurisdiction does not guarantee its application will be beneficial in another.

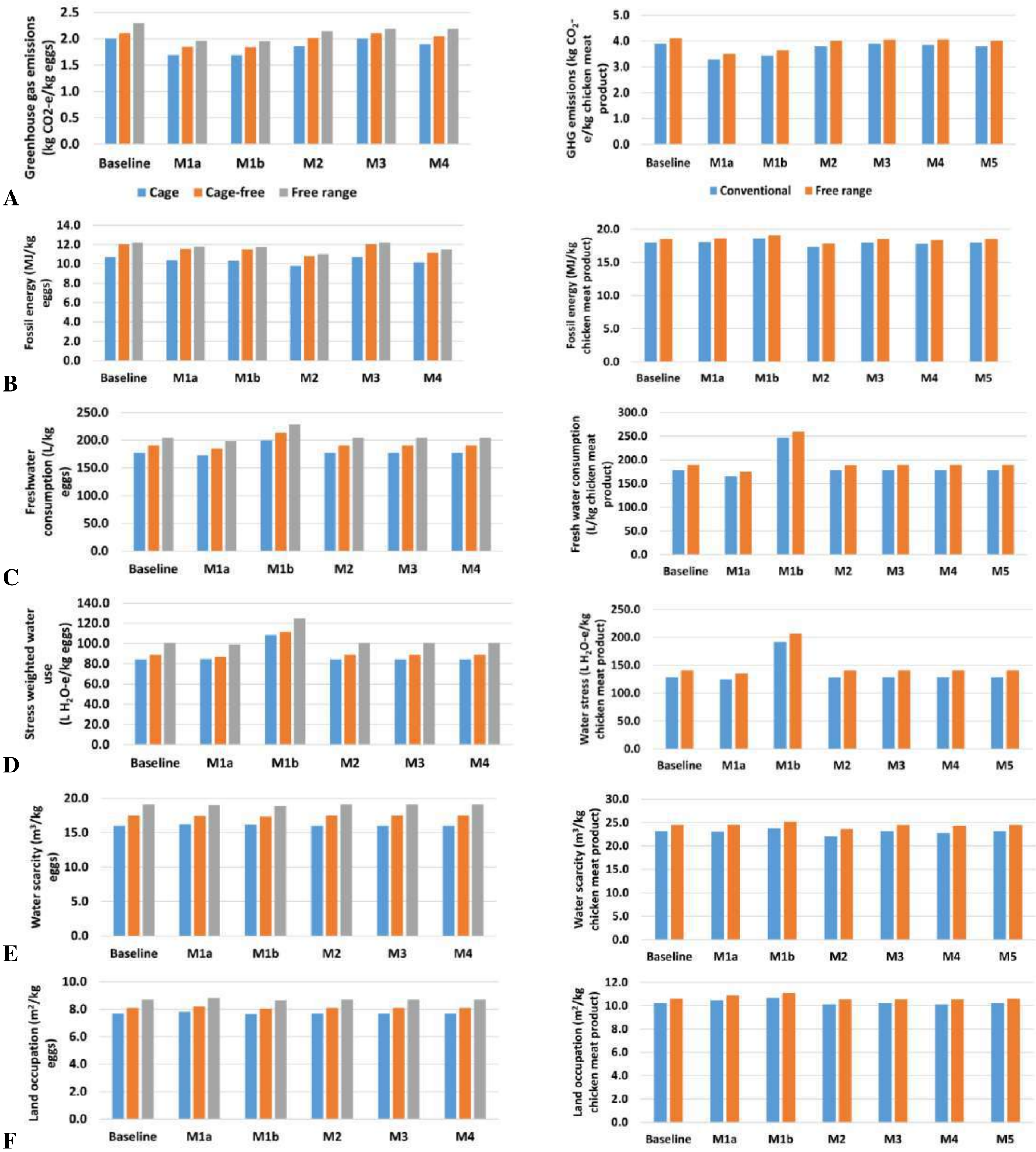

Figure 1. Greenhouse gas (A), fossil energy (B), fresh water consumption (C), water stress (D) and scarcity (E), and land occupation (F) impacts per kilogram of eggs and chicken meat under selected greenhouse gas emission reduction scenarios.

Conclusions

GHG emission reduction is arguably the major environmental challenge facing agri-food industries. However, there is a danger that agricultural industries will, in response to pressure from customers, consumers, governments and investors, take swift action and implement reduction strategies without adequate investigation of other impacts, leading to burden-shifting. Scenarios that consider GHG emissions alone can increase other impacts under some circumstances, but conducting multi-criteria analysis identified those that reduced GHG without trade-offs with other impacts considered here, providing an approach to delivering broader sustainability outcomes for poultry production.

While not the immediate focus of this paper, the results demonstrated how geographic factors can render emission reduction strategies viable in some regions and detrimental in others, highlighting how the viability of mitigation technologies and strategies needs to be assessed on a region-by-region basis rather than assuming that proven application and emission reduction in one jurisdiction will be reflected in all.

Efficiency and renewable energy strategies were found to more reliably reduce impacts across the indicators assessed. Conversely, substituting different diet commodities resulted in variable findings between impact categories. Preferencing strategies without burden-shifting risks is recommended.

For policymakers, the findings demonstrate the need for broader scrutiny of and consideration of burden-shifting risks in policies and targets; too narrow of a focus on one environmental priority now may inadvertently lead to greater harm in other (emerging) environmental priorities in future.

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Assessment of environmental and economic performance on Swiss farms

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Keywords: *environmental efficiency, economic performance, agriculture, product groups*

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Introduction

Agricultural production of food products accounts for a substantial share of humanities environmental impacts (Kuempel et al., 2020). In recent years, there is an increasing need to manage and improve its effects on the very resources it depends on. In Switzerland there have been multiple public votes on issues ranging from stronger regulation of plant protection products, protection of the natural landscape or on questions of animal welfare. At the same time, the generated income for family labor on Swiss farms is below the reference income for the third sector (Lips et al., 2017). Starting from these two observations, this study poses the question if the two dimensions environment and economy can be reconciled in agricultural production in Switzerland, or if there are inherent trade-offs at the product group level.
The role of the product group is of special importance, as many studies have shown, there is a large variability of the environmental impacts between product groups (Poore & Nemecek, 2018). Similarly, the contribution to the family workforce income varies considerably between product groups (Lips et al., 2017). Therefore, in order to gain an understanding of the fundamental relationship between environmental impact and economic performance of agricultural production, the assessment needs to be done at the product group level.
While there are multiple studies that assess the environmental and economic performance of agriculture at the farm level, to our knowledge there exist no joint analysis of the environmental and economic performance at the product group level, simultaneously covering multiple product groups.

Methodology

The sample used in this study consists of 191 farm year observations of Swiss farms producing output groups Milk, Cattle, Cereals, and Potatoes along the integrated farming guidelines. The farms cover all three production regions in Switzerland (valley, hills, mountain region) and includes 20% farms producing according the organic farming guidelines. The remaining farms produce according the Swiss proof of ecological performance (PEP) program.
We used the Swiss Life Cycle Assessment tool SALCA (Gaillard & Nemecek, 2009) to calculate the extent of nine environmental impacts per produced amount of output for each product group (Table 1). For the economic performance indicators full cost methodology was used to calculate the contribution of each product group to the family labor income (Lips et al., 2018). Full cost methodology uses standard costs to calculate the share of contribution to the family workforce income by accounting for all direct and indirect costs and revenues. The life cycle impact categories were aggregated using data envelopment analysis (DEA, (Andersen & Petersen, 1993)) to calculate the relative measure of environmental efficiency, where each observed producer was benchmarked against all other observations of the same product group (Pedolin et al., 2021). The usage of DEA in combination with LCA impacts allows the aggregation of the different impact categories in order to score the total relative environmental efficiency of the observed producers. The resulting score is a relative measure of efficiency, with the best observed producer for each product group achieving a

score of 1 (i.e. 100% relative environmental efficiency). In the recent years there has been an increase in studies with joint application of DEA + LCA (Vásquez-Ibarra et al., 2020).

Table 1. Used mid-point indicators in the impact assessment

Description	Unit	Method
Non-renewable fossil and nuclear energy	MJ eq	ecoinvent
Land competition	m^2 year	CML 2001
Deforestation	m^2	SALCA (LCI calculation)
Total water use	m^3	SALCA (LCI calculation)
Global warming potential 100a	kg CO_2 eq	IPCC
Acidification	cmol H+ eq	GLO
Eutrophication	Person year	GLO
Freshwater ecotoxicity organic + inorganic	PAF m^3 day	USEtox V2.11
Human toxicity cancer + non-cancer	cases	USEtox V2.11, combined with Fantke and Jolliet (2016)

Results

We found that the production region has an effect on the environmental efficiency, with production in the mountain region (milk and cattle) having lower environmental efficiency than in the valley and hill region (Figure 1).

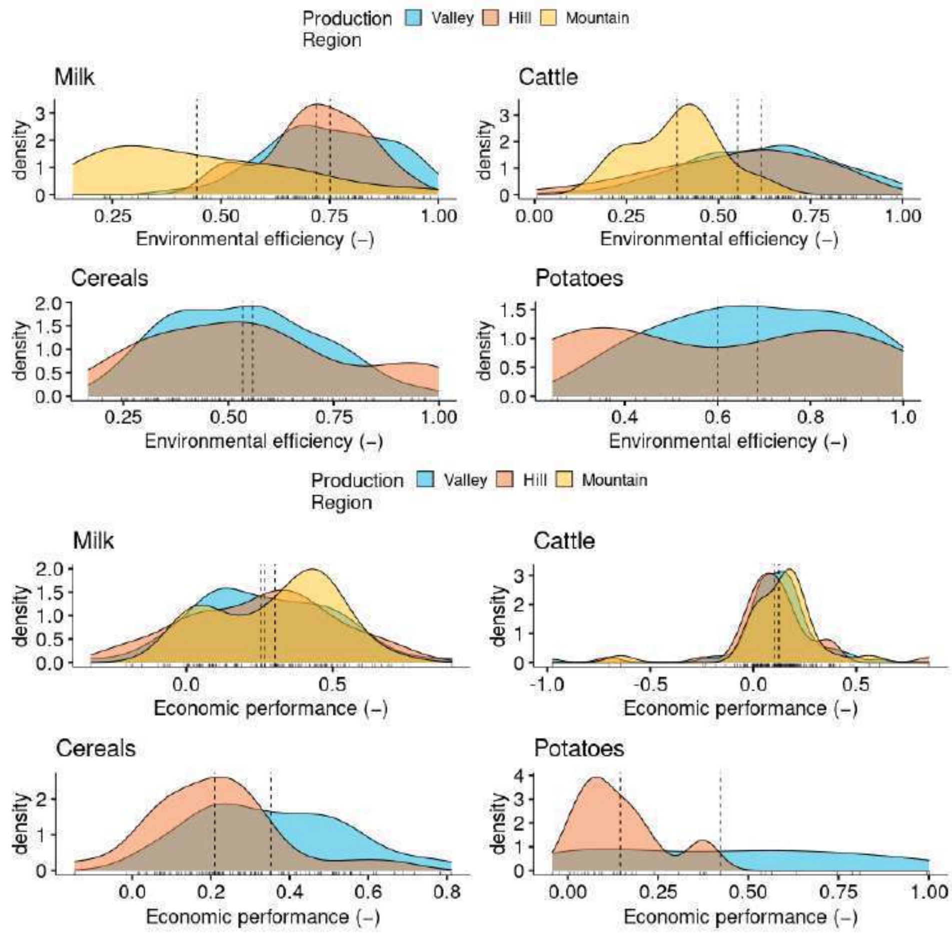

Figure 1: Distribution environmental efficiency score (top) and economic performance indicator (bottom) for PEP farms in the three production regions. Shown are density distributions (colored area) and man values (dotted lines). PEP = Proof of ecological performance (Swiss integrated farming guidelines)

We did not observe a corresponding effect on the economic performance. For the crop products (Cereals, Potatoes), we calculated slightly better economic performances for the valley region than hill and mountain. All observed differences were not significant at the 5% level. The differences in economic performances for crop products between the regions can largely be explained by differences in productivity. The valley region allows for higher productivity (due to favorable terrain and longer vegetation period) and is more suitable for mechanized farming. The lack of similar effects on the income is most likely due to compensation for production under difficult circumstances in the form of direct payments.

We could not identify any significant negative correlation for any of the assessed product groups between environmental and economic dimension. On the contrary, for milk in the valley region and cattle in the valley and hill region, we found significant positive correlations (Figure 1) between the two dimensions.

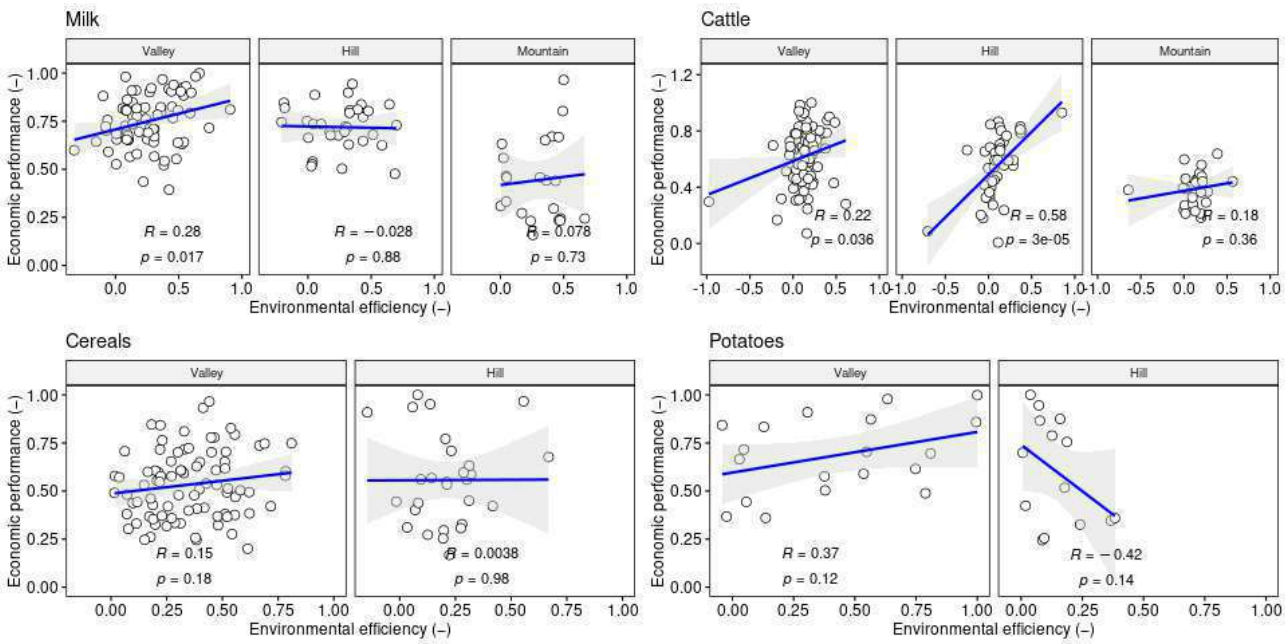

Figure 1: Correlation of environmental efficiency and economic performance for the production regions. Shown are Pearson's correlation coefficients R and their p-values.

Discussion

The negative effect of the production region mountain on environmental efficiency found in this study falls in line with results by Marton et al. (2016) who also found an overall higher environmental impact for cattle and milk production in the mountain region. However, they emphasize the comparative environmental advantage by freeing areas in the valley region for crop production. The relationship between environmental and economic performance found for milk production is similar to the findings by Repar et al. (2018), where Swiss dairy farms were assessed for correlations between economic and environmental performance at the farm level.

Conclusions

The findings imply that there is no inherent trade-off between economic and environmental performance, even for the less favorable production regions. The observed large variance in environmental and economic performance hints at a substantial potential for simultaneous improvement in both dimensions. Since the methodology used observed performances as benchmarks and not some hypothetical best-case scenario, we can expect that the observed gap could (at least partially) be closed, if the producers with below median performances were able to learn from their better performing colleagues. This potential for learning and adaption is at the focus of a current publication using the same data and methodology.

Additionally, we showed that the combination of life cycle assessment, data envelopment analysis and full cost analysis can be used to successfully identify potential synergies between economic and environmental performance of agricultural production systems.

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Environmental profile of chicken meat supply chains: focus on food wastage, consumer behavior, and packaging

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Despite life cycle assessment (LCA) being a robust and standardized methodology, LCA research has overlooked some items within food supply chains such as food loss and waste (FLW) (Notarnicola et al., 2017). FLW is defined as "the decrease in quantity or quality of food along the food supply chain". Food loss occurs at the beginning of the supply chain and food waste at the end (FAO, 2019). Food-packaging systems and consumer behavior can affect FLW in numerous ways and are often excluded from scientific research. One example is packaging that is too large, which hampers the entire consumption of foods in time (Molina-Besch et al., 2018). Also, consumers lacking routines of reusing leftovers might waste more food (Bravi et al., 2020). However, little research has addressed FLW and its relation to food-packaging systems and consumer behavior in estimating the environmental profile of foods. Particularly, products with high environmental burdens such as chicken meat are relevant to investigate.

This study aims to assess the environmental impact through LCA of the combination of four packed chicken products and four types of household behaviors within a Belgian (Flemish) context. The chicken products are diced chicken breast 0.5 kg, chicken breasts 1 kg, chicken breasts 0.5 kg, and frozen chicken breasts 1 kg sold at various Colruyt supermarkets across Flanders. The household behaviors include, amongst others, various household chicken waste percentages as stated in Cooreman-Algoed et al. (2021). They were called, in increasing percentages of chicken waste, non-wasters, minor wasters, mild wasters, and major wasters.

The life cycle covers the chicken farm, poultry processing, meat cutting and packaging, distribution, retail, consumer, and end-of-life (EoL). The functional unit is "the average yearly consumption of a packed Colruyt chicken meat product per Flemish household (18 kg)". The impact assessment method is the Environmental Footprint 2.0 single score (EC, 2013).

The results demonstrate that the behavior of 'major wasters' increases the environmental profile of the entire food chain by 8.4% compared to the 'non-wasters'. The impact of the product with the worst score, diced chicken breast 0.5 kg, rises 9.6% compared to the one with the best score, chicken breast 0.5 kg. Both these increasing percentages are chiefly attributed to the peeking food waste levels in households and surplus food (i.e. edible food that is not sold or consumed by the intended customer; Garrone et al., 2014) amounts at retail, respectively. The burden of food waste at the consumer level is by a factor of ten higher than those of packaging production and EoL. Overall, the environmental impact of the average Flemish consumer is 2.3-4.0% higher than for 'non-wasters', depending on the purchased chicken product.

This study stresses that LCA research on foods should not overlook food wastage in relation to consumer behavior and food-packaging systems. It offers insight into the importance of minimizing FLW in order to allow global food security, particularly relevant for countries with strong or fast-growing agricultural production systems such as emerging economies.

More details on this research can be found in Cooreman-Algoed et al. (2022).

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Global warming and eutrophication potential of a sweater produced from Peruvian alpaca fiber

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1. Introduction

In the Andes, the production of alpaca fiber is an activity of high cultural and economic importance and especially in Peru, which is home to 72% of the world's alpaca population (Midagri, 2021) this activity contributes to the economic livelihood of more than 82 000 smallholder families (Midagri 2019a). In 2019, alpaca fiber production represented 1.35% of total Peruvian exports and 5% of non-traditional exports (Midagri, 2019b). As textile production is among the world's most polluting industry sectors (Change NC, 2018) and current consumer trends in international markets show a growing preference for products that meet environmental, social and cultural standards, interest in sustainable alpaca fiber production is also growing in Peru. In order to provide basic data about the environmental impacts of Peruvian alpaca production systems as well as information related to the use and end of life of a garment made of alpaca fiber, a life cycle analysis of this product has been carried out.

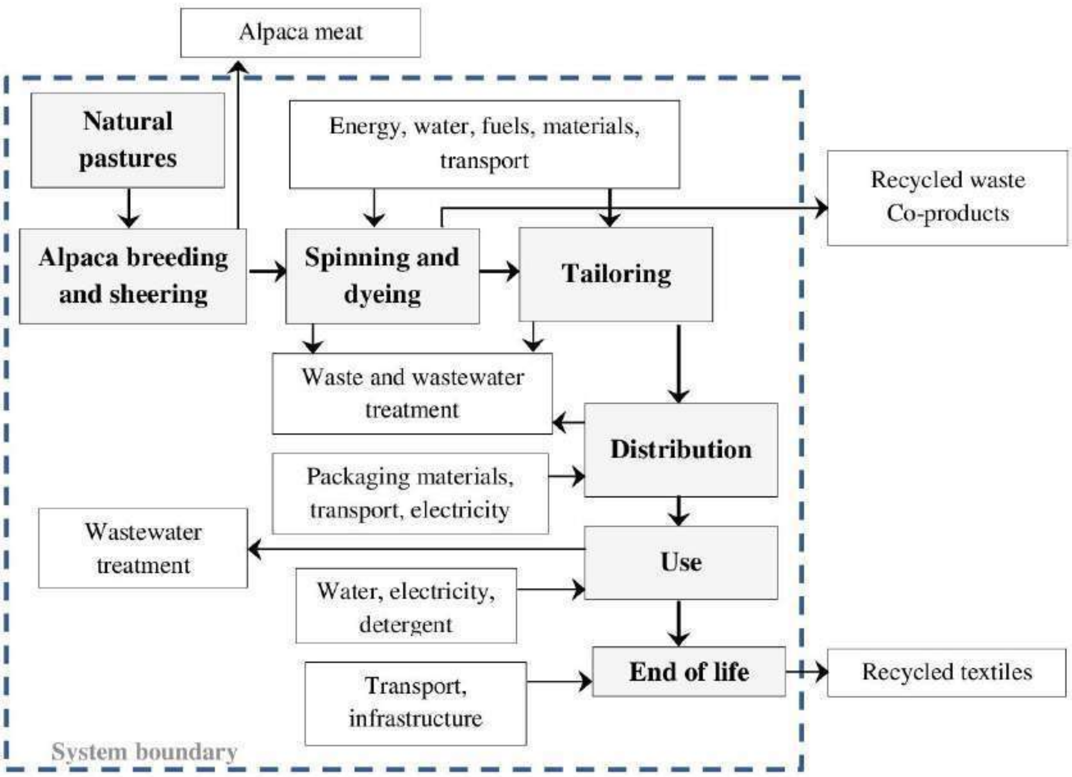
2. Material and methods

The functional unit of the study was one (01) use of a 100% alpaca fiber sweater, with a product weight of 400 g. Although most LCA studies on textile products use a functional unit based on fabric mass, this functional unit does not consider the quality, functionality, and life span of the garment (Watson et al., 2019) and may therefore not allow for a fair comparison between durable and short-lived garments.

The scope of the study covered the cradle-to-grave life-cycle stages of the garment´s supply chain including raw material sourcing in the Peruvian Andes; spinning, dyeing, and knitting/tailoring of the garment in the cities of Arequipa and Lima (Peru); exporting the final product; its use in different countries and its end of life (see figure 1).

Data on processes related to the stages of fiber procurement (natural pasture management, alpaca breeding and shearing) were obtained for the year 2019 from interviews with 42 individual alpaca herders or associations from the regions of Arequipa, Pasco, Puno and Huancavelica, which are important alpaca fiber producing regions in Peru. Cusco is another Peruvian region where alpaca fiber is produced but it has not been included in this study due to limited availability of data. According to national statistics (MIDAGRI, 2020), the flow of fiber from the four regions to the Peruvian spinning companies considered in this study has been determined to be 82.5%, 9.3%, 4.5% and 3.7% for the Puno, Arequipa, Pasco and Huancavelica regions, respectively. Emissions to air, soil and water from the alpaca rearing stage were estimated based on literature data and emission models available for other livestock species, in many cases for sheep but local and alpaca-specific data was used whenever available. The impacts related to fiber procurement were allocated to fiber and meat with a 50:50 ratio. This allocation represents the distribution of the alpaca herders´ annual income from fiber and meat products (according to an interview with the International Alpaca Association (IAA)) and is also in the range of values used for biophysical allocation in sheep (e.g. 46% and 48.5% for sheep wool in Wiedemann et al. (2020)).

Figure 1.
System boundary for the system studied



Footnote to figure 1: Grey boxes = life cycle stages, white boxes = input and output flows.

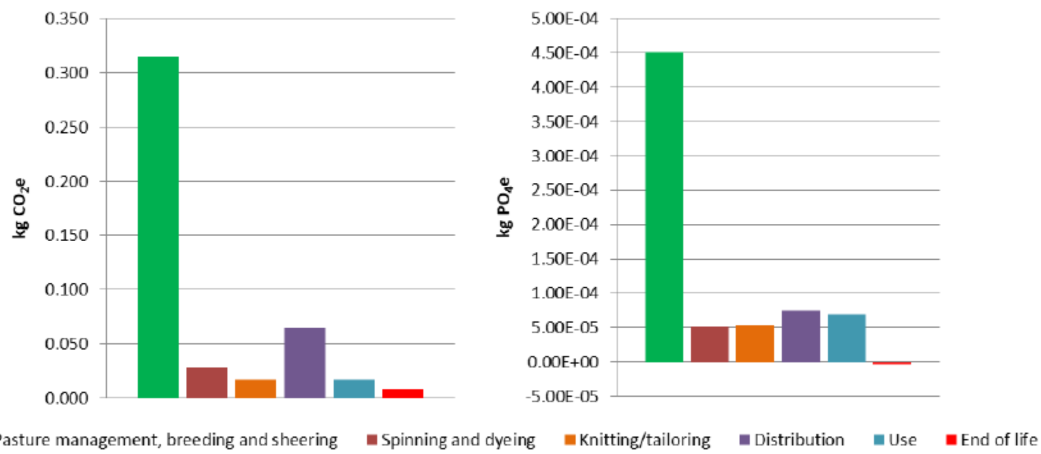
For garment production (spinning, dyeing, and knitting/tailoring), data was obtained for the year 2019 from five alpaca fashion companies, four located in the city of Arequipa and one in Lima. Input and output data were collected for one year and impacts were allocated to alpaca yarn according to the mass of different fiber types used as raw material for yarn production. Allocation of impacts during the knitting/tailoring stage was based on the production volume of each product.
The distribution stage included packaging, export (63.10% to the USA; 13.01% to Germany; 9.54% to Japan; 9.35% to France; 5.00% to the UK; percentages calculated for the period 2015 to 2019; Veritrade, 2021), transport to the point of sale, electricity consumption at the point of sale and transport to the consumer. The two transport means considered for exportation were air and sea transport (Veritrade, 2021). Furthermore, the study included an average transport distance from the port/airport to the point of sale of 1173 km (Pesnel and Payet, 2019), electricity consumption in the retail center of 3.69 kWh/kg garment (estimated according to Wiedemann et al., 2020) and a transport distance from the retail center to the buyers home of 6.25 pkm/garment for car and train transport (Wiedemann et al., 2020).
The use stage comprises the washing of the garment with different methods (hand wash, machine

wash and dry cleaning) considering that the garment is used 109 times and that it is washed after each 5.2 uses, which leads to a total of 21 washes during its lifetime (Wiedemann et al., 2020). The combination of three different washing methods, machine wash, hand wash and dry cleaning, was estimated for each country where the garment was considered to be used based on data by Wiedemann et al. (2020) for EU countries and The Nielsen Company (reviewed in Laitala 2018a) for Japan and USA. Also, the use of water, energy, natural gas and detergent was estimated for each one of the countries considered with data from different sources (Laitala and Vereide, 2010; Henry et al., 2015; Laitala et al. 2018b, Wiedemann et al., 2020).
Finally, the end-of-life stage considered all environmental impacts that occur during the transport of the waste to the treatment facility and during the end-of-life processing. It was assumed that in European countries and Japan 28.5% of alpaca fiber garments are recycled after the end of their lifetime (Wiedemann et al., 2020; for wool garments) and in the United States 13.6% (EPA, n.d.). No upstream impacts were allocated to the fiber entering the recycling process. This cut-off method is, according to Sandin et al. (2018), the mostly used method in LCAs involving fiber recycling. The waste fiber not recycled is considered to be disposed of in landfills or in incineration facilities with and without energy recovery. Ecoinvent (Wernet et al., 2016) waste and wastewater processes were used for respective impact estimations.
Climate change factors from IPCC 2013 (IPCC, 2013) were used for estimation of global warming potential, CML-baseline 2013 characterization method (Huijbregts et el. 2016) for calculation of the eutrophication potential, Ecoinvent 3.8. processes for background data (Wernet et al., 2016) and Simapro 9.0. software for modelling (PRè-Product Ecology Consultants, 2017).

3. Results

The estimated global warming potential was 0.449 kg CO_2-equivalents (CO_2e) for each use of the garment which corresponds to a total life-cycle emission of 48.95 kg CO_2e/sweater. 70% of this impact correspond to the fiber procurement stage, 9.02% to the fiber processing stage (spinning, dyeing and garment manufacturing), 14.45% to the distribution stage, 3.87% to the use and 1.80% to the end-of-life stage (see figure 2). During fiber procurement, the methane resulting from the enteric fermentation process in the digestive tract of the alpacas is responsible for 85% of the impact. The stage with the second highest contribution to global warming potential is the distribution stage. Export account for 54%, road distribution for 36% and energy consumption during retail for 9% of the impact in this category.

Figure 2.
Global warming potential (kg CO_2e) and eutrophication potential (kg PO_4e) for 1 use of a Peruvian alpaca sweater



The eutrophication potential amounts to 0.0007 kg PO_4-equivalents (PO_4e) for each use of the garment, which corresponds to a total life-cycle emission of 0.076 kg PO_4e/sweater. Fiber procurement is again the stage with the highest impact (65%) due to nitrogen emissions from alpaca feces and phosphorus mobilization from the soil due to grassland erosion. The fiber processing stage contributes with 15% to this impact, the distribution stage with 10.75%, the use stage with 9.96% and the end-of-life stage with -0.43%. The impact for the end-of-life stage is slightly negative because it is considered that a part of the garment is transferred to a solid waste incineration plant with energy recovery, and the recovered energy replaces energy from the national grid.

To show the potential for impact reduction, a scenario was calculated assuming an improvement in the grassland management, alpaca breeding and shearing stage. In this scenario it was assumed that in all producing regions (Puno, Arequipa, Pasco and Huancavelica) all animals older than 1 year are sheared. This is theoretically possible but was found only in few of the participating alpaca production units. The scenario resulted in a reduction of impacts by 28% in the global warming impact category and by 29% in the eutrophication category, compared to the original scenario.

4. Discussion and conclusions

Enteric fermentation as well as nitrogen excretion and soil erosion are the main contributors to global warming and eutrophication potential, respectively. Animal and pasture management are therefore crucial for impact reduction. Measures to improve environmental performance in this life cycle stage could focus on the development of measures to increase the alpaca shearing rates (percentage of adult alpacas sheared annually) or measures which improve the fleece yield of animals. Compared to a study realized by Wiedemann et al. (2020) for a woolen sweater (300 gr) global warming potential is higher by 62% in the present study which might partly be due to the lower product weight but also to higher wool yield per animal used in the study by Wiedemann et al (2020) (4 kg vs 2.12 – 3.13 kg in this study).

According to Steinberger et al. (2009) over 70% of greenhouse gas emissions of a cotton T-shirt can occur after purchase and also Wiedemann et al. (2020) showed that for a wool sweater the use phase was responsible for 12-31% of environmental impacts. In the present study impacts during the use-stage are relatively low due to the conservative care methods applied such as washing at low temperatures and after several uses.

One mayor limitation of this study was the low availability of data and emission models for alpacas, and we therefore recommend conducting studies to fill these data gaps. These studies should focus on protein metabolism in alpacas in order to obtain data for the calculation of allocation factors, chemical transformation processes at the soil-air interface of alpaca manure, enteric fermentation and related methane production. Furthermore, the role of high Andean wetlands as carbon sinks and the role of traditional alpaca herding for the maintenance of these very carbon intensive ecosystems should be investigated as their inclusion in a LCA of alpaca products could have a positive impact on the greenhouse gas emissions of the system studied.

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Chicken: from soy and insects to eggs and meat

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Rationale and objective of the work

Along with rise of the world's population and living standard rises the need for dietary protein. Protein of animal origin is however related to high environmental impacts, making keeping up with the demand difficult and unsustainable. Poultry meat and eggs are among the most consumed protein-rich foods of animal origin. Also, when compared to foods coming from e.g., ruminants, they have a relatively lower environmental impact (Poore & Nemecek, 2018).
The environmental hotspot in poultry production chains is feed production, being responsible for most environmental impacts. New environmentally friendly sources of protein for feed are required to reduce the ecological footprint of poultry production. The use of insects as feed ingredients is a hot topic for a couple of decades already. The considerable progress led to the authorization and use of insects in a variety of feeds, in the EU being fish, swine, and poultry feed. Additionally, several insect species can convert a wide range of organic side-streams, which highlights them as a sustainable alternative to conventional chicken feed, allowing a decrease of the overall environmental footprint of chicken rearing.
This research, performed in the scope of within Poultrynsect project (funded through SUSFOOD2 and CORE ORGANIC ERA-Net), aims to identify an environmentally beneficial way to produce chicken protein. Therefore, two systems of chicken protein production are compared: one directed towards eggs (and laying hens) and another one for broiler production, partial substitution of chicken feed diet by live insect larvae, which is expected to lower the environmental footprint of the production.

Approach and methodology

Food proteins originating from poultry come in 2 main forms: eggs and meat. In modern poultry rearing, those are produced in 2 different rearing systems, laying hen rearing (for egg production) and broiler rearing (for meat production). These systems are rather different: per example, broilers were reared for 34 days, and laying hens for 77 weeks, which resulted in 1 t of feed protein being

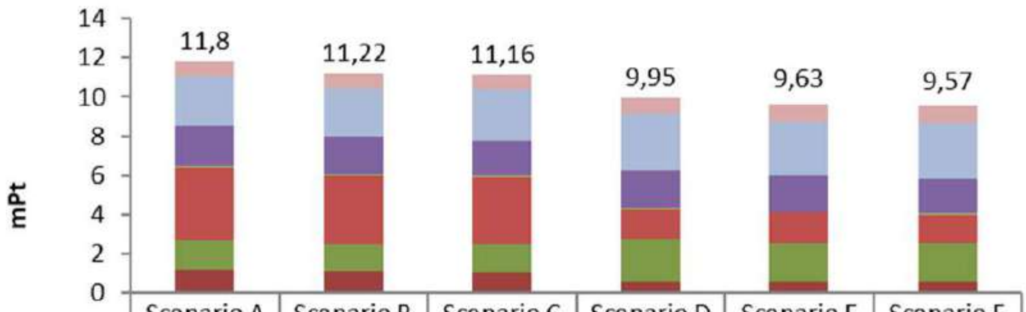
sufficient to feed 1730 broilers and only 144 laying hens. In an attempt to compare these 2 systems, we considered 6 different scenarios, 3 for each system (reference scenario included typical chicken rearing systems, based on commercial feed; alternative scenarios included a part of feed protein substituted by black soldier fly larvae (BSFL)). Protein replacement rates of about 5 to 15 % appear to be common in studies (Ipema et al., 2020; Ruhnke et al., 2018). Therefore, feeding of BSFL protein at the rate of 10 % was assumed (Balolong et al., 2020; Ipema et al., 2020; Ruhnke et al., 2018). Since not only in poultry but also in insect production the feed has the highest influence on sustainability, two different feeds were compared for insect production: one was Gainesville diet (GVD) and the other one was composed of fruit and vegetable waste (FVW).
The study followed the cradle to slaughterhouse gate (or egg production gate) perspective including feed production, hatchery, poultry and egg production and slaughterhouse. Two functional units were used, assessment of the utilization of 20t of feed protein, and assessment of the production of 1 kg of poultry protein. Data used in this study are based on literature, mainly (Dekker et al., 2011) (The Netherlands) for laying hen production and (González-García et al., 2014) (Portugal) for broiler chicken production. The LCA was developed using a modular and attributional approach. The underlying data was calculated in the software SimaPro 8.5.2.0 (PRé Sustainability B.V., Amersfoort, The Netherlands) and followed the standard LCA approach (ISO 14040, 2006 and ISO 14044, 2006). Background data were taken from the ecoinvent 3.4 (ecoinvent, Zurich, Switzerland) and Agri-footprint 4.0 (Blonk Consultants, Gouda, The Netherlands) databases. The methodology of the life cycle impact assessment was IMPACT 2002+. Monte Carlo simulation analysis (1000 runs) was conducted to examine the uncertainties of the resulting impact.

Main results and discussion

In laying hen production, protein conversion efficiency (PCE) stood at 2.4, while in broiler chicken production, PCE was 2.24. Thus, protein is converted more efficiently in broiler chicken production. However, since laying hen protein consists of egg and meat protein, the difference in quality must also be considered. The egg protein's Digestible Indispensable Amino Acid Score (DIAAS), determined by amino acid sequence and digestibility, is 116.4. As DIAAS of chicken meat protein stands at 108.2, egg protein is of higher quality (Ertl et al., 2016). The PCE was corrected accordingly: 2.06 in laying hen production and to 2.07 in broiler chicken production. Regarding the environmental impacts, the reference scenario of broiler chicken production stood at 9.95 mPt per kg protein (where 1 kPt is the average environmental impact caused by one person in Europe for one year), being significantly more sustainable than the corresponding scenario of conventional laying hen production (11.8 mPt per kg protein). Also, all insect integrating scenarios of broiler chicken production were significantly less impacting than those of laying hen production. Furthermore, for both laying hens and broiler chickens, the scenario in which the BSFL were fed FVW tended to be the most sustainable per production system, followed by the scenario in which the BSFL were fed GVD. In terms of midpoint categories, some trends are clear: broiler production had higher impact on global warming and respiratory inorganics, while laying hen systems impacted terrestrial ecotoxicity in a higher rate. The inclusion of insects into chicken feed led to a decrease of impact across all relevant categories.

Conclusion

Results of life cycle assessment showed higher environmental impacts in laying hen production (11.8 mPt per kg protein) than in broiler chicken production (9.95 mPt per kg protein) (Figure 1).



	Scenario A	Scenario B	Scenario C	Scenario D	Scenario E	Scenario F
Non-renewable energy	0.712	0.7588	0.8057	0.8361	0.8885	0.9313
Global warming	2.5944	2.5219	2.5802	2.8505	2.7637	2.8169
Land occupation	2.0159	1.8789	1.8202	1.9386	1.8346	1.781
Terrestrial acid/nutri	0.0645	0.061	0.0592	0.0476	0.0462	0.0446
Terrestrial ecotoxicity	3.7496	3.5066	3.4346	1.5609	1.5349	1.4692
Respiratory inorganics	1.49	1.4027	1.3876	2.1476	2.0102	1.9964
Non-carcinogens	1.1277	1.0441	1.0246	0.5002	0.4803	0.4625
Carcinogens	0.0476	0.0451	0.0462	0.074	0.0702	0.0712

Comparing processes; FU2: 1 kg produced chicken protein
Method: IMPACT 2002+ V2.14 / IMPACT 2002+ / Single score

Figure 1: Comparison of scenarios A to F as single score in Pt per impact category for FU2; A - conventional laying hen production (LHP); B - LHP with Gainesville diet (GVD) fed black soldier fly larvae (BSFL) in feed; C - LHP with fruit and vegetable waste (FVW) fed BSFL in feed; D - conventional broiler chicken production (BP); E - BP with GVD fed BSFL in feed; F - BP with FVW fed BSFL in feed

This was predominantly due to the composition of the feed and the amount of feed consumed per bird; the environmental impact per bird is higher in layer production than in broiler chicken production due to the longer life cycle. Scenarios that supplemented BSFL in the feed improved production in both cases, with fruit and vegetable waste fed BSFL performing slightly better, as no environmental impact was attributed to waste treatments of fruit and vegetable waste. The results were mainly influenced by the production and composition of feed, so improvements in cultivation techniques, crop yield as well as the optimal composition of the feed could be recommended. At the same time, the inclusion of about 10% of protein coming from insects into the feed has shown to have a positive impact on chicken welfare, productivity, and environmental impact.

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Anticipating educational outcomes among children of milk producers in central Madagascar's agroecological mixed farming systems: a case study application of Social LCA

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Promoting sustainable food systems and achieving sustainable food security go hand-in-hand for sub-Saharan Africa's family farms, where agronomic diversity, chronic poverty and environmental risk delineate most aspects of small-scale food production (Rapsomanikis, 2015; Wiggins, 2014). At the same time, promoting sustainable domestic agricultural growth in those economies requires evidence-based, context-adapted interventions and policies designed to maximize rural smallholders' potential (Andersson & Giller, 2019). New transdisciplinary approaches and tools are essential to ensuring those outcomes (Nelson & Coe, 2014). Social LCA offers research and practice a highly contextualizing methodology to complement environmental and economic analyses (Petti et al., 2018) for sustainably transforming agri-food systems in developing countries (CIRAD, 2016).

This case study focuses on the central highlands region of Vakinankaratra in Madagascar, where an international agricultural research-for-development (AR4D) consortium[1] has been promoting and evidencing agroecological intensification as a widespread, context-appropriate approach to sustainable food systems transformation for the region's family farms. At field level, agronomic research activities support farmers' adoption of improved agroecological practices, primarily related to the region's ubiquitous mixed crop-livestock farming systems (Côte et al., 2019). At national policy level, World Bank-funded value chains analyses have established that there exists sufficient domestic demand for fresh milk that is not yet met by farmers in the area's "Dairy Triangle", while milk powder is simultaneously being imported for use in Madagascar's commercial dairies (Bélières & Lançon, 2020). There is an opportunity to support farmers' increased milk production for sale and household consumption, contributing to a reduction in food insecurity and income poverty – but without adequate social impact analyses, the efficacy and efficiency of agricultural investment may be jeopardized.

This case study presents Social LCA as a complementary resource to the existing agronomic and

[1] Anchored by Madagascar's National Center for Applied Research in Rural Development (FOFIFA) and Center for Research and Rural Development in Agriculture and Livestock (FIFAMANOR), alongside the French Center for International Cooperation in Agronomic Research for Development (CIRAD), the consortium has been conducting research in the region for nearly 30 years, frequently accompanied by various other project-specific research partners.

economic evidence bases for Vakinankaratra's small-scale crop-livestock farms. Taking the UNEP (2021) guidelines as a starting point, the methodology was adapted based on the regional production context and the available data. The system boundary was defined as 'cradle to gate' and the area of protection (AoP) as human wellbeing. An extensive review of gray literature from two AR4D projects [2] was conducted to enable stakeholder categorization, materiality assessment, and identification of potential impact categories, following from which an impact chain was constructed. The case study opted for a Type II Social LCA, informed by findings from the projects' stakeholder dialogues and leveraging 2018/2019 data from their two farm-level surveys (N=699) of crop-livestock farmers in the region.

The first phase of data analysis took an econometric approach, fitting a stochastic frontier production model with technical inefficiency effects (Battese & Coelli, 1995) for the (n=147) sub-sample of milk producers. The fitted frontier model contained a count of cows owned, annual feed expenditure, total value of household (HH) assets as proxy for poverty/wealth, and the farmer's proportion of time allocated to on-farm production activities. The inefficiency sub-model comprised an index of improved cow breed used, level of integration into the dairy market, farmer's years of experience (also a proxy for age), presence of off-farm income, and distance to market. Based on the fitted model, we identified the socially relevant variables; results showed that poverty and rurality (i.e. kilometers from town and physical access to dairy value chain infrastructure) significantly influence milk production. When the sample was divided into terciles based on predicted inefficiency scores, it was then possible to explore other variables in the dataset for social relevance. The difference in farmers' level of education was statistically significant between the least and most efficient groups, as were the agricultural work units calculated for the 12-to-14-year-old age group. The latter finding was hypothesized to be related to familial decisions around adolescents continuing with schooling or increasing their farm labor activities. Results from the stochastic frontier analysis revealed that poverty, rurality, and education are factors of social impact within this representative sample of milk producers that should be explored further.

The social impact assessment phase of Type II Social LCA aims to investigate and/or anticipate the effects of production on a specific social outcome using quantitative methods (Sureau et al., 2020). In the first phase of analysis, the stochastic frontier model's findings validated regional stakeholders' articulated concerns regarding income constraints, lack of access to services, and low levels of education as some key challenges faced by farmers. Since the dataset contained a variable on educational attainment for each household member, education was selected as the social outcome for investigative impact analysis. Building from literature evidencing the links between agricultural labor and schooling outcomes (Asenso-Okyere et al., 2013; Moyi, 2011; Nkamelu & Kielland, 2006), as well as education and well-being (Neugebauer et al., 2014), the focus of the investigative social impact assessment was school-age children[3] from the sample's milk producing HHs.

Two outcome variables were considered: first, a measure of children's years of education attained 'on par' with their age (e.g. 0 = no schooling, 1 = ≥3 years behind in school, and 2 = on par or up to 2 years behind in school), and second, children's education attained by class (e.g. 0 = none, 1 = primary, 2 = lower secondary, and 3 = upper secondary school). Predictor variables were either continuous or categorical measures of: children's age, gender, school status and on-farm agricultural activities; parents' individual educational attainment; HH size, distance to market and road access; farms' total number of (taxonomic) animal and/or crop types produced; total value of HH assets (as proxy for

[2] EcoAfrica (ECOlogical intensification pathways for the future of crop-livestock integration in AFRICAn agriculture) from 2018 – 2022; CASEF (Projet de Croissance Agricole de SÉcurisation Foncière) from 2018 – 2022

[3] Children from ages 5 to 17 were selected for the sub-sample, in alignment with the Malagasy educational system's ages of attendance for primary, lower secondary, and upper secondary school.

poverty/wealth). Differences in sample sizes for the two models subsequently described are due to observations being dropped because of missing data for some fathers' or mothers' education attained, and observations were clustered in each model due to the familial nature of the dataset.

A multinomial logistic regression (MLR) model (n=231) was fitted for the 'on par' outcome. Predictors regressed were gender, age, school status, animal types, crop types, parents' education, HH size, distance to market, and HH assets. The statistically significant average marginal effects produced by the model predicted that girls are 10% less likely to be ≥3 years behind than boys and 13.9% more likely to be on par. Children's increasing age makes it much more likely that they will fall behind in school (31% for adolescents and 45.8% for teenagers). Having fewer on-farm responsibilities in addition to full-time school attendance means that children are 10.5% more likely to be on par than their 'busier' peers. Being part of a family farm raising more types of livestock means that children are 5.2% less likely to fall behind, while a HH producing more crop types means they are 6.3% less likely to be on par. Having a more educated father makes a child 10.7% more likely to be educationally on par, while being part of a very large family living farthest from town makes a child 18.8% and 15.2%, respectively, more likely to fall behind. Finally, children from the poorest households are 21.7% less likely to achieve schooling on par with their age.

An ordinal logistic regression (OLR) model (n=239) was fitted for the educational class outcome. Predictors regressed were gender, age, father's education, HH size, road access, animal types, and HH assets. Interpretation of the significant average marginal effects produced by the model showed that girls are 3.9% more likely than boys to attain lower secondary schooling. As children age, it is logical that they are more likely to attain more schooling overall, but the results reveal that this occurs at a decreasing rate: 4.7% for lower secondary but only 2.8% for upper secondary. The more educated a father, his child is 1.4% more likely to reach upper secondary school. The larger a child's household size, the less likely it is that that child will advance in schooling (1.4% less likely for lower secondary and 0.9% less likely for upper secondary). Partial road access to the home makes children 2.4% more likely to reach upper secondary school, and a family farm tending more types of livestock makes children 10% less likely to attain primary school but 12% more likely to reach lower secondary. Those children in the poorest asset class are 7.5% less likely to attain lower secondary schooling and 4.1% less likely to reach upper secondary school.

When brought together, the combined results of this case study's three phases of quantitative analyses tell a compelling story[4] about children's gender and agricultural labor, the relevance of their fathers' educational attainment, the over-arching influence of family farms' rurality and poverty, and the degree of diversification in the region's crop-livestock production systems. Girl children are more likely to be educationally on par and have better overall educational attainment, at least until lower secondary level. This suggests that boys may bear the burden of a gender-based division of on-farm labor that keeps them out of school more often than their female peers.

The more educated a father, the more likely it is that his child(ren) will continue to secondary school and stay on par with their age. In contrast to the first finding, this reflects the vital importance of educating boys so that the next generation's children benefit from this influential relationship. Children from HHs with less than seven members are better positioned for on par educational attainment; effective and culturally appropriate family planning services in the public health system could support moderation of HH sizes. Children who live fewer than seven kilometers from market/town, with at least partial road access, go further in their schooling and are less likely to fall

[4] The narrative described by the case study's results will be validated in the field during July-August 2022 through participatory farmer dialogues, the findings from which will be integrated into the conference presentation as well as an eventual scientific paper for publication.

behind, which emphasizes the importance of rural road infrastructure. Severe poverty is a major problem for the bottom quartile of family farms, negatively impacting both agricultural production and children's educational outcomes; this consistent finding reminds us that policies and interventions must continue to address chronic poverty, considering this population's needs differently than better-off counterparts.

Finally, the case study's findings on the influence of multiple types of crop and livestock production are of particular interest, especially since crop-livestock diversification is the region's norm. While children with fewer on-farm tasks overall are better positioned to be educationally on par, there are significant relationships between children's education and the respective degrees of crop and livestock diversification. A farm producing more types of crops means that its children are more likely to fall behind in school; this is likely due to the need for additional labor during multiple harvests throughout the year, with families pulling children out of school to help meet this need. It may also be related to low-skill, labor-intensive tasks like weeding being allocated to younger HH members. Conversely, raising more types of livestock helps children stay on par with their schooling and increases the likelihood that they will attain at least a lower secondary school level of education. Perhaps tending livestock is a task more often allocated to older HH members, or the volume of labor is more easily confined to pre- and post-schoolday timeframes. These findings suggest that the educational outcomes of children on family farms could benefit from a more limited amount of crop diversification but more intensified production of a wider range of livestock taxa.

In conclusion, sustainable food systems thinking requires holistic approaches to agricultural transformation, particularly for smallholders in the Global South (Côte et al., 2019). In pursuit of innovatively comprehensive methods, this regional case study positions Social LCA as a highly complementary tool for designing agricultural research and development activities in Africa, as well as informing policy in African countries. But, as the analyses demonstrated, its utility and value depend on context-appropriate adaptation from the outset, acknowledgement of the data limitations in developing country settings, and substantial participatory input from the full range of stakeholders. When paired with environmental and econometric analyses, this case study shows how impact assessment in Type II Social LCA can help researchers, practitioners, and policymakers anticipate social impacts from changes in agricultural production, contributing to more efficient investment and more effective policy interventions.

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Life cycle assessment of low-cost technologies for digestate treatment and reuse in small-scale farms in Colombia

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Keywords: *Life Cycle Assessment, anaerobic digestion, waste management, organic fertilizers, sand filter, vermifilter.*

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Introduction

Anaerobic digestion (AD) is a practice that is mainly carried out to give treatment to different kinds of organic residues (e.g. food waste, manure, agricultural residues) in order to obtain biogas and produce bioenergy. Because of its nature, the generated biogas is considered to be a renewable energy source, henceforth an important strategy in the fight against climate change. Anaerobic digesters carry out the AD process under specific conditions to allow microbial communities to develop and decompose organic matter (OM) into the desired biogas. In addition to biogas, the degradation of organic waste in the digester also produces a liquid effluent (digestate) (U.S. EPA, 2021).

This exiting digestate is a combination of solid and liquid fractions from the AD process, rich in nutrients and OM. Because of its characteristics, digestate is a valuable effluent, as it can be used as organic fertilizer and spread on agricultural lands (Panuccio, et al., 2018). The use of digestate as fertilizer has several benefits, such as boosting crop growth and quality, acting as soil amender, or mitigating greenhouse gas (GHG) emissions (Wang & Lee, 2021). Nonetheless, depending on the characteristics of the feedstock and on the further use of the digestate, it has to undergo treatment and/or stabilization to avoid the spreading of pathogens, toxic metals or other pollutants that might be present in it (Cucina et al., 2021; Wang & Lee, 2021).

For this study, this rationale has been implemented in Colombian low-income small-scale farms. Colombia is a country with a great agricultural tradition, considering that by 2017 more than 15% of the domestic extraction of the country was related to the agricultural industry (Material Flows, 2019). Nevertheless, even though Colombia has expected a considerable growth throughout the past 30 years, up to 50% of its population is considered to live in poverty (Garfí, et al., 2019). Consequently, low income populations have to rely on self-sufficient farming and traditional fuels such as firewood and dry dung for cooking and house warming. For these reasons, low-cost digesters have been implemented in several Colombian communities to cope with homely energy demands and substitute the risky traditional fuels that end up affecting both people and the local environment (Garfí, et al., 2011).

It is in this context that several studies have been carried out to analyze the environmental performance of anaerobic digesters in rural conditions in the Andes (Garfí, et al., 2012; Garfí, et al., 2019; Mendieta, et al., 2021). However, these studies have focused on the implementation of the digester and the biogas use, but have not deepened in the treatment and use of the digestate. Even though these studies have considered a direct use of digestate, other authors have stated that, despite the benefits of this practice, it might have associated risks if no further treatment of the digestate is carried out prior to its application on land (Cucina, et al., 2021). Therefore, the main objective of this study is to analyze the environmental impacts of three alternative scenarios for the digestate treatment and reuse from a low-cost anaerobic digester: 1) digestate treatment with a sand filter and its reuse as biofertilizer 2) digestate treatment with a vermifilter and its reuse as biofertilizer; 3) a baseline scenario without digestate treatment (direct use on land).

Materials and methods

A cradle-to-grave Life Cycle Assessment (LCA) is to be carried out to assess the potential environmental impacts of the treatment and agricultural reuse of digestate generated by a low-cost tubular anaerobic digester implemented in a small-scale farm in the Colombian Andes. For this, a functional unit of 1 m^3 of treated digestate has been selected. The system boundaries considered for this study include the acquisition of raw materials, the construction and operation of the filters, and the use on land of the digestate. LCA modelling is carried out in the SimaPro 9.3 software, having primary information acquired on-site and secondary information primarily obtained from the Ecoinvent 3.8 database. With regards to the impact assessment methods, for the impact category of climate change, the IPCC 2013 method will be used, while the ReCiPe 2016 method will be applied for the remaining impact categories.

The digester and the agricultural lands subject to this study are located in the surroundings of the population of Cachira (*Norte de Santander* region), in the northeastern area of the Colombian Andes (*Cordillera Oriental*). This zone has an average altitude of between 1800 and 2000 m.a.s.l., and an average ambient temperature of 17 ± 3 ºC (Cucina, et al., 2021). The scenario that will go under analysis in this study is based on a co-digestion scenario considered by Cucina and other colleagues in a previous study that explored the benefits and risks of plastic tubular digester digestate reuse in agriculture (Cucina, et al., 2021). In particular, in the case of the present study, the three scenarios under analysis will be focused on a psychrophilic tubular digester with a feedstock composed by cattle manure and cheese whey, shown in Figure 1.

Figure 1: Psychrophilic tubular low-cost digester implemented in Colombia. Source: Personal archive.

Results and discussion

Results obtained from this study are expected to show lower impacts in categories related to energetic and material consumption for the baseline scenario, mainly due to lower material inputs because of the lack of treatment. However, this scenario is also expected to have higher impacts in water and soil related categories (i.e. eutrophication, acidification, toxicity). With regards to the vermifilter and sand filter, the former is contemplated to have lower overall impacts, as it has lower material and energetic inputs throughout its life cycle, has a longer lifetime, and has fewer maintenance requirements. Both sand filtration and vermifiltration are foreseen to perform considerably better from an environmental point of view while considering water and soil quality implications, therefore evidencing the benefits of digestate filtration prior to its application on land.

Conclusions

The implementation of filtering technologies after anaerobic digestion systems is a process that can gain relevance in low-income communities, as these can improve their life-quality. Main results will show benefits from the application of the filtering technologies to the digestate in comparison to its direct application on land. The strong points of these filters in low-income rural communities shows not only environmental benefits, but also improvements in the quality of the crops, health of the inhabitants of the community, and consequently economic benefits. The proper application of these technologies can empower farmers and lead them into sustainable farming.

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Assessing the sustainability of coconut chain in Sanquianga region, Colombia

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Introduction

The concept of sustainable development has been widely worked on since its introduction by the Brundtland report (Keeble, 1988), establishing three fundamental pillars: economic viability, social equity, and ecological integrity. Current social and economic imbalances between regions highlight that efforts toward sustainable development must focus on increasing the economic and social conditions in the poorest and emerging economies while encouraging effective practices that generate low environmental damage.

Sanquianga, located in south-western Colombia, is an agricultural region in the territories prioritized by the national government for implementing sectoral plans and programs within an integral rural reform framework. These actions intend to mitigate the incidence of armed conflict, poverty, institutional weakness, and the rise of illicit economies, which have historically characterized the socio-economic conditions of this region (EVA, 2017; DANE, 2020).

Coconut is a crop culturally rooted in the Sanquianga region and with great economic potential. Nevertheless, its productive chain is weak, mainly because of low-tech farming and insufficient pest control knowledge, where neither machinery, fertilizer, nor pesticide products are used. In addition, no extensive use of the generated outputs is carried out, since only the edible part of the harvested fruit has traditionally been considered valuable output.

This study is framed in a two-year project that aims to boost the socio-economic context of the Sanquianga region by contributing to develop a sustainable coconut supply chain. Specifically, the project evaluates the pre-feasibility of a proposal to create a processing plant for products derived from coconut fruit to make comprehensive use of this commodity (UPV, 2021). As a project deliverable, a report will be carried out. This report aims to be a basis for seeking funding from the government or NGOs to build a coconut processing plant owned by the local community. The pre-feasibility evaluation refers to both the evaluation of the technical and legal feasibility, as well as the viability of the three pillars of sustainability. In this study, a preliminary analysis of the current social, economic, and environmental impacts of the coconut production chain in Sanquianga is developed, so that it serves as a basis for establishing the incremental factors of the project proposal compared to the existing one.

Materials and methods

This study has been developed under a life cycle approach. Specifically, the scope of the system ranges from the production of farming inputs to be used in the agricultural stage, to the sale of the fruit by the farmer, either in a local market or in the city of Cali. For the presentation of the quantitative results, one hectare cultivated in one year is used as functional unit. Data on agricultural practices and socio-economic characteristics were obtained from interviews carried out in 2021 to eight representative coconut experts from the region. To assess the social dimension of sustainability, two sLCA indicators were used, a qualitative one, the informal labour hiring, and a quantitative one, the percentage of participation of family labour in farming. Climate change, as kg CO_2 eq., fossil depletion, as kg oil eq., and photochemical ozone formation both to the ecosystem and human health, as kg NOx eq. were the environmental indicators chosen. The economic dimension was assessed through financial LCC, estimating farmer financial results, expressed as USD·ha^{-1}·year^{-1}, for the most popular cultivars in the region. To integrate the results of the economic and natural environmental dimensions, the environmental productivity for each impact category was calculated as the ratio between the profit and the environmental impact (Heijungs, 2022).

General aspects of the coconut chain in the Sanquianga region

The interviewees consider that the economic dynamic of the region is weak, due in large part to the lack or low quality of access to public infrastructure (of public services and transportation). However, they envisage that there is potential in the region for the current and future population to remain in the territory, and this may be materialized through the development, in a sustainable way, of agricultural, timber and fishing activities. In particular, coconut, banana, and cocoa crops are highlighted as the crops with the most significant economic feasibility in the region. The main features of coconut cultivation in Sanquianga are that it is not mechanised and that no agricultural inputs (fertiliser, pesticide) are applied. Weevil pest is the main problem in the farming stage, causing a decrease in the coconut yield, being palm burning the conventional way to fight this pest. Under this context of low yield, and the rise of fruit prices due to the current fruit scarcity, in this study, the most common coconut varieties in the region were assessed, namely *Enano, Manila, Táparo,* and *Criollo* cultivars, as there are usually called in the region. The average yield considered for each cultivar was 3,834 kg·ha^{-1} for *Enano*; 5,110 kg·ha^{-1} for *Manila*; 4,657 kg·ha^{-1} for *Táparo*; and 5,111 kg·ha^{-1} for *Criollo*. Coconut produced in Sanquianga is totally marketed without processing and when consumed locally only the edible part is used, the rest of the fruit goes to the river and to uncontrolled open dumps.

Results and discussion

Economic dimension

Table 1 shows the financial results of the coconut cultivars produced in Sanquianga and marketed locally or in the Cali market. The information was originally in Colombian Pesos (COP), but for a better understanding, it was expressed in United State Dollar (USD) using the average of the representative rate of both currencies (COP/USD) from 21/06/2021 to 20/06/2022 (BRC, 2022).

Table 1. Financial results from coconut production in Sanquianga region in Colombia, USD·ha^{-1}·yr^{-1}.

	Coconut cultivar			
Heading	*Enano*[a]	*Manila*[a]	*Táparo*[a]	*Criollo*[a]
Income for sales in the local market	1,365	1,359	1,292	1,482
Income for sales in the Cali market	1,820	2,052	2,040	2,100
Land preparation cost	41	43	43	43
Sowing cost	4	5	5	5
Fertiliser cost	-	-	-	-
Pesticide cost	-	-	-	-
Harvesting cost	704	762	762	762
Other on-field operations cost	185	142	142	142
Total cost from agriculture activity	934	952	952	952
Total cost for the local market	1,095	1,071	1,040	1,034
Post-harvest treatment	161	119	89	82
Transport cost	277	263	305	365
Informal tax	62	59	69	82

Total cost for Cali market	1,434	1,393	1,415	1,481
Profit for the local market	271	289	252	448
Profit for Cali market	387	658	625	619

[a] Commonly named in the region

For the fruit marketed locally, farmer income ranges between 1,292 USD·ha^{-1}·year^{-1}, for *Táparo* cultivar, to 1,482 USD·ha^{-1}·yr^{-1}, for *Criollo* cultivar., When the fruit is marketed in Cali, the incomes tend to be increase (on average 46% greater), being 1,820 USD·ha^{-1}·year^{-1} for *Enano* cultivar, and 2,100 USD·ha^{-1}·year^{-1} for *Criollo* cultivar. Generally, the incomes from the Cali market. As differences in the costs are relatively lower than those in the incomes, when the local and Cali markets are compared, the profit from the Cali market is 89% greater, on average, that is, coconut fruit is more valued in Cali. However, it should be noted that, logistically, this is a difficult market due to the transport infrastructure conditions in the region; besides, farmers market their products in isolation, without any kind of cooperation. Despite the fact that the analysis is carried out in a context of low yield, both coconuts marketed locally and in Cali show a great relative profit, being *Tarparo* cultivar marketed locally the one with the lowest margin of profit (19%). This can be explained because the coconut chain in Sanquianga is an informal economic activity in which taxes are not paid to the government, a great part of the labour force is familiar (generating a low cost of labour) and financial costs are not considered. Another aspect to be highlighted is that to reach the Cali market an informal tax must be paid to illegal armed groups in Buenaventura (a city located between Sanquianga and Cali) which corresponds, on average, to 3.41% of the incomes.

Social dimension

Social indicators of the agricultural stage exhibit a high degree of informality, mainly as concerns the commercial agreements, as they are totally verbal, and labour hiring. In addition, accounting supports and operation records are not carried on. As regards labour, in the agricultural stage, around 55% corresponds to family labour, and the remaining 45% to people informally hired. At the distribution stage, 100% of the personnel for transport and logistics is informally hired. Consequently, the workforce employed in the supply chain is not insured. As concerns these social issues, differences between coconut cultivars are not found.

Environmental dimension

The absence, or non-significant, mechanisation and the fact that no agricultural inputs (fertiliser, pesticide, or other products) are used in the agricultural stage, which is common in other regions such as the Philippines (Bessou et al., 2013; Hirsinger et al., 1995; Tan el al., 2004), makes the environmental impact from this stage of the coconut supply chain in Sanquianga region to be irrelevant. A relevant aspect in the agricultural stage is the burning of the palms affected by the weevil, which can cause the death of the trees. This is a common practice for pest control that generates CO_2 emissions to air, however, these emissions have not been accounted for as they are biogenic carbon.

In the post-agricultural stages, the environmental impacts are subject to the market where the fruit is sold. As to the fruit marketed locally, and as commented above, only the edible part (endosperm) is consumed, the remaining ones (endocarp, mesocarp, and exocarp) are wasted, throw to the river or to open land dumps, generating environmental impacts. When the edible part is processed at home (e.g. to make coconut milk), a waste is generated that is usually used as animal food.

Concerning the fruit marketed in Cali, the exocarp and part of the mesocarp are removed from the fruit before it is shipped, and have the same end of life than when it is marketed locally. The end of life of the shipped fruit after consumption was not evaluated in this study, since it is possible that they are used as raw material for industrial and food products, understanding that Cali is a more robust market. Due to data lack, the impacts of the coconut waste thrown into the rivers and in open land dumps were not assessed quantitatively.

The impacts of the transport of the coconut from Sanquianga region to Cali are presented in Table 2. It can be observed that the yield is the only differentiating factor among the coconut cultivars, this makes that, regardless of the impact category, the scores in the four impact categories analysed have the same relative difference when one cultivar is compared to the others. The *Enano* cultivar is the one with the lowest environmental impact, considering the current agricultural and market practices in the Saquianga region. *Manila* and *Criollo* cultivars show 33% higher impacts than *Enano* one, whereas the *Táparo* is 21% greater than the *Enano* one.

Table 2. Environmental impacts of the transport of the Coconut fruit produced in the Sanquianga region and marketed in Cali, Colombia.

	Coconut Cultivar			
Impact category	*Enano*	*Manila*	*Táparo*	*Criollo*
Climate change (CC: kg CO_2 eq.·ha^{-1})	86.65	115.49	105.25	115.51
Fossil depletion (FD: kg oil eq.·ha^{-1})	28.72	38.27	34.88	38.28
Photochemical Ozone Formation, Ecosystems (POFe: kg Nox eq.·ha^{-1})	0.56	0.74	0.68	0.74
Photochemical Ozone Formation, Human Health (POFh: kg Nox eq.·ha^{-1})	0.56	0.74	0.68	0.74

Integrating the sustainability dimension

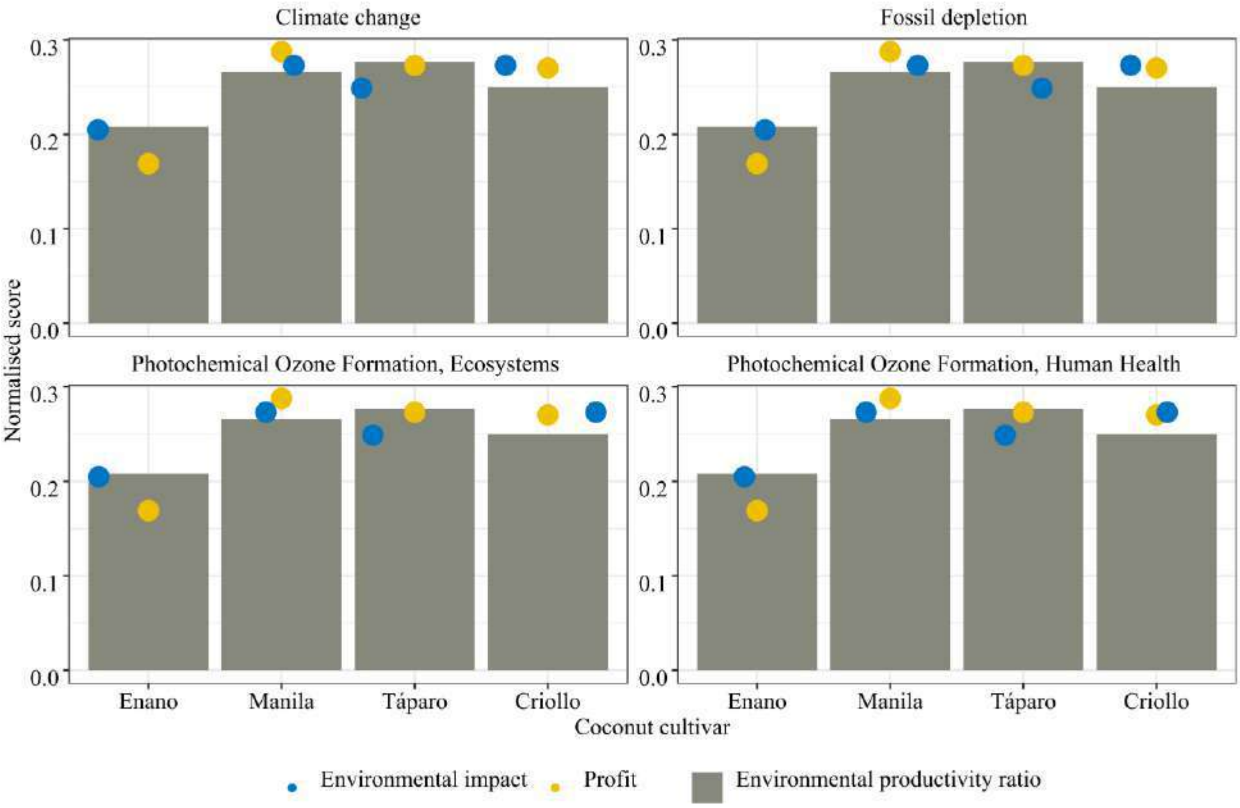

Fig. 1. Environmental productivity indicator for coconut produced in the Sanquianga region and marketed in Cali, Colombia

To compare the sustainability profile of the coconut cultivars produced in the Sanquianga region and sold in Cali market, the quantitative differential of the sustainability issues (namely the economic and environmental issues) are integrated. For each coconut cultivar, the normalised scores of the economic profit and environmental impacts were calculated by dividing the cultivar score for each variable by the sum of the scores for the four cultivars, as well as the environmental productivity for each impact category (Fig. 1). These results suggest that *Táparo* and *Manila* cultivars present the best environmental productivity. This means that these cultivars show the best marginal economic results with respect to the environmental damage generated. From the normalised scores, *Táparo* and *Manila* cultivars present higher scores in the economic dimension than in the natural environmental one, whereas *Enano* and *Criollo* cultivars show opposite results. The *Enano* cultivar shows the lowest environmental impact and also the lowest profit, in addition, the gap between the two dimensions is the most unfavourable

Conclusions

Strengthening the coconut supply chain can be a viable strategy toward endogenous development, closing social gaps, and mitigating the incidence of armed conflict and illicit economies in the Sanquianga region. From the results of this analysis, weaknesses at the organizational and technical levels are observed. The promotion of cooperatives could drive the development of a coconut-based industry in the region, boosting good practices in the hiring processes and in the information and resources management. If the fruit continues to be marketed for fresh consumption, without any transformation process, from both an economic and an environmental perspective, a good choice is to grow *Criollo* cultivar for the fruit to be consumed locally and the *Táparo* and *Manila* ones for the fruit to be consumed in the Cali market. From the agronomical point of view, cooperatives could also provide technical advice about sustainable pest control, increasing the yield and thus decreasing the environmental load (e.g. carbon footprint) per unit of output. A comprehensive use of the coconut is a pertinent strategy to strengthen the coconut chain in the Sanquianga region, diversifying the offer of coconut derivatives with greater value-added.

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Artisan curd-type cheese production life cycle assessment in a cattle farm at Puerto López, Colombia

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Keywords: Cheese; Cattle farm; Colombia; Small producer; Environmental impacts

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The dairy chain of curd-type cheese represents a form of livelihood that is significant for small rural communities. Through a life cycle analysis, the environmental impacts were identified for an artisanal process that includes everything from the production of animal concentrate to distribution, including the production of milk and cheese.

The environmental impacts were evaluated using the NTC-ISO 14044:2017 method. As a main result, it was obtained that the production of animal feed represents more than 80% of the total environmental loads in the production chain of curd-type cheese, considering the Eco-indicator 99 method, being mainly due to the use of fossil fuels and the occupation and transformation of the land.

On the other hand, when the elaboration of curd-type cheese is analyzed in isolation, it presents as critical points the use of cleaning agents, the acquisition of inputs, and the distribution of the product to the vendors, contributing greatly to the categories of fossil fuel depletion (FFD) and land use (US).

Finally, it was identified that to reduce the environmental impacts of the production of this type of cheese, it is necessary to use caustic soda as a degreasing agent and to increase cheese production, reducing between 98% in the category of the US and 63% in the ACF, taking into account the OAT (One-at-a-time) method.

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Evaluating Environmental, Economic, and Social Aspects of an Intensive Pig Farming Production Farm in the South of Brazil: Case Study

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Pork is now the world's most widely eaten meat, with consumption expected to increase further over the coming decades. Brazil is one of the biggest producers, currently the world's third-largest producer and exporter (Shahbandeh, 2021). Thus, the pork industry is systematically important to the Brazilian agricultural economy, especially in southern states where much of the pork production is to be found. Growth in pork production has been largely achieved through intensification over the past two decades. However, this has led to a variety of social, economic, and environmental impacts, not just for the Southern states, but also more widely in other Brazilian states where feeds are grown (Silva and Bassi, 2012).

The intensification of pork production has been driven by capital-intensive, vertical coordination of the value chain. As part of this, small family farms (< 50 ha) have become a mainspring used by large, integrated enterprises to undertake different stages of the production process, from grain cultivation to finishing (IBGE, 2018). The importance of these family farms beyond their role in pork production has not always been considered. Family farms are not just economically important, but socially and ecologically important as well. Therefore, what has arguably been missing is a systematic approach to understanding sustainability (environmental, social, and economic) issues related to pork to allow all actors to make intelligent decisions for the Brazilian port industry.

This study aimed to better understand and outline the impacts associated with intensive pig production by studying a family farm located in the state of Santa Catarina, in the south of Brazil. By doing this, weaknesses (hot spots) of the pig production life cycle were identified using the environmental, economic, and social indicators, in a Life Cycle Sustainability Assessment (LCSA) framework. The intention was to allow the farmer to understand the different sustainability issues at play, isolate opportunities and problems and identify ways forward. The approach can also guide and support decision-making processes by a variety of stakeholders and actors, ranging from the pig farmers to the large integrators, to academics and LCA practitioners and those governing the system.

The environmental performance of the pig production system (e-LCA) was based on the methodology set out by the ISO 14044 standards, which was a cradle-to-farm gate analysis. The set of environmental impacts (ReCiPe Methodology) includes Global Warming (GWP), Acidification (AP) and Eutrophication (EP), midpoint impact categories covered in the background data (upstream processes). The Function Unit (FU) was one Kilogram of Liveweight (kgLW). The structure of the LCSA was based on Neugebauer et al. (2015) and Chen and Holden (2018), who proposed a tiered LCSA framework to evaluate the impacts on the environmental, social, and financial aspects of a product.

The economic dimension or Life Cycle Cost (LCC) focused on farm-level activities, Productivity

Cost, Profitability, Labour Productivity and Animal Losses. The LCC followed the general method proposed by Hunkeler et al. 2008. The social aspect followed the 'Guidelines for Social Life Cycle Assessment of Products' (sLCA) published by UNEP/SETAC (2009). The social analyses were concentrated on two stakeholders, the farm worker, in terms of Fair Wage, and the farmer, in terms of Income Capital, Working Hours Per Year, Educational Level and Age Structure indicators. The results of this study were compared to reference values found in national literature. This includes environmental indicators from eLCA studies, the 2017 Brazilian Agricultural Census database (IBGE, 2018) for social indicators and economic data from the Brazilian Association of Pig Breeders (ABCS, 2016).

Overall, considering all the variations in data input, assumptions and methods choice among the pig production eLCA studies, the environmental impacts assessed are within the same order of magnitude a: GWP varies from 1.84 to 2.55 kg CO2 eq., Acidification potential from 32.2 to 56 g SO2 eq., and Eutrophication Potential from 13.1 to 33.81 g PO4-3 eq. These data reflect the pig production in southern Brazil, rather than national average production, since all eLCA papers are set in the same region of the country.

The Production Cost for the farms was $0.0451 kgLW, which was similar to the literature value of $0.0459 kgLW. However, Profitability was lower for the farmer ($0.0126 kgLW) compared to the reference value for the state of $0.0169 kgLW, even though the Number of Pig Losses (16x10-5 pig/kgLW) and the Labour Productivity (14.12 sec/kgLW) were significantly better than the benchmarks of 29 x10-5 pig/kgLW and 17.06 sec/kgLW respectively. Therefore, the monetary returns for finishing pigs are mainly due to the efforts of the farmer and farm worker to ensure high productivity and low animal mortality but come at the cost of very long hours of work.

In terms of social indicators, the fattening farm paid a wage of around $750 per month, practically the same as data from the 2017 Census of Agriculture. The Education Level of the farmer, which is primary education not concluded, was typical for the farmer cohort aged between 45 and 65 years old. The farmer worked longer hours (58 h/week) than the "standard" 40-hour week and receive a lower Income Capital, estimated at $ 1133 per month, which was around 14% lower than the regional average.

There are a small number of eLCA publications examining pork production systems in Brazil, however, none have applied Life Cycle Sustainability Assessment covering economic, social, and environmental issues. More such studies would be of great value to all stakeholders in the Brazilian pork sector, from farmers to integrating companies to governments. The small family farms that represent most pig producers in South Brazil require sustainable livelihoods and wellbeing, which will depend on sustainable practices covering all dimensions. Improvements in manure management could avoid many environmental impacts associated with pig production at farm levels. There was also evidence of a need for more education for small farmers, which is known to have a positive correlation with the adoption of new methods. Such actions could improve wellbeing and livelihood, thus reducing adverse environmental and social impacts and increasing economic returns leading to a slow down or reversal of the rural exodus.

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Bringing biodiversity to the Agribalyse database

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Endeavours to integrate biodiversity indicators in LCA are ongoing. One recently published method is the biodiversity value method by Lindner, Fehrenbach et al. (2019) based on principles described by Fehrenbach, Grahl et al. (2015) and Lindner, Eberle et al. (2021). It uses land use management parameters as input and yields a holistic, aggregated biodiversity value as output (contrary to other methods that yield more specific information about species disappearance (e.g. Chaudhary & Brooks 2018). It is sometimes referred to as the BVI method, for its unit *biodiversity value increment*, or BVI.

Agribalyse is the French food LCA database, provided by ADEME and currently available in version 3.01. In a current project, Bochum University of Applied Sciences, ifeu, and Koch Consulting are integrating a biodiversity indicator derived from the BVI method into 2,700 Agribalyse datasets. Apart from the general goal of having a biodiversity indicator in Agribalyse, one requirement is to distinguish organic from conventional production. Given how yield-optimized conventional agriculture is, addressing organic agriculture in an efficiency-focused assessment tool such as LCA can be challenging.

The BVI method can be very detailed, but such applications require correspondingly highly detailed inventory data. Such data are not available in existing Agribalyse datasets, and it is out of scope for this project to establish detailed inventory data from scratch. A coarse application of the method is generally possible (Lindner & Knuepffer 2020). Rather than calculating the index on a continuous scale, discrete index values can be determined based on hemeroby classes assigned directly to broad land use types. However, some information about land management practices *is* available in many Agribalyse datasets and it should not go unused.

The challenge is to make use of what little (but relevant) information there is in existing Agribalyse datasets, yet patch over data gaps with a coarse assessment where information is lacking. It is essentially about striking a balance between too high and too low resolution while dealing with data gaps. In order to address the challenge, the following work flow is applied:

Aggregated Agribalyse datasets are disaggregated into the main unit processes (those that contribute most to the total occupation). Occupation flows are then extracted from the datasets and the link to the respective products is maintained. Land use management information is extracted from the datasets (some of these data are somewhat spread throughout in the dataset documentation), if available. The intermediate result are close to 700 occupation flows arranged in a spreadsheet with data on fertilizer input, pesticide application, and tillage as numerical values.

A variant of the BVI method with reduced complexity is developed to calculate the biodiversity value of each land-using process. The variant uses only three input parameters (fertilizer, pesticides, tillage) rather than the full suite of over 10 parameters as described by Lindner, Fehrenbach et al. (2019). The occupation flows are sorted into land use classes and those are then matched with hemeroby classes. This matching list serves as a default assumption where no input parameters are available. In such cases, the biodiversity value is assigned only based on the name of the occupation flow.

Ecoregion factors (essentially global weighting factors for local biodiversity values) are calculated for countries and geographic regions. Originally assigned to WWF ecoregions (Olson, Dinerstein et al. 2001), country-specific factors are calculated as area-weighted averages. Some factors refer to the production volume based on FAO statistics instead, if this is possible and meaningful; e.g. for large countries which include many different ecoregions with strongly differing factors, and where the production of specific crops is not evenly distributed.

Finally, biodiversity values and biodiversity impacts (in BVI) are calculated for 2,700 Agribalyse datasets. Organic and conventional agriculture can be distinguished, but there neither practice is consistently favored over the other. In some cases, the higher biodiversity value of land under organic management makes up for lower efficiency, in other cases the efficiency advantage of conventional agriculture overcomes the lower biodiversity value.

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The ILCIDAF Project for the development of an Italian database of Life Cycle Inventory of agri-food products: focus on the cereal sector agricultural

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Abstract One of the major problems of the implementation of LCA for Italian agri-food product systems is the absence of geographically representative background data. The project entitled Italian Life Cycle Inventory Database of Agrifoods (ILCIDAF) intends to overcome these problems through the creation of Life Cycle Inventory datasets for the most representative production chains in the Italian agri-food sector. Similarly, the application of scientifically valid models to the Italian territory is necessary in order for the model to be properly implemented for a correct estimation of emissions. This paper describes the methodology followed for the creation of datasets on the cultivation of Italian durum and soft wheat, with particular reference to the adaptation of the Swiss SALCA-SM model (Freiermuth, 2006) for the estimation of heavy metal emissions to the Italian territory. In order to assess the robustness of these changes, a comparison was made of the results obtained by subjecting existing and newly constructed datasets (ILCIDAF) to LCIA, with and without the application of the SALCA model.

Introduction

The cereal sector is particularly important for the Italian economic system, especially for the pasta industry. In 2020, Italy harvested approximately 6.7 million tons of wheat of which almost 60% was durum and just over 40% was soft. In addition to these quantities, imports amounted to 2.9 million tons (80% durum wheat and 20% soft wheat). Pasta production in the same period was 3.5 million tons (according to EUROSTAT). Furthermore, Italy is among the world leaders in pasta consumption, followed by the USA (2 million t), Brazil (1.1 million t) and Russia (1 million t).

Currently there are different LCA databases developed for the agri-food sector and very few are related to Italy. Among the datasets concerning Italian wheat-based product systems six are from the Agri-footprint database and nine from WFLDB (Notarnicola et al., 2022a). These datasets are only partially based on Italian site-specific data and often contain data from other European countries or global non-specific data. Considering the absence of an Italian LCA database relating to the agri-food sector, the Research Project of Relevant National Interest PRIN, entitled "Promoting Agri-Food Sustainability: Development of an Italian Life Cycle Inventory Database of Agri-Food Products (ILCIDAF)", funded by the Ministry of University and Research (MUR), seeks to overcome this limitation with the aim of developing an Italian LCI database of the most significant agri-food products. This article describes the methodology followed for the development of ILCIDAF datasets concerning the agricultural phase of Italian wheat production, with a focus on the SALCA model adapted to the national territory. In order to confirm the robustness of the emissions estimated with this model, a comparison of the results obtained by subjecting existing and newly constructed datasets (ILCIDAF) to LCIA, with and without the application of the SALCA model, was carried out. The outcome of the comparison of the eco-indicators indicates that the adaptation of the SALCA model to the Italian soil is in line with the data implemented in the other databases, albeit with some minor variations due to the regionalisation of the data necessary, to ensure geographical representativeness of heavy metal emissions.

Approach and methodology

Among the main features of the ILCIDAF project is data representativeness. For the development of the database a six-year time interval (2015 – 2020) was chosen to consider average values that take into account variations in agricultural yield over time. Furthermore, the most productive regions, representing at least 80% of national wheat production, were taken into consideration. This procedure was followed considering durum and common wheat production, conventional and biological. Input data collection is characterised by the combination of statistical, literature and on field data. Statistical data (such as yield, cultivated area and quantity harvested) were collected from the national databases ISTAT (National Statistical Institute) and SINAB (National Information System on Organic Farming). The cultivation of durum wheat is characteristic of central and southern Italy regions: Puglia, Sicilia, and Marche are the most significant regions and account for 23.5%, 18.9% and 10.9% of national production respectively. Common wheat is mainly cultivated in northern Italy (Po Valley). The largest production is in Emilia Romagna (30.6%), Veneto (19.4%), Piemonte (13.9%) and Lombardia (11.7%). Field data collection was carried out locally for the durum wheat cultivation (raw material for pasta production), considering the province with the highest production as representative at national level, i.e. the Foggia province responsible for 17.68% of Italian production. The field data was acquired through the "field logbooks" of the farmers who collaborated on the project. The most cultivated cultivars for the Foggia province are: *antalis, iride, saragolla, sfinge, PR22D89, simento*, *quadrato* and *latinur*. The literature data considered in this study were taken from the following sources:

1. regional integrated production guidelines, which are important for defining regional fertilisers application limits of N, P_2O_5 and K_2O to be applied to the soil;
2. agricultural handbook (Ribaudo, 2017) from which the fuel and lubricating oil consumption of agricultural operations were taken for different production scenarios distinguished by macro-area and elevation land;
3. agro-pharmaceuticals handbook (Muccinelli, 2011) useful to determine which pesticides are supplied to the crop.

The data were subsequently adapted to the reference region. The territorial configuration, divided into plains and hills (mountainous terrain was excluded as it is an impervious territory for wheat cultivation) was acquired from the ISTAT database. The outputs of the agricultural system are determined by the emissions caused by the consumption of materials (fertilisers, herbicides, fungicides and by the types of soil tillage). Soil fertilisers application results in the emissions of the following substances, into different environment compartments: nitrous oxide, carbon dioxide, nitrogen oxides, ammonia in the air compartment; nitrate and phosphorus in the water compartment. Quantities emitted to the environment are determined according to the JRC Technical Report (Zampori et al., 2019) and the IPCC methodology (IPCC, 2006 and 2019 refinement). Emissions of plant protection products were calculated as described in Zampori et al., 2019. Leaching (into groundwater) and erosion (into rivers) were modelled to account for heavy metals emissions. These emissions are calculated according to the Swiss SALCA–SM model (Freiermuth, 2006) appropriately adapted to the Italian territory (Notarnicola et al., 2022b). Although the method has been used by other databases to define national datasets, including the Italian one, the heterogeneity of the Italian peninsula requires greater considerations not only on a national, but also on a regional scale. Therefore, modelling this method for a more limited area than the whole country is necessary, as a larger scale of geographical representativeness allows a more detailed characterisation of the model results.

In substance, the method is based on the fact that agricultural operations such as ploughing, clearing, harrowing, sowing, fertilising, weeding, harvesting, in addition to consuming materials in terms of fuel, lubricating oil and wear and tear on agricultural equipment, encourage the normal processes of leaching and erosion to which the soil is naturally subject. This leads to a consequent increase of heavy metal emissions into the environment. Representative heavy metals in agriculture are chromium (Cr), cadmium (Cd), copper (Cu), mercury (Hg), nickel (Ni), lead (Pb) and zinc (Zn). This concept, in the SALCA-SM model, is summarised by the determination of a multiplicative factor that quantifies the contribution of agriculture to the phenomena of soil erosion and leaching. This multiplication factor (A_i), referring to the ith metal, depends on the concentration of the ith metal contained in fertilisers (Desaules & Studer, 1993; Manzi & Kessler, 1998), active ingredients (Perkow & Ploss, 1994 and FAW & BLW, 2000) and seeds (Schultheiss et al., 2007) multiplied by the amount of fertilisers, active ingredients and seeds applied to the soil. It also depends on the amount of heavy metals deposited in the soil (ISPRA, 2019). All these parameters vary depending on the geographical area and from region to region according to:

a. the maximum amount of fertilisers applicable in a given region (regional integrated production guidelines);
b. the type of active substance chosen, which depends on a particular cultivar type typical of one area rather than another;
c. the type of cultivation, conventional or organic;
d. the reference period chosen, because every year many active substances become obsolete, non-standard and not applicable by law, and therefore need to be replaced with different active substances with different heavy metal concentrations.

The SALCA model has several formulas referring to: the amount of heavy metal "i" removed from the soil by erosion that can be attributed to cultivation ($M_{Erosion,i}$); the amount of eroded soil ($S_{Erosion,i}$); the estimated load of heavy metal "i" that is removed from the layer by leaching and can be attributed to cultivation ($M_{Leach,i}$). Using data published on the European Soil Data Centre (ESCAD) database, it was possible to characterise many of the factors in these formulas at the national level and for each Italian region. In particular, with regard to the formula for estimating the amount of eroded soil, the factors R, c_1, c_2, P and LS were characterised on a regional scale, while a national average value was assumed for the $K_{stoniness}$ factor (Panagos et al., 2014). The $C_{TOT,i}$ factor contained in the formula for estimating the amount of heavy metals removed by erosion is characterised for four Italian macro-areas (north, centre, south and islands). The approach given in the SALCA-SM model (Wolfensberger & Dinkel, 1997) were followed to estimate the heavy metal load "i" removed by leaching from the soil.

Main results and discussion

Having defined the scientific methodology and the modifications made to the SALCA model, it was possible to create 59 datasets: 30 relating to conventional cultivation (16 for durum wheat and 14 for soft wheat), 20 referring to organic cultivation (11 for durum wheat and 9 for soft wheat) and 9 more specific ones taken from the data collected on-field referring to the different cultivars.

Below, for illustrative purposes, is a national average dataset on the inputs of conventional cultivation of one hectare of durum wheat. Inputs related to agricultural operations are presented in aggregate form due to lack of space.

Table 1: Italian average input dataset for conventional cultivation of one hectare of durum wheat

INPUT					
Description	Quantity	Unità	Description	Quantity	Unità
Occupation, annual harvest	10 000	m^2	Fertilisers P_2O_5	72.06	kg
Seeds	234.67	kg	Fertilisers K_2O	89.71	kg
Fuel	116.98	kg	Bromoxilin	4.85	kg
Electricity	0.5	kWh	Mecoprop	4.33	kg
Lubrificating oil	2.14	kg	Iodosulfuron	0.06	kg
Rail transport	91.60	tkm	Fenpropimorf	0.81	kg
Road transport	51.27	tkm	Piraclostrobin	1.06	kg
Water transport	45.66	tkm	Epoxiconazolo	1.19	kg
Fertilisers N	125.59	kg	Cloquintozet-mexyl	2.28	kg

By implementing the SALCA-SM model in the ILCIDAF database, it was possible to observe, through a Life Cycle Impact Assessment (LCIA), how it affects the results by increasing the value of the final eco-indicator. The impact assessment was done by including and excluding the estimated emissions of heavy metals, thus obtaining a percentage change (Δ%) in terms of the eco-indicator. The LCIA was conducted for all ILCIDAF datasets related to conventional wheat cultivation. Table 2 shows the percentage differences for: national average value for durum and soft wheat and an overall average value.

Table 2: Percentage difference in terms of the resulting eco-indicator obtained by performing the LCIA with and without the application of the SALCA-SM model - using the datasets for the conventional cultivation of one hectare of Italian durum and soft wheat (ILCIDAF database)

	Average Italian durum wheat	Average Italian soft wheat	Average Italian wheat
Δ%	1.07	0.34	0.71

The same approach was followed for the existing LCI datasets (8 Ecoinvent, 13 WFLDB, 12 Agri-footprint) and the results (Table 3) were compared with the previous ones illustrated in Table 2.

Table 3: Percentage difference in terms of eco-indicator values obtained by using the Ecoinvent, WFLDB and Agri-footprint datasets for wheat cultivation with and without the application of the SALCA-SM model during LCIA

	AR	AU	CA	DE	ES	FR	HU	IN	IT	PL	RU	US	ZA
Ecoinvent		2.41	3.96	3.48	1.73	3.09		0.31				1.8	0.1
WFLDB[1]		2.02	2.29		5.44				3.09				
WFLDB[2]	0.54	3.62	0.68	1.17		0.73	0.25			1.4	0.1	1.2	
Agrifootprint	1.83	1.08	2.52	3.95	4.02	3.18	3.15	0.94	3.64	4.51	2.51	2.09	

Note: 1 for durum wheat WFLDB processes; 2 for non-irrigated wheat WFLDB processes

A maximum value was obtained for Spain (WFLDB) with a Δ% value of 5.44%, while minimum values were calculated in South Africa (Ecoinvent) and Russia (WFLDB) with a Δ% of 0.1%. The ILCIDAF database shows an average Δ% value for durum wheat of 1.07% higher than the average value for soft wheat of 0.34%. These values are in line with the values in Table 3. Furthermore, the WFLDB database allows comparison of processes for non-irrigated wheat cultivation where the Δ% is lower than for general cultivation, excluding Australia where an opposite trend is observed. Irrigation, therefore, further promotes erosion and leaching. Analysing the Δ% relative to the Italian territory, for ILCIDAF the minimum variation of 0.71%; for WFLDB it corresponds to a value of about 3.09%, while for Agri-footprint the maximum variation of 3.64% is recorded. These differences can be attributed to the choice of data used for the application of SALCA.

Conclusions

In conclusion, the adaptation of the SALCA model to the Italian territory applied for the ILCIDAF database allows the geographically representative estimation of heavy metal emissions.

By comparing the eco-indicators obtained by subjecting the existing datasets (Ecoinvent, WFLDB and Agri-footprint) and the newly constructed datasets (LCIDAF) relating to wheat cultivation in different countries to LCIA, with and without the application of the SALCA model, it can be stated that the results obtained for the ILCIDAF database are in line with those found for the existing datasets, albeit below average. The Italian average Δ% for durum wheat is 1.07%, while for soft wheat it is 0.34%. In contrast, for the existing datasets, $\Delta\%_{max}$ of 5.44%, $\Delta\%_{min}$ of 0.1% are recorded.

The high variability of the Δ% is due to the regionalised application of the model. In fact, the data used in the ILCIDAF datasets are different from those in the described documents of the other analysed databases. The factors used for estimating erosion and heavy metal deposition are exclusively related to the Italian territory and furthermore characterised for each region. This makes it possible to state that the regionalised application of the SALCA model to the Italian territory is necessary in order to obtain representative site-specific results. Furthermore, this implies a useful development of the LCA methodology to the Italian agri-food sector and in particular to the agricultural phase.

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Adapting MEANS-InOut LCA software to food engineering, in relation to the PO² food ontology and PO²-BaGaTel food engineering database

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1- Rationale and objective

Food systems are the main contributors to environmental impacts (e.g. climate change, water scarcity, land use). Meanwhile, half humanity suffers either from lack of food or from low-quality diets. Drastic changes in diets and in food production are necessary both to decrease environmental impacts of food and to improve global human health (Willet et al., 2019). To accompany or pilot these changes, data on food are necessary. In France, databases such as Ciqual and Agribalyse provide information on nutritional composition and environmental impacts, respectively, of standard food products. However, they neither cover the huge variability of products in the food sector nor help to assess new products or the new ways of production that are needed. The DataSusFood project aims to develop a modular IT system to organize, store and share data related to food engineering, and to assess the composition, nutritional and sensory properties, and environmental impacts of food products. Initially, researchers will be the main users of the IT system, but the data and knowledge produced will be available in open access.

The IT system of DataSusFood relies on two tools: the PO² ontology developed by INRAE (French national research institute for agriculture, alimentation and environment) and MEANS-InOut, developed by INRAE and Cirad (French agricultural research and international cooperation organization working for the sustainable development of tropical and Mediterranean regions). The PO² ontology (Ibanescu et al., 2016) organizes all relevant information about food and bio-product engineering; its core model is embodied in the PO²-BaGaTel database that capitalizes data on production processes and product characteristics. MEANS-InOut (Auberger et al., 2018) is a user-friendly web app that helps users to apply life cycle assessment (LCA) by building life cycle inventories (LCI) from data that describe the system studied. MEANS-InOut is currently operational to generate LCI of agricultural production systems at farm gate. In the IT system of DataSusFood, the role of MEANS-InOut is to support the calculation of environmental data about food and bio-products. The objective of this presentation is to describe how MEANS-InOut has been adapted to food and bio-product engineering, in relation to PO² ontology and PO²-BaGaTel database.

2- Approach and methodology

The DataSusFood project organizes collaboration between methodological questions and development of MEANS-InOut. First, two scientists in food and bio-product engineering defined user needs. Next, a larger group of food-engineering scientists and LCA practitioners at INRAE reviewed, enriched and validated these needs. The main users targeted are food and bio-products engineering scientists, who are specialists of the systems and processes they want to assess; secondary targeted users are people who want to assess food processes without being familiar of food engineering. The needs were thus defined for users who want to gather detailed information about processes, and to be guided for LCA modelling. The users' needs were translated into requirements of MEANS-InOut. Two requirements fall under "general functionalities" of software. MEANS-InOut should (1) be user-friendly for food scientists, rather than for LCA practitioners; (2) connect LCA data to other tools, especially PO² ontology and PO²-BaGaTel database, in order to capitalize knowledge on food and bio-product engineering. The objective is to store in PO²-BaGatel database the data describing the process, the associated Life Cycle Inventory and the LCA results: the values of environmental impact indicators related to a functional unit. Three requirements are related to the implementation of LCA of food and bio-products processes. MEANS-InOut should: (3) cover a wide range of production processes and of food and bio-products; (4) allow all information relevant for LCA of food and bio-products and/or their production processes to be collected to create life cycle inventories of good quality; and (5) address several questions about environmental impacts of food and bio-product engineering, such as identifying hotspots, comparing processes for the same product, comparing products.

The first phase of developing MEANS-InOut for food and bio-product engineering is completed. MEANS-InOut has been presented to food scientists regularly during the development phase to verify that the tool is adapted to their needs. Food scientists have tested it, which has revealed modeling errors and omissions. These errors have been corrected before the delivery of MEANS-InOut to users.

3- **Results and discussion**

We describe the main features of MEANS-InOut developed to meet the requirements for food and bio-product engineering (Figure 1). In MEANS-InOut, users will be able to study food and bio-product transformation at the process scale, by describing the foreground system. To represent a process under study, users draw a process-flow diagram. This is a usual way of process description for food and bio-product engineering scientists, (requirement 1). The process-flow diagram defines all steps of the process, including cleaning and transport. A generic framework was developed to describe the steps (requirement 3). Each box in the diagram generates input forms to guide data collection for process flows: ingredient and product flows, energy, water, cooling practices, packaging, equipment, consumables, detergents, waste or water treatment, pollutant emissions and transport (type and distance). The forms are built at a fine level of detail, for the process study. These detailed forms ensure that users do not forget important input, product, waste, or pollutant flows. Mass-balance checks are performed between inputs (ingredients and product under process, coming from previous step) and outputs (product under process going to further step, coproduct going out of the process, losses, waste, and emissions) for each step of a given process to reduce the risk of data-entry errors (requirements 1 and 4). A reference vocabulary (e.g. names of ingredients, products, processes, steps) comes from the PO² ontology (requirement 2). This reference vocabulary is used to assist data entry using drop-down menus and to specify the products and processes under study. An export function generates LCI files from the information collected by users. The creation by MEANS-InOut of these process or product Life cycle inventories is based on an embedded mapping between the resources mobilized by the process (ingredients, energy, machines, waste treatment...) and LCI from ecoinvent and Agribalyse databases (requirement 1). This ensures the coverage of background system. Depending on their objective, users can create a process LCI or product and coproducts LCI, and for the latter, several allocation methods are possible: mass on a dry or wet basis, volume, protein, fat, energy or economic. Process LCI and products LCI are structured as a combination of unit operations and ingredients, which allows identifying the hotspots of the process (requirement 5). The LCI files generated with MEANS-InOut are ready to be imported in LCA software, which is required

to calculate environmental impact indicators.
The developments are not yet fully adapted to represent a food supply chain, as data collection forms have been designed for the fine description of the processes. The consistency of the forms with other steps of a value chain such as retail has not been evaluated. A further adaptation of MEANS-InOut to the whole food supply chain is thus needed. It should be based on concepts to be added in PO2-ontology, which describe the elements of the supply chain.

Web services are under development to exchange data on processes (process description, LCIs, LCIAs), first from MEANS-InOut to the PO²-BaGaTel database. We also plan to create a link between MEANS-InOut and OpenLCA, to launch directly from the interface of MEANS-InOut the module for calculating the indicators of environmental impacts of the studied system (requirement 2). Being able to export LCA data from MEANS-InOut to the PO²-BaGaTel database and connect it to other dimensions of food products will be an achievement for the DataSusFood project.

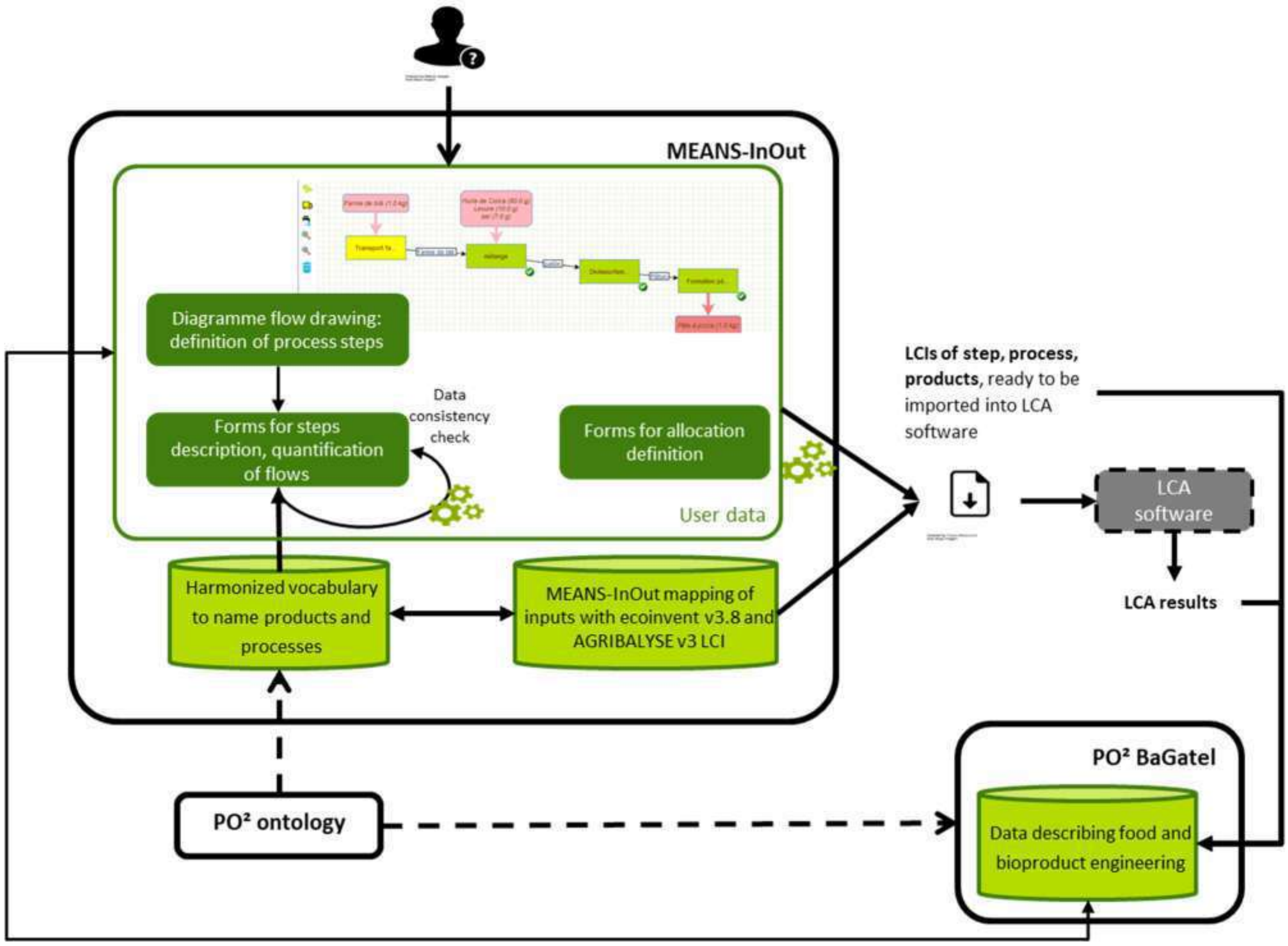

Figure 1 : Main functions of MEANS-InOut for food and bio-product processing, link to PO²-BagaTel database will not be available at first delivery but after further developments.

The generic framework for collection forms allows describing processes with flexibility. Users can describe systems with more or less details, more or less unit operations aggregated in steps and test different process scenarios. However, in this generic framework, default or reference values for specific processes such as energy consumption for sterilization, or the quantity of water needed to clean a membrane are not available. The absence of default values is intended to make MEANS-InOut more flexible to use for food and bio-product engineering specialists, to study all types of processes, including innovative processes or processes for which few references are available. But this absence of default values may also make MEANS-InOut more difficult to use for those who are not specialists of their studied process, or users who study food engineering within a system, when food engineering is not the core issue. The possibility of querying PO²-BaGaTel from MEANS-InOut, which is intended in further developments, will be helpful to overcome this limitation: knowledge and data available on food and processes in PO²-BaGaTel will be accessible to MEANS-InOut users in order to perform LCA with adequate system descriptions and data.

PO² ontology defines both a data structuration to describe the food and bio-products production processes and the vocabulary associated. It is a reference in INRAE for food and food processes description. Process representation and data collection forms in MEANS-InOut are based on PO² data structuration and vocabulary. Using PO² data structuration ensures that MEANS-InOut data format for food and bio-product processing is validated by the scientific community, and is shared with INRAE food and bio-products engineering scientists. It also ensures the connection with PO²-BaGaTel database and the capitalization of the data generated with MEANS-InOut. However, MEANS-InOut collects data that are specific for LCA calculation (e.g.: functional unit, factor used to calculate allocations) or documentation (e.g.: PEF quality notation, temporal boundaries of the process). It can also be data important in environmental assessment but initially not identified as essential when describing a transformation process, such as data about cleaning of equipment (detergent types, quantity of water involved).

Therefore, new concepts have been added in the PO2 ontology to allow the description of these data specific to LCA. Thus the intended inter-operability between PO2 ontology and MEANS-InOut has not only given a structure to the latter but also it has enriched PO2 ontology.

4- Conclusion and perspectives

MEANS-InOut aims to become an international reference tool for environmental assessment in the agri-food sector. It was able to calculate agricultural production LCIs at farm gate. The described new developments of MEANS-InOut allow to calculate food or bio-products LCIs at food-plant output gate. In the next years, further developments will be pursued to model food chains and perform economic assessment at the food-chain scale, allowing environmental and economic assessment of complete value chains from farm to fork. By studying agricultural systems in MEANS-InOut or addressing methodological questions, users have identified new needs, which have led to improvements in the tool for agricultural systems. We therefore look forward for the use of MEANS-InOut for the study of food engineering systems to arise needs or to improve existing functionalities.

Access to and use of MEANS-InOut (available in English and French) is open to anyone, free of charges for six months. Further use is subject to the terms of a service contract.

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Development and harmonization of environmental footprint assessment of food products in Finland

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Abstract

Political and business decision-making and communication about the environmental footprints of food products should be uniform and comparable. Our work aims to ensure that at least Finnish companies and actors would assess and communicate the environmental footprints of food products in a comparable way, especially when bringing information to the public discussion and environmental claims. The work will facilitate and promote the assessment of other environmental impacts in addition to carbon footprint assessment. Although the food LCA methods and different standards and guides have developed, a common challenge is still the large number of individual choices and solution possibilities offered by LCA assessment methods at several points in the assessment, which weakens the comparability of the results. In our project, a general guideline for the food LCA method will be completed, which outlines, among other things, allocations, system boundaries, data quality requirements, soil carbon changes and a number of assessment and equation formulas for, for example, animal and plant production. In this regard, our guidelines will be more harmonized than the generic PEF, which does not aim for comparability between product groups. It is essential to harmonize the main principles regarding the environmental footprint of foodstuffs so that the assessment are comparable between product groups as well. At the same time, our aim is to prepare the guidelines as PEF-compatible as possible. However, despite our goal, it does not mean that nutritionally different products can or should be directly compared to each other as such. From the company perspective, around 30 Finnish companies are involved in the project, and the participation of companies speeds up the implementation of the harmonization and development work of food LCAs.

Introduction and background

Carbon and environmental claims and labels and LCA based environmental information of food products have widely entered into public discussion and debate. Also the Intergovernmental Panel on Climate Change has raised food and its consumption and consumption changes as one of the key means in the fight against climate change. Finnish, especially the largest companies, are currently investing a lot in determining and reducing the environmental impact of their products and supply chain, albeit with an emphasis on the carbon footprint.

Scientific articles on Life Cycle Assessment (LCA) of food highlight new methods and approaches, calculation models and results from the perspective of both food products and diets and the environmental footprints of production and consumption. Carbon neutrality is being pursued in the companies' value chains and especially attempts to increase carbon soil in primary production is in headlines. There is a desire to reduce the environmental impact of food. However, there is still a long way to go to uniformly measure the carbon and environmental footprints of food products.

Finnish companies are already quite well aware that carbon and environmental footprint assessments carried out at different times and places and by different companies and organizations are not automatically comparable. The challenge is the large number of solution possibilities and choices offered by the LCA methods, approaches and standards at several points in the LCA process, which weakens the comparability of the results. Therefore, we should answer e.g. to the following questions in our current methodology harmonization initiative.

Are the soil carbon stocks of food products (also potential carbon sinks) included and how could they be included in the assessment in uniform way? How are CO_2 emissions released from peat fields interpreted in the carbon footprint assessment, since this is essential element especially in Finland. How are emissions allocated in side stream situations or are they compensated and with what principles in different types of circular economy situations, regarding e.g. manure use and side-stream based feed raw materials? What tier level of emission models should be used for the biological processes of primary production to make the results comparable? Whether and how is the carbon footprint of use stage, especially food preparation and transportation of households, determined and communicated as part of the product LCA results, since there are many options to prepare food by consumers? Is it necessary and to what extent should there be actual primary activity data from primary production farms?

The extensive Finnish LCAFoodPrint work aimed at harmonizing food LCAs started in 2021 and will end in the summer of 2024 to answer these challenges. Cooperation with around 30 companies and associations operating in Finland is in the core of the project, in addition to actual methodology development and harmonisation work. The starting point of the national harmonisation work is the work by the European Commission on the assessment of the environmental footprint of products (Product Environmental Footprint, PEF). It has many strengths. Furthermore, the Commission will probably push for the fact that in the future companies must carry out the assessment in accordance with the PEF assessment, if they want to launch lifecycle-based environmental footprint claims. The participating companies will get to know several food LCA related classic and newer challenges and areas and their solutions throughout the project and ongoing methodological harmonization and development efforts by the research team. The participation of companies speeds up the implementation of work in the field, and the collection of initial data on farming operations and chain processes becomes easier.

First Finnish climate assessment protocol of food products was already developed by Katajajuuri et al. 2012, and the learnings, results and background work from that process will be utilized in the current work.

Rationale, objective and scope

Common rules are needed for assessment and calculation methods to enable consistent, harmonized and comparable carbon and other environmental footprinting of food, public debate and decision-making. ISO 14040 series, ISO 14067 standards and Product Environmental Footprint guides (European Commission 2017) and newest suggestions for PEF improvements by Zampori and Pant (2019) and related food product category rules (PEFCRs; also Helmes et al. 2020) provide an excellent basis for that. However, there are certain contradictions between them (see e.g. Pedersen, E. and Remmen, A. 2021) and also PEFCRs of different food product groups consists of different type of methodological solutions and suggestions. As we see that PEF seems to be even stronger in the future, and it might be mandatory to make the LCAs based on that, if aimed for public use, our methodology is meant to be as closely compatible with PEF and PEFCRs as possible. Furthermore, suitability and acceptability of the methods and models is important from the company point of view. The environmental impact categories included in the work are climate impact (ie. carbon footprint), water footprint and eutrophication. In the future, also other essential environmental footprint impact categories should be included, as required by PEF.

First preliminary results – comparison of LCA methodologies of current PEFCRs
As the first international output of our work, Hietala et al. 2022 summarizes the key differences within current actual food PEFCRs and some draft versions of PEFCRs. The PEF and PEFCR guidelines were observed in parallel and the comparability of the life cycle assessment results thus defined was also assessed between product groups. Due to the generic PEF guidelines, most PEFCR guidelines follow largely the same methods and requirements, but some critical differences also exist to enable comparability. In addition to the functional unit, the most significant differences were observed in allocation, system boundaries, especially in the definition of the use phase, and in the hierarchy levels of the modelling. It should be noted that this comparison was kept at a relatively general level. A more detailed examination could refine these results and the differences between the PEFCR could be better identified. Our comparison was challenged by the fact that PEFCRs vary in quality and documentation. Based on our analysis, it is clear that current PEFCRs does not aim to make LCAs of different food product categories comparable at all as stated in the PEF documentation as well, and from that reason it would be important to have one "food PEF" covering all the food products with uniform requirements.

Additionally, the soil carbon stock changes have been taken into account in only a few PEFCR guidelines, which is one of the most crucial 'newer' challenges in food LCAs and mostly soil carbon changes have been discarded in previous individual food LCAs, or carried out with large methodological variation (e.g. Joensuu et al. 2021, Hietala et al. 2022). It should be noted that according to the general guidelines of PAS2050: 2011, changes in soil carbon stocks should not be taken into account when they are not due to direct land use changes (BSI 2011). As a result, for example, the effects of cultivation measures on carbon stocks should be disregarded according to the PAS2050 guideline. In conclusion, the requirements for the treatment of biogenic carbon in several PEFCRs are loose. The increase in soil carbon stocks has been taken into account in only a few PEFCR guidelines and the PEF general guideline is based on the PAS2050: 2011 guideline (European Commission 2017, BSI 2011). The assessment of soil carbon stocks need to be developed and integrated much better in food LCAs, and this is now even more important when companies have many initiatives to increase soil carbon and they are keen to communicate this as well.

In addition, some national calculation rules will be developed for regionalized eutrophication impact category, and also some further assessment models for improved LCA (not harmonized) will be recommended during the project.

Conclusions and next steps
Although PEF has some contradictions and ambiguities, it is still the most ambitious attempt to harmonize LCA calculation so far. Based on PEF, it would be possible to make LCA calculations internationally comparable, also between different product groups, but this needs to be improved. H owever, it does not mean that nutritionally different products might or should be directly compared t o each other as such. To obtain internationally harmonized methods, the development of PEFCRs will be followed, when possible and uniform, and all national methods are aligned with them in our development and harmonization work. PEFCRs exist only for a few food product categories, but all

food sectors need harmonized rules, also between food product categories.

In the project, a general guideline for the LCA method of food products will be completed, which aligns with PEF as far as possible, based on, for example, allocations and side stream handling, system boundaries, soil carbon changes, data quality requirements and a number of individual calculation formulas for, for example, animal and plant production. There is clear demand for that kind of generic and uniform food PEFCR, covering all the food product categories.

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In addition to Natural Resources Institute Finland (Luke), the Ministry of Agriculture and Forestry and food chain companies, organizations and associations, the Finnish Environment Institute SYKE, the University of Helsinki, Technical Research Centre VTT, LUT University, the Ministry of Environment and WWF Finland are participating in the project. The project advances the Governmental Program by developing life cycle assessment methods of food in broad cooperation. The project is mainly financed by Ministry of Agriculture and Forestry, Luke and participating companies and associations. See more at www.luke.fi/projektit/LCAFoodPrint.

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The use of the Environmental Footprint methods to measure and communicate the life cycle environmental performance of food products

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Introduction

The food system is responsible for significant environmental impacts, among others on climate change, land use and biodiversity. Many studies reveal how an increasing global population, changes in consumption models, and a considerable generation of food waste pose serious challenges to the overall sustainability of food production and consumption [1] European Commission. 2021. Commission Recommendation (EU) 2021/2279 of 15 December 2021 on the use of the Environmental Footprint methods to measure and communicate the life cycle environmental performance of products and organisations, OJ L 471, 2021

[2]. Life cycle thinking and assessment, and their analytical power in assessing supply chains, have been advocated as reference methodologies for assessing those impacts (Notarnicola, Sala, et al. 2016) [11]. A major criticality lies in the coexistence of different and non-harmonized methodologies and guidelines for assessing and labelling the environmental performance of food products, which can create confusion among consumers and other stakeholders involved in the food supply chains. Furthermore, it poses an unnecessary burden on those organizations requested to evaluate the environmental performance of their product according to several different methodologies. The European Commission and its science and knowledge service, the Joint Research Centre (JRC), are committed to address this issue, developing the Environmental Footprint (EF) methods as a commonly-agreed and science-based framework to ensure that environmental assessments are scientifically reliable, transparent, and consistent in supporting informed choice.

This presentation aims at providing an overview on the principles, characteristics and opportunities underlying the EF methods and on the effort that is being made by the European Commission and other international organizations to harmonise these methods with other methodologies internationally recognized for the life cycle assessment applied to food sector.

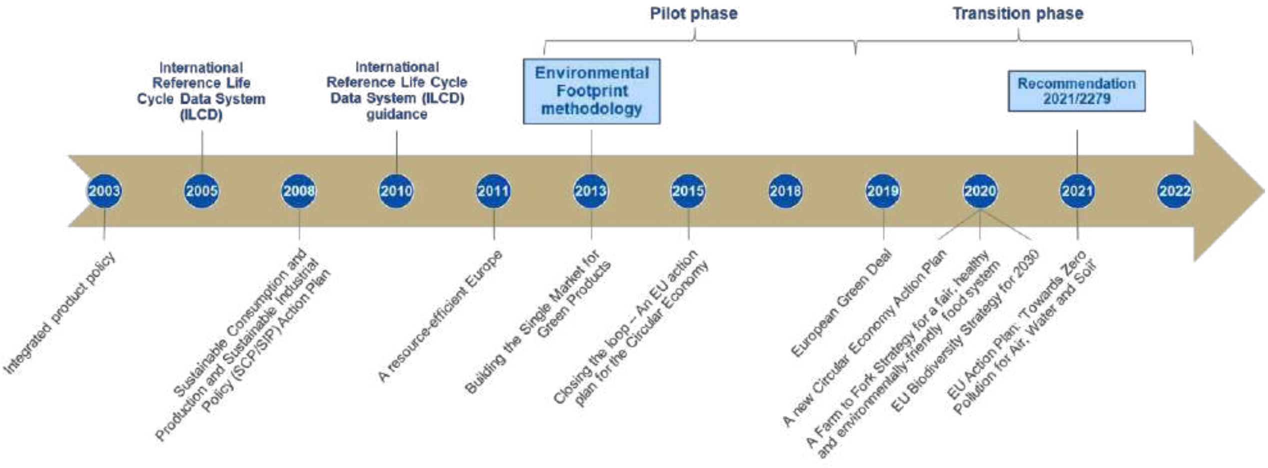
General framework and current status of the Environmental Footprint methods

A company wishing to market its product as environmentally friendly in different EU Member States faces a confusing range of choices of methods and initiatives for quantifying and communicating its environmental performance. Sometimes, they have to use different methods for different markets. This results in additional costs for companies and confusion for consumers.
The European Commission developed the Product Environmental Footprint (PEF) and Organisation Environmental Footprint (OEF) methods as a common way of measuring the environmental performance of products and organizations, adopting in December 2021 the revised Recommendation on the use of Environmental Footprint methods [1].

The overarching purpose of PEF and OEF information is to enable reducing the environmental impacts of goods, services and organisations taking into account supply chain activities (from extraction of raw materials, through production and use to final waste management). This purpose is achieved through the provision of detailed requirements for modelling the environmental impacts of the flows of material/energy and the emissions and waste streams associated with a product or an organisation throughout the life cycle.

A systemic perspective is needed to support decisions that have effects on the sustainability of policies, production systems and services, i.e. the environmental, social and economic spheres in which the concept of sustainability is articulated. Life Cycle Assessment (LCA) represents the practical realisation of this concept, aiming to analyse comprehensively potential environmental implications of a decision-making process. LCA forms the scientific and methodological foundation of the PEF and OEF methods (JRC, 2021) [6]. Following the framework standardised by ISO 14040-44 [9] [10], the EF is structured in similar steps, yet providing further specifications necessary to achieve a higher degree of robustness, consistency, reproducibility, and comparability.

Figure 1: Timeline of the Environmental Footprint methods development



The methods were tested between 2013-2018 by more than 280 volunteering companies and organisations (mainly industry associations, large OEM's from EU and globally). This pilot phase resulted in 19 PEF Category Rules (PEFCRs) and 2 OEF Sector Rules (OEFSRs), which complement the PEF and OEF methods by providing additional guidelines for specific product categories/sectors [5]. Among them, several dedicated to the evaluation of value chains in the food sector – dairy products, feed for food producing animals, pet food, pasta, beer, wine, packed water – including one for retailing activities.

In the light of the results of the pilot phase, the European Commission is now implementing a transition phase (2019 – 2024) to include new methodological developments in PEF and OEF, to monitor and further develop PEFCRs and OEFSRs as well as to explore how to incorporate them in upcoming policies and initiatives.

Five new PEFCRs are currently under development.

The environmental footprint methods in the food sector

The food sector demonstrated a strong interest in the process of EF methods development, with several stakeholders contributing to the development of PEFCRs during the pilot phase. Overall, 11 PEFCR projects on food products were initiated, of which seven came to a successful output. Other three product groups, namely coffee, meat and olive oil were discontinued during the pilot phase, due to various reasons. The PEFCR for marine fish will be finalized during the transition phase.

The revised methodology published in 2021 [1] also provides detailed guidance and requirements on how to model specific life-cycle stages, processes and other aspects of the life cycle, among which agricultural production and biogenic carbon.

During the pilot and transition phase a Technical Advisory Board (TAB) was created with the aim of providing technical advice and expertise to the Commission. The issues to be discussed include, but are not limited to, analysis of the content of newly developed PEFCRs/OEFSRs, consistency of approaches among different PEFCRs/OEFSRs, and new methodological developments deemed necessary within the EF context. Given the interest demonstrated by stakeholders from the food sector to the EF methods, a working group on agriculture (AWG) was set up to deal with issues related to EF applied to the food sector. The objective of the group is to build consensus between government, academia, and industry on inventory modelling and impact assessment of relevant aspects of agricultural production activity. The main topics addressed by the AWG relate to the modelling of pesticides, fertilizers, manure management, water use, impacts on biodiversity, and data collection at farm level. After presentation to the TAB, the Commission may consider the inclusion of AWG recommendations in the PEF and OEF methods.

Methodological harmonisation efforts

The PEFCRs for food products set common rules for realizing PEF studies and provide environmental footprint benchmarks for the average representative products sold on the EU market. Many of these products involve in their supply chains agriculture and ingredient productions occurring in emerging economies, therefore having a potential future impact on these production patterns.

Given the interconnection between EU and Extra EU economies in relation to food products supply chain, the European Commission has built partnerships to implement common initiatives towards a more sustainable production of food and to ensuring interoperability of the EF methods at global level. Relevant examples of these partnerships are:

- ***UNEP-Life Cycle Initiative – Global Guidance on Environmental Life Cycle Impact Assessment Indicators (GLAM)***: the aim of this initiative, under the United Nations Environmental Programme umbrella, is to enhance global consensus on environmental life cycle impact assessment indicators, providing practical recommendations for different environmental indicators and characterization factors for Life Cycle Impact Assessments (LCIA). This is done through the joint effort of an international expert task force who prepares recommendations on the individual topic areas. Building on the recommendations from the first two phases, the ongoing GLAM Phase 3 aims to advance methodological development on important aspects of the impact assessment on human health, ecosystem quality, natural resources and ecosystem services [8].

The European commission is a funding partner of the Life cycle Initiative, and the Joint Research Centre (JRC) is supporting GLAM at different levels, participating in meetings and providing scientific inputs, documentation and technical support, in order to follow possible alignment with the International Life Cycle Data system (ILCD) [4] and EF methods' development.

- ***LEAP – Livestock Environmental Assessment and Performance Partnership***: it is a multi-stakeholder initiative that is committed to improving the environmental performance of livestock supply chains, whilst ensuring its economic and social viability. Farmers, consumers and other livestock stakeholders are increasingly in need of more information about the environmental performance and the sustainability of livestock supply chains. Although a wide range of environmental assessment methods have been developed, there is a need for comparative and standardized indicators in order to switch focus of dialogue with stakeholders from methodological issues to improvement measures. LEAP develops comprehensive guidance and methodology for understanding the environmental performance of livestock supply chains, in order to shape evidence-based policy measures and business strategies. [7]

This presentation is part of a set of EF capacity building and information events that the partnership Green Soluce - Studio Fieschi & soci - ALDA are implementing on behalf of the Directorate-General for the Environment of the European Commission, aiming at raising awareness on the principles, characteristics and opportunities underlying the EF methods.

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SALCAfuture: developing an expert system for life cycle assessments of agricultural products and farms

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Keywords: *agricultural LCA; farm LCA; crop LCA; SALCAfuture; environmental impacts*

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Introduction

Primary agricultural production plays a significant role in supplying the population with food, but also causes various desirable and undesirable environmental impacts. Agricultural systems are located at the interface of environment, nature and technology, are characterised by numerous interactions with these areas and are thus complex and stochastic. Estimating the environmental impacts of these systems therefore requires a large amount of data, specific models for calculating direct emissions and characterising environmental impacts as well as high-quality background databases. In order to be able to manage these elements together, efficient calculation tools are needed. We have been working on the development of such a tool over the last years, which we present herewith. This article describes: i), the process of development of an expert system for conducting life cycle assessments for agricultural products and farms in the context of research projects (SALCAfuture) and ii) the main goals and implemented functionalities.

Rationale and objective of the work

The main goal of the SALCAfuture project was to develop an IT-supported expert system for life cycle assessments of agricultural products and farms that allows collection of primary data and precise inventory modelling and assessments at different levels of agricultural production (farm, animal husbandry, plot, crop). Another important goal was to cover all relevant environmental aspects, viz. the use of natural resources (energy, land, water) and numerous environmental impacts (climate change, acidification, eutrophication, human toxicity, biodiversity, soil quality). Furthermore, a high level of scientific quality, transparency and reproducibility shall be reached.

Approach and methodology

SALCAfuture was designed as a project involving experts from different disciplines: i) experts from IT and data management for the implementation of the software solution; ii) experts from different agronomic and natural science disciplines (e.g. carbon and nitrogen cycle, crop production, animal husbandry, agricultural engineering, soil science, pesticides etc) for the implementation of the models for calculating direct emissions and iii) experts in agricultural LCA for developing the data collection interface, calculation workflow and quality control procedure.

Results and discussion

The resulting software has been designed as a combination of two significantly different parts interacting with each other. The first part is a flexible framework that enables data collection, emission calculation and the compilation of calculation results for a wide range of applications. The second part contains the necessary background data, modules for data preparation, plausibility check and emission calculation. Support from IT-specialists is needed to manage the framework, whereas the second part can be self-managed by the research team.

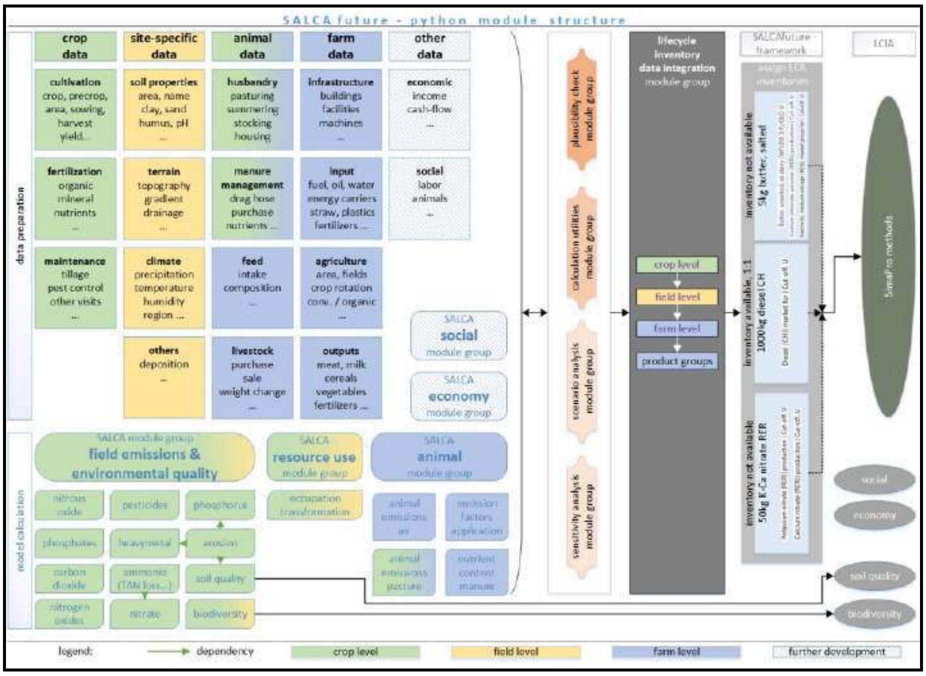

Figure 1: Schematic representation of the modular approach for data collection, processing, and emission calculation of SALCAfuture

Figure 1 shows a schematic representation of the modular approach as well as of theworkflow implemented in SALCAfuture. As first step of the workflow, a LCA specialist creates project-specific data entry forms, which can be accessed via a web application. Afterward, the IT system validates the entered data according to predefined rules to ensure high data quality. The collected data is then available for calculations and analyses via a programming interface. Modules specially developed by LCA experts calculate the direct emissions of the production system under consideration. The calculation models used in the modules are essentially updated versions of the SALCA emission models (Gaillard and Nemecek 2009). Different procedures are applied to allocate inputs and outputs at different stages of assessment. The IT system also provides various interfaces for importing resp. exporting data into resp. from the system. The export is used, among other things, to transfer the calculated values to SimaPro, where life cycle inventories (LCI) are completed by linking them to Ecoinvent V3.8 (Wernet et al 2016) as background database and finally calculating the environmental impacts.

Conclusion

SALCAfuture is an expert tool for the preparation of life cycle assessments for agricultural products, food and farms in the context of research projects. SALCAfuture makes it possible to efficiently calculate the environmental impacts. The main strength of SALCAfuture lie, in its flexibility and in the possibility to map different hierarchical levels of agricultural production precisely and differentiated with regard to their environmental impacts (farm, field, crop, livestock) while considering all relevant emissions.

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Ecosystem Dynamic model for biodiversity impact assessment in LCA: Proof of concept on fisheries in the Adriatic Sea.

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Keywords: *Dynamic ecosystem modelling; biodiversity; fisheries; Life Cycle Impact Assessment.*

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Rationale

Global decline in wild capture fisheries is now widely accepted. Principle factors contributing to this decline include pollution, climate change, destructive and unsustainable fishing practices, discard mortality and illegal, unreported and unregulated fishing (FAO, 2020). Over-exploitation of wild capture fish stocks is the most direct threat to the future of global seafood, arising due to global human population growth, increasing demand for fish products, and inequality in fisheries policy and management efforts (IPBES, 2019). Life Cycle Assessment (LCA) methods are a robust way of understanding potential environmental impacts of products and human activities such as fishing, a crucial step to achieving sustainability and resilience in seafood supply required by international Agreements and targets including UN Sustainable Development Goal 14 (SDG14). In Life Cycle Impact Assessment (LCIA) methods, marine impact pathways are relatively under-developed in comparison to terrestrial counterparts. This limitation means these impacts are not currently included in LCA studies nor any subsequent decisions that are informed by these studies. This lag in development however, provides both impetus and opportunity to develop these impact pathways, improving assessments and their contribution to tools and decision making towards more sustainable fisheries.

Objective & Approach

This work introduces a novel LCIA methodology, incorporating ecosystem dynamics into cause-effect modelling and applied to marine ecosystems, to holistically quantify the impact of fishing activities on biodiversity. The approach incorporates the cascade of impacts initiated at ecosystem level including the natural variation within the ecosystem otherwise hidden from impact assessment, to enable a more realistic assessment of the impacts of human activity on ecosystem quality.

Building on the pioneering LCIA approach developed by Hélias *et al* (2018) and Hélias and Bach (2021) quantifying the impact on targeted stocks based on individual species modelling, this approach explores the inclusion of dynamic ecosystem modelling. The assessment is thus elevated from species to ecosystem scale, through consideration of inter-species interactions. The ongoing objective of the work is to define how best to integrate the dynamic representation of biotic ecosystem change into the LCIA framework at both the midpoint and endpoint level until the quantification of damage to the Ecosystem Quality Area of Protection (AoP). Proposals will be made to quantify characterisation factors (CFs) using the recommended metric Potentially Disappeared Fraction (PDF) of species to represent biodiversity loss.

A proof of concept is presented, using fisheries and ecological data from the Adriatic Sea ecosystem

(FAO fishing area 37. 2.1), as the first step towards regionalised, global characterisation of the holistic, ecosystem scale impact of biomass removal by fisheries, using the data that is currently available. The Adriatic Sea is a sub-region of the Mediterranean and Black Sea FAO fishing area, a region currently experiencing disproportionally heavy exploitation levels. It is also well studied from an ecological perspective, making it a suitable choice for a proof of concept in terms of data availability and studies for comparison, as well as being a manageable size in terms of preliminary data collection and modelling groundwork.

Methodology

Ecopath with Ecosim (EWE), a suite of models based on trophic food-web interactions, is widely cited as one of the most robust and commonly implemented ecosystem models. It has been applied at a broad range of scales both in fisheries management and ecological studies and even in conjunction with LCA, to achieve more holistic assessment of systems and supply chains of seafood products (Avadí *et al*, 2014). Whilst the choice of model itself is not a novel fusion with LCA, the aim of this work is to build a generic modelling framework that can be fed with region-specific fishery and biophysical information in order to achieve a globally consistent approach to the endpoint. Whilst previous efforts have provided integration of a range of mid-point indicators for over-fishing, trophic level impacts (Hornborg *et al.*, 2013), potentially lost yield (Emanuelsson *et al.*, 2014) and most recently distance-to-target indicators (Bach *et al.*, 2022), these predominantly relate to impacts on the Resources AoP (Langlois *et al.*, 2014) and are not currently operational.

Using an adaptation of the time dynamic module of EWE (Pauly, Christensen and Walters, 2000), temporal changes in the biomass of species and/or functional groups are simulated in response to fishing pressure and species interactions. This allows the effects of predation and other mediating factors occurring in the marine ecosystem to be integrated. Each year of the simulation is fed by the biomass produced as a result of these interactions during the previous year. Figure 1 emphasises the main phenomena encompassed by the modelling.

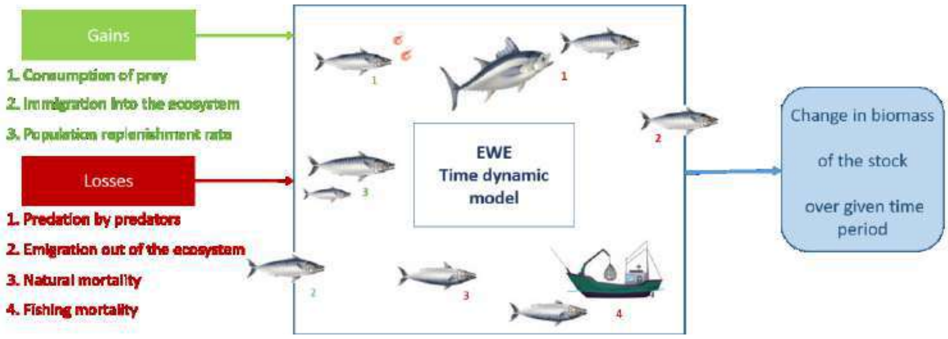

Figure 1. Principles of the dynamic modelling approach

The Adriatic Sea model consists of 188 marine species and 42 Functional Groups reported in FAO catch data for the area, and for which biological data is available online in Fishbase and Sealifebase databases. With this data it is possible to have two approaches, one making use of individual species level detail provided by FAO FishStatJ database of any species included in catch reported by fisheries operating that that area. A second variation, commonly implemented in EWE models, is the use of up to 44 Functional Groups, which categorise marine species based on ecological and physical traits including habitat preferences and size, and an average value is derived for each input parameter.

Dynamic inter-species interactions are simulated through a system of ordinary differential equations. Interactions are introduced as predation pressure on each prey type, based on a version of a generic diet matrix defined by Christensen *et al* (2008) where each species is both predator and prey as defined by column or row, represented as a proportion of the biomass making up the diet of each predator. Foraging arena principles (Ahrens *et al,* 2012) also enable detail to be added on fish behaviours relating to predation effectiveness and predator avoidance, as well as the direct influence of biomass removal by fishing.

Main results & Discussion

The modelling approach allows the characterisation of the ecologically dynamic impact of fishing activity in the Adriatic Sea. Midpoint CFs are developed for fish stocks, as the first step to quantifying the direct and indirect impacts of biomass removal on biodiversity into the LCA framework. A predictive time series of biomass for each species and functional groups will allow the calculation of a range of fisheries relevant indicators to explore the relative state of stocks over time as well as providing a midpoint CF for biotic change. These can be explored for ancillary understanding and comparison of impacts in the ecosystem, as well as the data for calculating damage level CFs.

The key novelty that this approach ultimately aims to provide is the completion of the impact pathway for biomass removal to the endpoint for Ecosystem Quality. The derivation of an endpoint indicator in PDF is a central line of work, to ensure harmonisation in line with UNEP-SETAC GLAM recommendations (Frischknecht and Jolliet, 2016) and has raised some challenges. The calculation of PDF, a metric that is closely linked to land use change impacts where an impact in the ecosystem can be assumed to affect any species occurring there to some extent, is most commonly measured using unspecified species richness changes. As fisheries are both the impact and the impacted medium, with species level data available this presents the possibility to have a more detailed level of assessment through change in abundances within the ecosystem. This is however, a deviation from the typical method of applying PDF. Possibilities to consider are outlined in Figure 2. Options include deriving a fractional PDF that incorporates abundance information over the total ecosystem, or applying a fisheries relevant threshold, to link depletion of abundance to the potential disappearance of the species, similar to the PAF (Potentially Affected Fractions of species) to PDF approach applied to ecotoxicology impacts. In this sense, several options will be discussed to estimate CFs at the endpoint level.

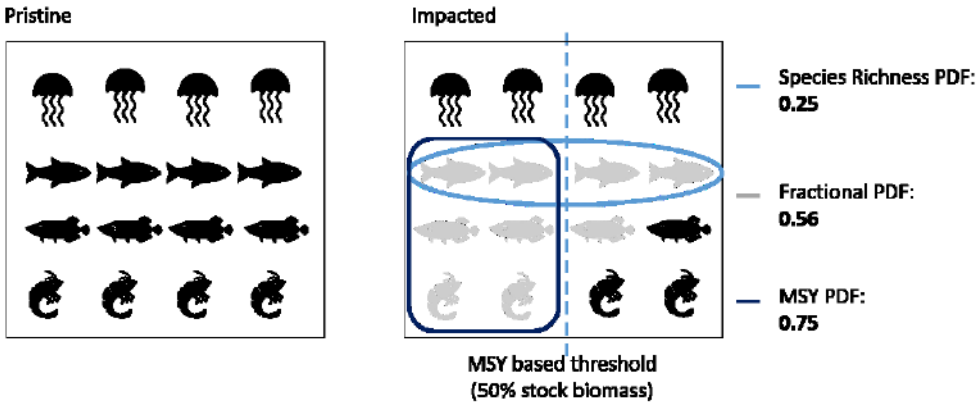

Figure 2. Possibilities to derive endpoint Characterisation Factor consistent with PDF metric.

Another novel element introduced into impact assessment is by this method is how to represent the temporal dynamism of the system and of the impact. This therefore poses several methodological questions, including how to deal with temporality within the static structure of characterisation factors, and how to link the midpoint to the endpoint.

Several methodological challenges and limitations are acknowledged, stemming from a variety of currently unavoidable elements. Ecological modelling is inherently data intensive, and EWE is no exception. When coupled with the ambitious scale of the approach to deliver regionalised modelling with global coverage, data availability and consistency becomes a key challenge, due to differences in reporting quality, formats and regularity between regions. Due to the size of the model, there are instances where data is not available requiring an estimation to be introduced in order to maintain a globally consistent approach, including the use of a generic diet matrix which can be adapted to reflect the constituents of each ecosystem. The requirement of certain input data to be estimated rather than coming from real world data also introduces an additional source of uncertainty. The need to strike a balance describing a system as complex as the ocean with the simplification required by modelling, is then further reduced down to one indicator metric in the LCA framework.

Conclusion

The ability to include a more holistic representation of fishing impacts improves the comprehensiveness of impact assessments relating to the lifecycle of seafood products. This in turn improves the informative capability of LCA as a tool for guiding decision-making and tangible action towards achieving the goals defined by treaties and conservation targets, including SDG14. Application of the approach globally using FAO Major fishing areas for regionalisation represents the next step. This proof of concept presents an approach to improve the accuracy of fisheries LCIA using dynamic ecosystem modelling, thus providing a step towards more realistic, regionalised understanding of impacts to be faced in the future of global seafood supply. This advance, when applied globally can guide the development of more sustainable fisheries policy. Thus facilitating improved stock management in individual ecoregions to a more uniform standard, towards the goal of creating a sustainable industry capable of feeding the world whilst conserving and improving ocean health.

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Sustainable fisheries: towards operationalization of decision-making accounting for biodiversity through LCA indicators

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Keywords: *LCA, Overfishing, Maximum Sustainable Yield, Marine Biodiversity, Seafood eco-design.*

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Abstract

Rationale. Overexploitation of biotic resources constitutes a major threat on marine biodiversity while demand for seafood will rise in the next decades. Application of Life Cycle Assessment to marine ecosystems needs further research to allow a quantitative characterisation of the impact of sea-based products on biodiversity. Moreover, there is a rising demand for product eco-design, as illustrated in Business @ Biodiversity studies; presently, corporates and policy makers do not have proper tools to decide for sustainable practices regarding seafood production.

Introduction and methods. This study aims to apply existing assessment methods of the impact of overexploitation on biotic resources (Langlois et al. 2014 and Emanuelsson et al. 2014) to 125 marine stocks fished in the 14 marine areas drawn by the FAO. We present how the results can be reproduced, including what kind of database can provide for the data needed. We discuss how results can be interpreted as a proxy for biodiversity assessment and the ecological limits of the methods. Finally, we propose operational guidelines for sustainable production and efficient conservation policies.

Results. We show that unsustainable fishing is responsible for a loss of up to 30 times the potential yield of major fish stocks such as Atlantic cod, red snapper and bluefin tuna. We identify depleted fish stocks for which biomass is up to 15 times lower than it should be (yellownose skate fished in South America) and stocks facing fishing mortality up to $1.9*10^7$ times higher than the maximum required to allow sustainable recovery (Pacific Ocean perch fished off the US West Coast). Regarding intrinsic biodiversity, our study shows that we are not able to understand the consequences of overfishing through a cause-effects chain due to lack of science knowledge. However, we display how to limit the impacts on biodiversity by using complementary indicators at species and ecosystem level.

Recommendation. While methods seemed to compete against each other in the impact assessment of marine stock overexploitation on biodiversity, this study shows their complementarity. Hence, in the aim of making seafood more sustainable, a combination of the indicators they provide should be used. The complexity of marine ecosystems and the remaining limits of methods are discussed, showing the compelling need for further data collection and analysis, and opening ways for targeted research.

Introduction

The latest report of the IPBES indicates that direct exploitation of biotic resources sets the main threat on marine biodiversity and ecosystem services (IPBES, 2019). This driver impacts natural resources at species and ecosystem level. It endangers taxa like sharks, rays, and chimaeras globally, some being already extinct (Dulvy *et al.*, 2021). On the other hand, marine ecosystems provide vital services including source of protein for many coastal populations across the world. Both for the intrinsic value of biodiversity and for its contribution to human, a sustainable management of marine resources and fisheries is needed to reach the challenges of the next decades (FAO, 2020). Although Life Cycle Assessment (LCA) consistency and reliability is gaining robustness on terrestrial ecosystem assessment, it still displays major shortcomings for marine ecosystems (Asselin *et al.*, 2019). Several studies proposed frameworks towards the inclusion of biotic resources exploitation into Life Cycle Assessment (Guinée and Heijungs, 1995; Emanuelsson *et al.*, 2014; Langlois *et al.*, 2014; Taelman *et al.*, 2014; Sonderegger *et al.*, 2017; Crenna *et al.*, 2018; Hélias *et al.*, 2018). In this study, the two methods mentioned by (Woods *et al.*, 2016) are reviewed: i) Emanuelsson *et al.* (2014) and ii) Langlois *et al.* (2014). Both are based on the concept of Maximum Sustainable Yield (MSY) introduced by Schaefer (1954), commonly used to assess the sustainability of fisheries. The goal of this work is to: i) apply both of these methods to more stocks on a worldwide updated database (RAM Legacy Stock Assessment Database, 2018), ii) understand methods and their limits based on results of this application and iii) propose a guideline for decision makers in the context of eco-design of fish products and conservation of marine ecosystems. We aim to answer: Is it possible to evaluate the impact of fishing on intrinsic biodiversity and improve the sustainability of seafood-based products as well as marine conservation policies? Considering the complexity of marine ecosystems and of their assessment, it is not expected to accurately evaluate impact of fishing on intrinsic biodiversity with any of these two methods. However, the methods are expected to determine if a stock is threatened and consequently to help decision making to build more sustainable stock management through product eco-design and conservation policies.

Material and methods

Two methods were selected to determine a midpoint impact of overexploitation: i) A method reflecting the difference between current and target fisheries management developed by Emanuelsson et al. (2014), and ii) a method quantifying the impact of stock exploitation at species and ecosystem levels developed by Langlois et al. (2014). Their values for each stock studied were compared. Among the drivers of biodiversity loss, overexploitation of biotic resources impacts ecosystems through the decrease in exploited stock at i) species level and ii) ecosystem level due to trophic interactions. Emanuelsson *et al.* (2014) focuses on the first impact pathway and Langlois *et al.*, (2014) proposes indicators on both impact pathways. The impact of by-catch is not included in this work so far. The methodology used to determine overexploitation impact on biodiversity is presented in Figure 1.

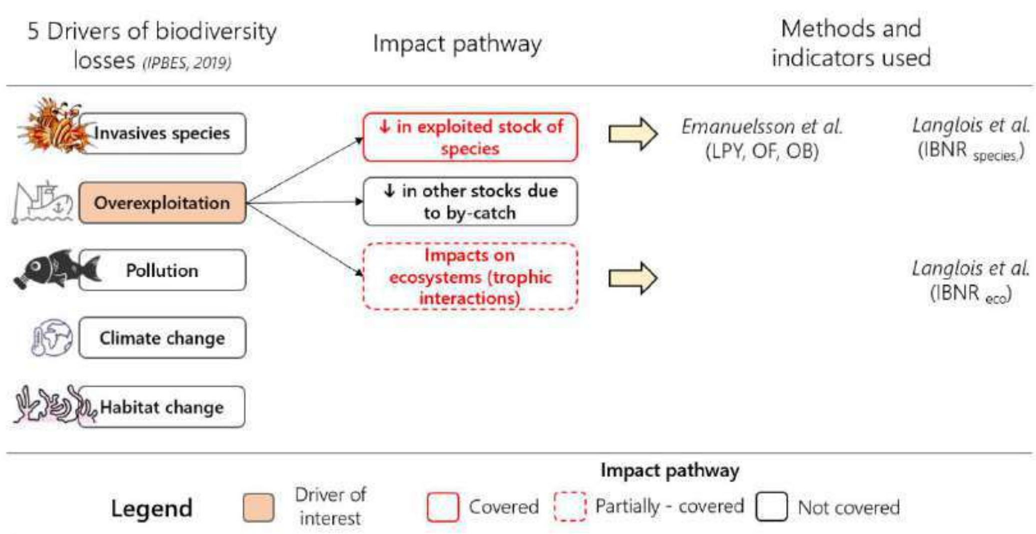

Figure 1: Goal and scope of our work to assess impact of fisheries on biodiversity.

Access to data was one of the major challenges of this study. Several databases have been considered to conduct this study. They were provided by: (i) regional organisms (NEAFC, NOAA, CCAMLR), (ii) species-specific oganisms (CCSBT, IPHC) or (iii) global and multi-species organisms (FAO FishStat, RAM Legacy Stock Assessment Database, ExioBase, FishBase, SeaAroundUs). Our final selection was based on the necessity to include fishing data, as well as biological timeseries and MSY parameters. It needed to be available on a worldwide scale, taking stock in all seas and oceans into account. Thus, the RAM Legacy Database was selected as main source of data, completed by biological and ecosystem information from FishBase and SeaAroundUs.

Results

Results from 'Lost Potential Yield (LPY)' and its complementary indicators led us to discriminate between four categories illustrating why potential yield was lost and directing what kind of decision should be taken:

- "Overexploited", such as 'Atlantic cod, European Union'
- "Overexploitation risk", such as 'King mackerel, US Southeast and Gulf'
- "Recovering", such as 'Bigeye tuna, Pacific Ocean'
- "Loss of opportunity", such as 'Argentine anchoita, South America'

Results from the 'Indicator of Biotic Natural Resources at ecosystem level ($IBNR_{eco}$)' allow comparisons of the ecological impact of fishing through the rate of Net Primary Production (NPP) uptake. Although individual values of this indicator don't provide information, we show that the higher the indicator is, the more NPP it requires.

The application of these indicators to 125 stocks among 14 FAO areas allowed us to build a decision-making guideline (see Figure 2, the full guideline is available in Gaillet *et al.* (2022)). It can be used by different stakeholders, in order to reduce their impact on biodiversity through overexploitation, by selecting which indicator corresponds to their goal and scope and how to interpret results or complete them with another indicator in case of a borderless score.

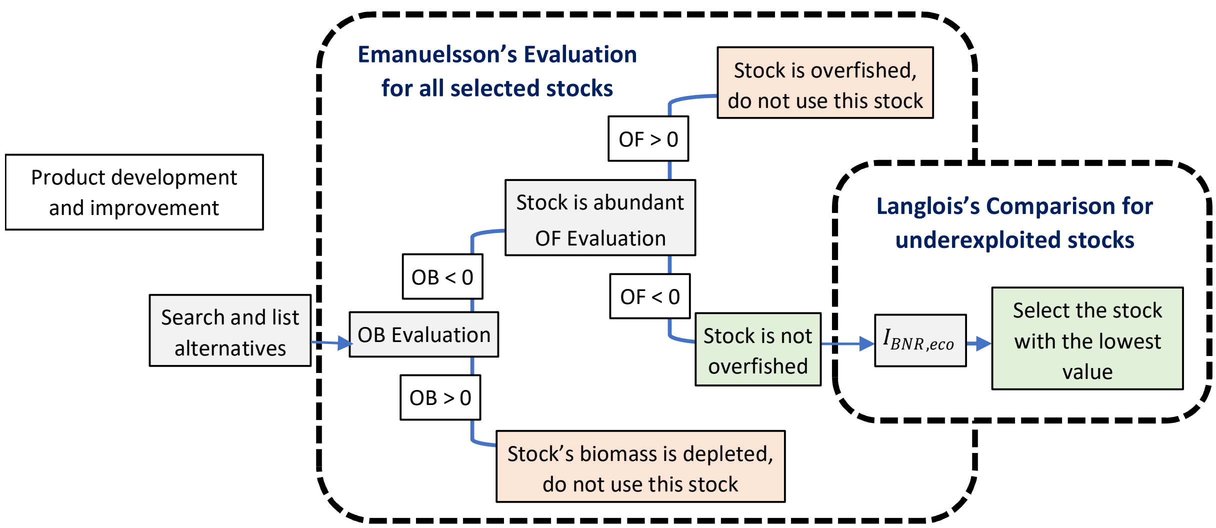

Figure 2. Partial decision tree for the use of indicators of overfishing impact on biodiversity. Both indicators should be used in eco-design of seafood-based products.

Discussion

The application of these indicators to 125 stocks among 14 FAO areas made us understand their strengths, as well as their limitations. Two main limitations of the indicators arose from the study.

The ecological significance of the indicators is limited. There is an overwhelming importance of top predators, and the ecosystem complexity is not considered, reflecting for example in the assumption that marine populations abundance are at their equilibrium. Because of such limitations, keystone species of low trophic level would not receive the warning they deserve. It is the case of Antarctic krill (*Euphausia superba*), representing 98% of catches of FAO area Atlantic, Antarctic. It wasn't calculated here because it doesn't appear in the database but it would receive a low 'indicator of Biotic Natural Resources at ecosystem level', due to its low trophic level. However it is a keystone species of the Antarctic ecosystem, being the main source of food for air-breathing animals (Murphy *et al.*, 2012).

The indicators focus only on a single-species fisheries. Fisheries can be more complex, most fishing campaigns are not fully specific and include the catch of several species. These simultaneous catches can have different vulnerability and come from stocks of different statuses. Hélias *et al.* (2018) proposed a framework to better assess multi-species stocks, extending one of the indicators analysed here (Langlois *et al.*, 2014). It also improves the assessment through the inclusion of multi-habitat stocks and has a relatively low data requirement. However, ecological considerations are still uncomplete, as shown by the low Characterization Factor of Antarctic krill which exploitation disturbs the Southern Ocean's ecosystem greatly (Mangel and Switzer, 1998; Murphy *et al.*, 2012).

Finally, the impact pathway of bycatch is not yet accounted for, despite its potential serious threat on species and ecosystems. Bycatch of not commercialised species such as air-breathing mammals, birds, and reptiles has a great impact on ecosystem as they often play a role in ocean's productivity through nutrient cycling and communities structure (Epperly *et al.*, 2002; Frankish *et al.*, 2021; Peltier *et al.*, 2021). In addition to this shortcoming, these indicators don't take into account the potential damage on habitat of various fishing techniques like ghost fishing and seabed trawling. All these impact pathways will be assessed in later works of the team.

Despite all these shortcomings, the indicators analysed here contribute to a better assessment of environmental impact of fishing. They provide initial tools for informed Ecosystem-Based Management of fisheries, which should be developed further.

Conclusions

Application of indicators of both methods on a wide range of stocks allowed us to provide an up-to-date stock status evaluation and to understand their implications, conclusions and limitations. Both methods still have limits preventing their application to all kind of stocks and fisheries. Impact on biodiversity calculated by indicators is partial and must be developed but it helps determining if a stock is threatened and consequently help decision making to build more sustainable stock management through product eco-design and conservation policies. The main obstacle against accuracy and reliability of the methods remains the lack of data. The specific and up-to-date biological and statistical data required only enabled us to provide them for some of the worldwide fisheries. By helping the assessment of overexploitation of fished stocks, this work makes a step towards a management of fisheries conserving biodiversity. It will be enhanced and developed further to include new indicators (Crenna *et al.*, 2018; Hélias *et al.*, 2018) and other impacts of fishing activities: mainly bycatch and habitat damage. Data analysis will be improved by the works on ecosystem-wide assessment in progress in the Ecopath with Ecosim project (Christensen *et al.*, 2005).

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On combined use of ecological risk assessment and life cycle assessment in capture fisheries

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Background

There is a plethora of challenges for future global seafood supply from capture fisheries. Fishery management need to consider an increasingly broader set of ecological objectives, including rebuilding of overexploited fish stocks, altered ecosystem structure and function, climate change adaptation, conservation of sensitive species and habitats, and more – in essence referred to as the ecosystem approach to fisheries (Garcia et al. 2003; Pikitch et al. 2004). Concurrently, it is increasingly important to consider our interference with vital planetary processes beyond aquatic ecosystems, such as land use and climate change mitigation (IPBES 2018; IPCC 2022).

Sustainable use of the ocean is also seen as a facilitator to solve many societal challenges through the development of a Blue Economy (United Nations 2021). Consumers may also be advised by national dietary guidelines to eat more seafood for planet and health – but may be uncertain on what to choose and whom to trust (Richter & Klöckner 2017). This uncertainty is in part an effect of the globalization of the seafood market; seafood is delivered on demand through complex trade routes, making it difficult for a consumer to observe and understand the different pressures seafoods may have on distant and local ecosystems (Crona et al. 2016). As a results, market-based sustainability assessments have been developed to guide consumers, such as eco-certification and seafood consumer guides. Still, no seafood assessment exists today that is complete – even if limiting the concept to environmental sustainability – i.e., comprehensively addressing pressures spanning from global (e.g., greenhouse gas emissions) to local (e.g., ecosystems).

To this end, to define sustainable seafood systems from capture fisheries has become increasingly complex for management, industry, practitioners, and consumers. Complexity calls for a systems perspective where different tools exist (Ness et al. 2007). Recent years have seen an increasing interest in combining elements of life cycle assessment (LCA) and risk assessments, both used as decision-support in environmental management (Peña et al. 2022; Muazu et al. 2021; Guinée et al. 2017; Harder et al. 2015; Linkov et al. 2017) – but capture fisheries remain absent in these reviews and perspectives. The application of the tools varies for capture fisheries where LCAs are generally more industry-oriented, with quantitative assessments of products, whereas various forms of ecological risk assessment (ERA) are utilized as decision-support in fishery management and eco-certification, offering a more semi-quantitative or qualitative assessments on a fishery basis (Ziegler at el. 2016). Given the combined application of the tools seen in other areas, what may the two tools offer when jointly considered for seafood from capture fisheries?

Objective and methodology

The objective is to present insights related to seafood sustainability from applying LCA and ERA to capture fisheries. Findings of a three-year research project are here summarized and discussed to provide perspectives on the future landscape of sustainability assessments of seafood production based on capture fisheries.

Results and discussion

Fisheries assessed

ERAs of capture fisheries have predominantly been developed and applied by researchers based in the USA and Australia, while LCAs are mainly published by European researchers, respectively. Studies on fisheries outside of Europe and North America are rarer for LCAs compared to ERAs; ERA has to a larger extent been applied to data-limited and non-industrial fisheries than LCAs.

LCAs have to a large extent been centered around gadoids, pelagic species and crustaceans. ERAs have generally been focused on data-deficient target species, sensitive species complexes such as elasmobranchs and by-catch risks in particular for seabirds. There are no LCA of elasmobranch fisheries, but several ERAs addressing these species. Both LCA and ERA fall short on assessments of freshwater fisheries.

Assessment approaches and applications

ERA is focused on assessments of local pressures from fisheries on the marine ecosystem. There are many forms of ERAs with different methodologies and coverage, spanning from qualitative to fully quantitative. Grey literature includes many full assessments of fisheries, i.e., covering a broad set of ecosystem components such as target species, by-catch, sensitive species, habitats and ecological communities (Smith et al. 2007), while the peer-review literature is centered around various forms of Productivity Susceptibility Analysis (for recent overview see Hordyk and Carruthers 2018). This analysis is semi-quantitative and combines a species' life history traits that determines sensitivity to fishing pressure (such as size and age for maturity) with metrics indicating susceptibility to the specific fishery (such as encounterability and selectivity) to derive at a single score for relative vulnerability of a species to a certain fishery indicating low, medium or high risk. The purpose of ERAs is decision-support to spark targeted management actions to decrease risks either by more data collection or implementation of measures to reduce risks to species and habitats.

Standard LCA methods applied on capture fisheries cover global pressures such as greenhouse gas emissions, but method development for fisheries-specific impacts in LCA is ongoing and occasionally applied (e.g., Woods et al. 2016; Ruiz-Salmón et al. 2021). LCAs of fisheries focus on fuel use intensity, which is the driver behind greenhouse gas emissions from capture fisheries, i.e., addressing global challenges that may seem out of scope for local fishery management. It has however been found that these emission levels are strongly depending on management measures (e.g., Farmery et al. 2014; Hornborg & Smith 2020). Even so, LCAs do not inform fishing policy.

The two tools also differ in terms of how impacts are assessed, i.e. absolute values (emissions of a product, quantified by LCA) versus relative risks for ecosystem components to a fishery (ecosystem perspective, considered by ERA). Addressing fisheries-specific impacts in LCA thus entails simple quantitative metrics that can be attributed to a product (such as discard quantity per tonne fish) but they do not convey ecosystem implications, such as associated risks from a specific fishery. However, ERA places the local fishing pressures in a context, e.g., habitat impact risks from a fishery in a specific ecosystem, or risks for different by-catch species in a specific fishery.

Comparable and/or common indicators

Trophic indices such as Primary Production Required/Biotic Resource Use are relatively easy to use and may also allow for comparisons with land-based production (e.g., Pelletier et al. 2009). However, even if indices related to trophic levels are used in both LCAs and ERAs, studies evaluating robustness of how the metrics are used in both tools show little support for their ability to inform on sustainability in current format (Duffy & Griffiths 2019; Hornborg et al. 2013a).

Both tools have approaches to address impacts on threatened and/or protected species. ERA may assess them separately (Hobday et al. 2011) and there have been suggestions on how to include this impact also in seafood LCAs (Hornborg et al. 2013b). A common challenge is by which criteria these species should be defined, data availability and frequency or methodology of assessments behind a species being categorized as threatened (e.g., the IUCN Red List of Threated Species).

Pressure on habitats from fishing activities have in LCAs, when included, mainly been addressed as an area measure, although approaches are emerging to consider recovery rates (e.g., Woods and Verones 2019). The future development of habitat assessment in LCA may benefit from looking at the ERA literature (e.g., Pitcher et al. 2017).

<u>Combined use</u>
Four studies on fisheries have combined ERA with LCA-related results (Table 1). No study has fully integrated the two tools but rather focused on separate assessments and integration of results. Full integration has also been seen as challenging in in general in other areas of combined use due to lack of data and differences in model structure (Linkov et a. 2017; Muazu et al. 2021; Luca Peña et al. 2022). However, since examples of combined assessments in fisheries are few, it would be of interest to provide more case study examples combining results of stand-alone assessments of the same fisheries to be able to draw more conclusions; still, there is a scarcity of fisheries being assessed with both tools although opportunities exist (e.g., many tuna fisheries).

Table 1 Studies with combined use of ERA and LCA-related assessment.

Reference	Fishery	How integration was done
Gilman et al. 2014	Marshall Islands longline bigeye tuna *Thunnus obesus* fishery	Semi-quantitative ERA results of bycatch risks (for fish, turtles, mammals and birds) were combined with fuel use data to consider opportunities for improved efficiencies.
Hornborg et al. 2018	Australian fisheries for Patagonian toothfish *Dissostichus eleginoides*	Results from existing ERAs (assessing target species, bycatch, protected species and ecological communities) were combined with assessment of greenhouse gas emissions and seafloor area swept per tonne.
Hornborg & Främberg 2020	Fisheries for cyprinid species in freshwater lakes in Sweden	An ERA was developed for assessing risks for data-limited freshwater species and combined with assessment of greenhouse gas emissions of the fisheries.
Gephart et al. 2021	Various fisheries in Central America and Europe.	ERA results of bycatch risks for marine mammals for specific gear types and regions were integrated with greenhouse gas emission estimates for the same fisheries.

Mixed messages on sustainability were conveyed from the four combined studies, indicating tradeoffs and improvement potentials for different actors (Table 2). Comparing outcomes between different LCAs and ERAs, i.e., to be able to say if a product is more sustainable than another, is complicated since methodological choices differs between studies and have strong implication on results (Ziegler et al. 2022; Piet et al. 2017). Both assessments also have a strong temporal component to consider; changes in a fishery over time in terms of stock status and management measures enforced have strong implications for the outcome of both assessments.

Table 2 Outcome of combined use of ERA and LCA perspectives.

Study	LCA	ERA
Gilman et al. 2014	Fuel use was in the range of similar fisheries but could be reduced through more frequent maintenance and upgrading vessel equipment and materials.	Highest relative risk to turtles, followed by elasmobranchs while seabird bycatch was likely not problematic. Risks for mammals and fish were not assessed due to lack of information.
Hornborg et al. 2018	Fuel intensity was in the higher range and had increased over time from a combination of market drivers (targeting pattern optimizing for size) and fishery management regulations (gears used).	Risks have decreased over time through targeted management actions including data collection.
Hornborg & Främberg 2020	Fuel use was exceptionally low and could be further reduced from landing more of the otherwise discarded cyprinids.	Risks were high or medium high for most of the species, increasing if more where landed that are today discarded, calling for development of management objectives and improved monitoring.
Gephart et al. 2021	Greenhouse gas emissions per ton differs between different gear types and target species, e.g., higher for bottom trawls compared to gillnets.	Risks for marine mammal differs between gear types and regions, e.g., gillnets are associated with higher risk compared to bottom trawls.

Conclusions and future perspectives

A future sustainable seafood supply from capture fisheries – as for all food systems – would benefit from supply chains incorporating indicators on local biodiversity pressures and local fishery management considering greenhouse gas emissions from management actions. Thus, a combination of ERA and LCA methods has the potential to be beneficial for both management and product assessments due to the complementary perspectives provided.

Benefits from application of both tools on a capture fisheries production system includes more holistic decision support. While local ecological risks such as fishing pressure on vulnerable species may be decreased through implementing different management measures (e.g., selective gears, fishing restrictions), an add-on LCA-perspective on the anticipated effects on the overall sustainability of the product from introduction of different measures can quantify potential trade-offs between the options, such as the potential effect on fuel use. For consumers, combining information on greenhouse gas emissions with local ecosystem risk level may allow for more informed decisions, but a disadvantage is the potentially increased complexity unless aggregated indices are used (e.g., certification including both aspects).

Further research on understudied seafood production systems and methodological aspects on how to make the most out of a combination of the tools are needed. To spark this effort, stronger societal incentives are arguably needed in the form of e.g. interest from fishery policy agencies in decreasing greenhouse gas emissions from capture fisheries, or for certification of seafood to expand the scope of sustainability assessment by setting a cap to what are acceptable emissions from a fishery to be certified.

At last, ERAs and LCAs have also been used to assess seafood from aquaculture systems (Holmen et al. 2018; Bohnes and Laurent 2019). Comparing these outcomes and studying potential for integration of the tools also for these production systems offers opportunities for the future.

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Methods Matter: Best practices to improve aggregation of food LCA data

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Making food systems more sustainable is one of humanity's largest challenges. Over two decades of life cycle assessment (LCA) research on the environmental performance of food systems has helped to inform efforts to address this challenge. Recently, attention has shifted to scaling up insights gained from individual food LCA studies to assess contributions to global-scale challenges that arise from specific diets or aggregate national- to global-level patterns of production or consumption (Tilman and Clark 2014; Clark and Tilman 2017; Clune et al. 2017; Poore and Nemecek 2018; Springmann et al. 2018; Willett et al. 2019; Clark et al. 2019). These efforts have sought to combine, or aggregate, results from individual food LCAs to identify broader impact patterns and impact reduction opportunities. Importantly, such efforts to aggregate and scale-up from individual LCAs are necessarily limited by the scope, coverage, representativeness, and methods used in the underlying studies (Henriksson et al. 2021). As importantly, however, *how* results of individual food system studies are combined to yield larger insights also varies widely, but has received little attention. Here we suggest three 'best practices' that address widely occurring, but easily avoided, pitfalls when aggregating results of individual food LCAs to the scale of diets or population-level production or consumption patterns.

Best Practice #1: *Define and populate groups on the basis of impact drivers that align with the goal(s) of the study*. To date, most studies that combine results of extant food system LCA research define the groups that they base their analyses on using familiar class or group delimiters. This often includes defining groups in terms of taxonomically related species or locale where production occurs despite these attributes often having little relevance to the phenomena being modelled (*e.g.* estimating GHG emissions of a diet, eutrophying emissions of a country's production, *etc.*). Our suggested best practice is to identify the main drivers of the impact being studied based on available literature and then define the groups in terms of these drivers (Fig 1). Doing so should result in fewer groups (increasing the number of useful observations within each group), lower within-group variance and greater between-group differences where these actually exist.

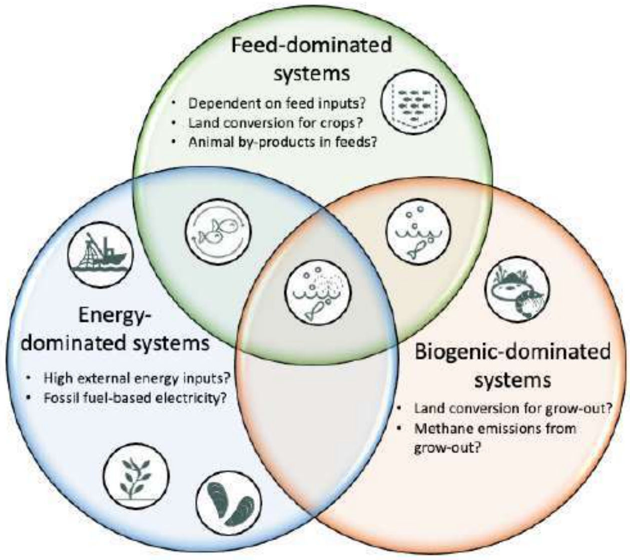

Figure 1. Conceptual demonstration of how food groups can be organized according to the drivers of the impact being assessed, here applied to seafood products from fisheries and aquaculture and their respective drivers of greenhouse gas emissions. While absolute emissions within each group vary widely depending on rates of inputs and outputs, groups share common drivers, improvement opportunities, and policy recommendations.

Best Practice #2: *Select studies that are relevant and whose underlying methods are consistent or can be aligned*. Frequently, studies building on food system LCA research appear to overlook relevant existing research while at the same time including results of studies whose methods are at odds with others used (Tilman and Clark 2014, Clark and Tillman 2017). While familiar to food LCA practitioners, fundamental differences in the methods employed by original study authors that can affect study results (*e.g.* attributional or consequential approach, system boundaries, co-product allocation, treatment of land use change), are often overlooked in aggregation studies. Similarly, marginal or emergent systems, which are disproportionately assessed in food LCA literature, are often included in aggregation studies alongside results of commercial-scale enterprises. Our suggested best practice in this regard is to define relevant inclusion/exclusion criteria, reflective of the goals of the aggregation, and apply those criteria to all available studies. Where possible, important methodological differences can be overcome by adapting, converting or re-calculating results based on inventory data to better align original study methods.

Best Practice #3: *Reflect the representativeness and distribution of data points within each group*. Often, results of existing studies of food systems deemed relevant to an aggregation study are simply averaged despite the frequent existence of substantial differences in scale of contribution to the aggregate system of interest (*e.g.* characterizing the average Canadian diet). Separately, given the positive skew associated with many impact contributions from a given food system (Poore and Nemecek 2018), reliance on a simple arithmetic mean, or a min-max range to represent some aggregate systems of interest will tend to over-estimate aggregate emissions. Our suggested best practices in this regard are to either apply appropriate production- or consumption-based weighting factors to relevant food LCA study results, to consider excluding unrepresentative, experimental or niche systems altogether via the exclusion process above, and to use median values over arithmetic means to represent each group when weightings are not applied.

Applying these best practices when aggregating data from the rapidly growing body of food LCA research should improve our understanding of actual impacts of aggregate food systems at all scales and settings. Not applying them risks sending unclear, inconsistent, or poorly representative messages to decision-makers tasked with guiding the transformation of food systems.

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Are the environmental benefits of seaweed lost in post-harvest processing?

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Objective and background

Seaweed cultivation is resource efficient regarding materials, energy and water and can mitigate local eutrophication (Thomas et al., 2020). As a result, seaweed has been brought forward as a promising alternative source of food and biomaterials to mitigate environmental impacts (European Commission, 2021). As an example, seaweed is currently used in the form of dry flakes in cooking and baking, as a food additive for texture, for printing in the textile industry, and for bioethanol (Nilsson et al., 2022). As the water content after harvest is around 85 %, seaweed is often preserved through sun drying or air cabinet drying to reach a more appropriate moisture level for storage and subsequent use, as well as to facilitate transportation. The Life Cycle Assessment (LCA) studies on seaweed that have applied a system boundary beyond farm gate have concluded that post-harvest processing e.g. by drying is a major environmental hot spot (Thomas et al., 2020; van Oirschot et al., 2017). Here we evaluated how the environmental performance of a seaweed value chain was affected by post-harvest drying as well as processing into a range of products in a biorefinery. In addition, we discuss other seaweed processing methods evaluated in LCA literature. This study aims to bring attention to the importance of including post-harvest activities when evaluating the environmental performance of seaweed.

Methodology and studied system

An LCA was conducted with a system boundary including collection of parent seaweed of the brown algae *Saccharina latissima*, cultivation in nursery and sea, harvest, post-harvest drying and ending after processing into final products in a biorefinery. The final products of the biorefinery were alginate for food, biomaterials for packaging, biogas for electricity and fertilizer. The functional unit used was 1 kg dry weight seaweed. We assessed the 19 impact categories included in the Life Cycle Impact Assessment method EF 3.0 but mainly focus on climate change. For the biorefinery a system expansion approach was applied. Primary data were collected for seaweed cultivation, alginate production and production of biomaterials for packaging. Biogas for electricity and fertilizer was partly based on literature. Brown algae seaweed was cultivated using long lines at a farm in Ireland. The biorefinery used dried seaweed as input material. Cellulosic residues after extraction of alginate were used for production of films that can be used as a packaging material. Residues that remain after the production of film were then sent to anaerobic digestion to achieve a no-waste concept.

Results and Discussion

At farm gate, just after harvest, the cultivated seaweed in its wet form had a climate impact of 0.16 kg CO_2 equivalents (CO_2 eq.) per kg, equaling 1.28 CO_2 eq. in dry weight (Nilsson et al., 2022). The dried seaweed material had a considerably higher climate impact of 6.12 kg (CO_2 eq.) per kg dry seaweed at post-harvest drying. Drying stood for 75 % of the climate impact and the drying process contributed to 38-95 % of total impacts for the 18 environmental impacts assessed, in addition to climate change. One kg of dried seaweed generated 0.3 kg alginate, 0.1 kg cellulosic film, 0.3 kWh electricity and 0.07 kg fertilizer (Nilsson et al., 2022). For alginate extraction in the biorefinery, the yield and purification after extraction are environmental hot spots. The climate impact from the modelled biorefinery was 12.94 kg CO_2 eq. per kg dry seaweed going into the processing when some assumed process optimizations are applied. The drying step could be excluded as long as the quality of the seaweed is preserved until further processing and the economic and environmental costs of transportation are reasonable.

Although the large environmental impact from post-harvest preservation by drying and freezing has been reported repeatedly in sustainability assessment studies of seaweed (Thomas et al., 2020; van Oirschot et al., 2017), it is rarely mentioned when the potential of seaweed products is described. A clear example are communications from the European Union (EU) on the role of algae in the EU Blue Economy (European Commission 2020; European Commission 2021). They describe how the cultivation of seaweed it efficient in comparison to other biomass cultivation and how algae products will reduce environmental pressures and contribute eg. to a more sustainable food sector. The resource intensive processing after harvest is however not mentioned as a problem to tackle, or listed among the 18 proposed targeted EU activities to support the sustainable growth of the algae sector.

The benefits of seaweed uptake of CO_2 and nutrients have here been left out. It is however, an additional way that post-harvest activities highly influences the environmental footprint of seaweed. The uptake has been shown to considerably mitigate eutrophication and climate change when applying a short time perspective or when the carbon and nutrients removed from the atmosphere and marine environment are prevented from reentering them (Seghetta et al., 2017; Thomas et al., 2020). For products like food, packaging and biogas, the captured carbon naturally does reenter the atmosphere and therefore the uptake can not be credited for such products.

Conclusions and recommendations

- Excluding post-harvest activities when evaluating environmental performance of seaweed risks leading to false conclusions of seaweeds potential to mitigate environmental pressures.
- As seaweed biomass offers new unique properties and functions and the cultivation is highly resource effective, efforts should be focused on lowering impacts from the later steps in seaweed production chains.
- In addition to changing from drying as a seaweed preservation method to more resource efficient preservation methods like hang-drying and ensiling, environmental performance would improve if preservation for storing in between production steps could be avoided e.g. by having geographical and temporal closeness between seaweed harvesting and end processing.

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Algae omega-3s as a sustainable alternative to fish oil

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Abstract
Algae omega-3 fatty acids, the original source of long chain omega-3s, are an alternative to fish oil, the traditional source of omega-3s in nature. To understand the environmental impacts of omega-3s produced by heterotrophic algae, a comprehensive Life Cycle Assessment (LCA), assessing six impact categories, was conducted for two algae omega-3 DHA (docosahexaenoic acid) products, in powder and liquid suspension formats. These products are manufactured at industrial scale using sugarcane for both feedstock and a renewable energy source. A comparison with fish oil, using data publicly available in LCA databases, indicated that the climate change impact of commercial algae omega-3 DHA product is about 30-40% lower than fish oil.

Introduction

Fish oil has traditionally been the primary source of long chain omega-3 fatty acids, which are essential nutrients for human diets as well as many aquaculture and animal feeds. The demand for fish oil is growing rapidly, due to an expanding aquaculture sector as well as rising demand in pet and livestock feeds, while the availability of fish oil from wild caught fish has levelled off over the past decade. Algae omega-3 fatty acids, the original source of long chain omega-3s, have been used now for a few years and are a sustainable alternative to fish oil.

This study aims at providing cradle-to-gate LCA information on commercially produced omega-3 DHA, from heterotrophically grown microalgae, by Corbion, as published in (Davis et al 2021). Additionally, the LCA results are compared with the environmental impact of producing omega-3s from fish oil, based on publicly available data.

Methodology

This LCA was performed according to the standard methodology described in ISO 14040 series by the International Organization of Standardization. The LCA model was created in SimaPro version 9.1.The functional unit was defined as 1 kg omega-3 fatty acids. The scope of the LCA is cradle-to-gate, the boundaries of the study are described in Fig. 1.

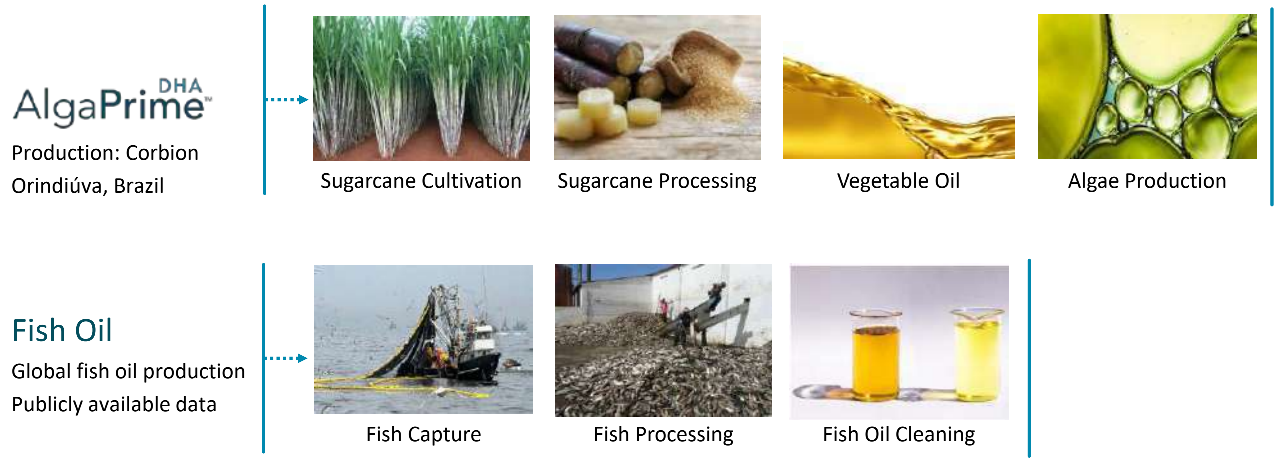

Fig 1. *System boundaries for the LCA*

The Economic allocation is applied, based on the EU product environmental footprint category rules (PEFCR) for 'Feed for food producing animals' (European commission, 2018), for the sugarmill co-products and for the different products from the fishmeal and oil plant. The LCA included the six most relevant impact categories defined by the same PEFCR.

Results and discussion

The algae omega-3 DHA products is 30-40% lower impacts for climate change compared to fish oil. The reason for the lower carbon footprint of algae omega-3s DHA is that its production is integrated with the neighboring sugar mill which uses a very efficient crop, sugarcane, to product both sugar and energy (steam and electricity) to the algae plant.

For the algae omega-3 DHA products, sugarcane cultivation has the largest contribution for most of the impact categories. The LCA results for the fish oil, based on datasets publicly available (Ecoinvent 3.6 and Agri-footprint 5) showed a large variability augmented by the wide range of the omega-3 content in fish oil (14-24%). As expected, agriculture related impacts such as eutrophication, particulate matter and land use impact categories are lower for fish oil then for algae omega-3 DHA.

One limitation of the current LCA impact methods is that the impacts on marine ecosystems of fisheries are not considered, therefore the reduced pressure on marine resource cannot yet be quantified.

Conclusion

In conclusion, the use of algae omega-3 DHA in feed contributes positively to maintaining or improving omega-3 levels in feed, reduces pressure on marine resources, and plays a role in improving the carbon footprint of feed formulations.

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LCA of different grape production systems integrated with RothC model to calculate carbon dynamics in soil

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Keywords: *Environmental performance; Carbon storage; Life Cycle Assessment; GHG emission; sustainable agriculture; sustainable wine; RothC model.*

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Introduction

Due to global warming, current regulations and guidelines to meet future climate targets require all sectors to pay special attention to their environmental performance, incentivizing the implementation of efficient strategies to reduce their greenhouse gases (GHG) emissions. In particular, all scenarios limiting global warming to 1.5 °C include the use of Negative Emission Technologies or Practices (NETPs) to achieve net zero by 2050 (IPCC, 2018). Among these practices, sustainable agriculture and land management can play a crucial role in increasing the organic carbon content in soil, which results in a net removal of CO_2 from the atmosphere (IPCC, 2022).

In 2019, agriculture was responsible for around 10% of the EU's GHG emission (European Parliamentary Research Service, 2020). Grape represents one of the most relevant fruit crops for economy and society worldwide, also due to its strong connection to the wine sector (Laca et al., 2021). Globally, the wine market had revenue of 245.6 billion euros in 2021 and it is estimated will rise to 305.2 billion euros by 2025 (Growth Capital, 2021). Only in Europe, the production of grapes for wine reached a yearly amount of 22.3 million tons in 2019, with Italy, France and Spain leading the sector (30.7% 24.4% and 24.3%, respectively) (Eurostat, 2021). In 2020, world wine production (excluding juices and musts) is estimated to grow (+1%) between 253.9 and 262.2 million hl (OIV, 2020).

In order to reduce emissions from the wine sector, the Port Protocol was officially launched in 2018, as an international initiative affiliated with the Climate Change Leadership event that encourages any company related to the beverage industry to sign up and share their most sustainable solutions (The Porto Protocol, 2022).

One of the most robust method to assess the GHG emissions and, consequently, to implement reduction policies, is Life Cycle Assessment (LCA). Through LCA it is possible to highlight the environmental hotspots of the life cycle of a product and act properly to reduce, mitigate and manage greenhouse gases and other pollutants. Life Cycle Assessment is widely applied to the wine sector across the world and in many ways. From scientific literature, it is estimated that the GHG emission of 1 kg of grapes is averagely between 0.06 and 2.71 kg CO_2 eq. (Villanueva-Rey et al., 2014 and Vázquez-Rowe et al., 2012) while the corresponding value of 0.75 l of wine is between 0.53 and 1.88 (Bosco et al., 2013 and D'ammaro et al., 2021).

LCA was not developed to consider the capability of soil to capture carbon, although it is fundamental for the global CO_2 balance. Today it has been estimated that the total amount of Soil Organic Carbon (SOC) stock on the planet is about 1500 Pg in the top 100 cm of soil and 700 Pg in the top 30 cm (Calvo De Anta et al., 2020; Jakšić et al., 2021). Therefore, estimating the carbon dynamics in soil represents an important element to be accounted for when evaluating the overall environmental performance of an agricultural product.

The purpose of the study is to assess the environmental performances of a grape and wine-sector product through the combined use of LCA method and the Rothamsted Carbon (RothC) model (Coleman and Jenkinson, 2014). Although there are several scientific studies that have performed the combined application of these two different tools on agricultural sector (e.g., Yao et al., 2017; Teixeira et al., 2021; Fantin et al., 2022), according to our best knowledge, only one is dedicated to wine-sector (Bosco et al., 2013).

As case-studies, three vineyard farms with different agronomic management and microclimatic, soil and altitude features have been chosen.

Materials and methods

The three studied vineyard farms are in Northern Italy in the Ravenna Province. Farm A and B are in South-eastern Po Plain on carbonate alluvial sediments, while farm C is on Apennine hillsides at about 350 meters above sea level on marly-arenaceous slope deposits. The three farms have average annual precipitations of 700-900 mm, minimum temperatures of about 0 °C and maximum temperatures of about 31 °C. The soils are classified according to the WRB system (IUSS, 2015) as Fluvic Cambisols (calcaric) in farms A and B and Haplic Cambisols (calcaric) in farm C, as reported in the Soil regional map (https://ambiente.regione.emilia-romagna.it). The vineyard training systems are: upside down cordon in farm A, Guyot and Geneva Double Courtin (GDC) in farm B and Guyot in farm C. In all three vineyards the inter-row space is grassed. Chemical weeding and micro-irrigation are carried out on farms A and B in the under-row space, while mechanical weeding and no irrigation are accomplished on farm C. Table 1 summarizes the main agronomical interventions in each farm.

Table 1. Main distinguishing features related to the anthropic management of the three vineyard farms.

Farm	Pesticide treatments			Fertilization		Irrigation	Weed control
	Fungicides	Insecticides	Herbicides	Chemical	Organic (compost)		
A	Yes	Yes	Yes	Yes	Yes	Yes	Chemical
B	Yes	Yes	Yes	Yes	No	Yes	Chemical
C	Yes (1)	No	No	No	No	No	Mechanical

(1): only copper- and ventilated sulfur-based products.

The LCA system boundaries are "from cradle-to-gate", i.e. from the raw material production phase to the harvesting of the product, excluding the phases of vineyard planting as well as the production and maintenance of the infrastructure and machinery used in the cultivation phase. The functional unit is "100 kg of grapes". The inventory data relating to the grape growing process were collected directly on the farms and represent the average of consumptions and yields of years 2018-2020. Secondary data is from databases GaBi® professional v. 10.6 and Ecoinvent version 3.7 (2020). When pesticides and fertilizers were not available in those databases, datasets of suitable proxy were used. PestLCI software (Dijkman et al, 2012) was used to quantify emissions due to the pesticide application in the various environmental compartments based on soil type, climate and seasonality in the study area. In order to calculate the emissions due to fertilizer application, the PEFCR wine guidelines were followed (European Commission, 2018). The impact categories recommended in the ILCD/PEFCR recommendation v. 1.09 have been selected; for space reasons, in this paper only the impact category Climate Change (excluding biogenic carbon) are reported.

The RothC model simulates the turnover of organic carbon in non-waterlogged surface soils, applying a monthly time step to calculate SOC (in t C ha^{-1}) on a chosen timescale from years to centuries (Coleman and Jenkinson, 1996). RothC requires input on soil depth, clay and SOC content, temperature, precipitation, evapotranspiration, vegetation cover and C input from crop residues and organic fertilizers. To this regard, 8 soil samples were taken in farm A and 6 in farms both B and C at 0-30 cm depths, representative of the inter-row and under-row space of each vineyard. For each sample, texture and SOC were analyzed. The three farms A, B and C had mean clay concentrations of 14±1, 26±1 and 33 ±1% and mean SOC contents of: 42±6, 44±5 and 45±6 t C ha^{-1}, respectively. Carbon inputs of organic fertilizers and vineyard above-ground biomass residues (pruning and grass) were directly measured, while below-ground biomass residues (root exudates) were estimated following Farina et al., (2017). In RothC input, the under-row soil was assumed bare for few months following weeding, while inter-row soil perennial vegetated was considered. A 100-year simulation was performed for each sampling point. The net emitted CO_2 eq. (ΔCO_2 eq.) were calculated from the annual variation in SOC on 100 years. The single values were averaged for each farm and combined with the respective Climate Change (excl. biogenic carbon) 100 years assessed by LCA method.

Result and discussions

Potential impacts on Climate Change (excl. biogenic carbon) of Farms A, B and C are 6.02, 8.95 and 4.77 kg CO_2 eq. q^{-1}, respectively. Figure 1 presents the percentage contributions on the total GHG emissions of the life-cycle processes considered in the system boundaries for each farm. As it is possible to observe, the main contributions are due to diesel consumption for machineries and emissions in air from fertilizers (only farms A and B). The GHG emissions due to the use of fertilizers are mainly N_2O and CO_2. The production of fertilizers has also a significant role in farms A and B.

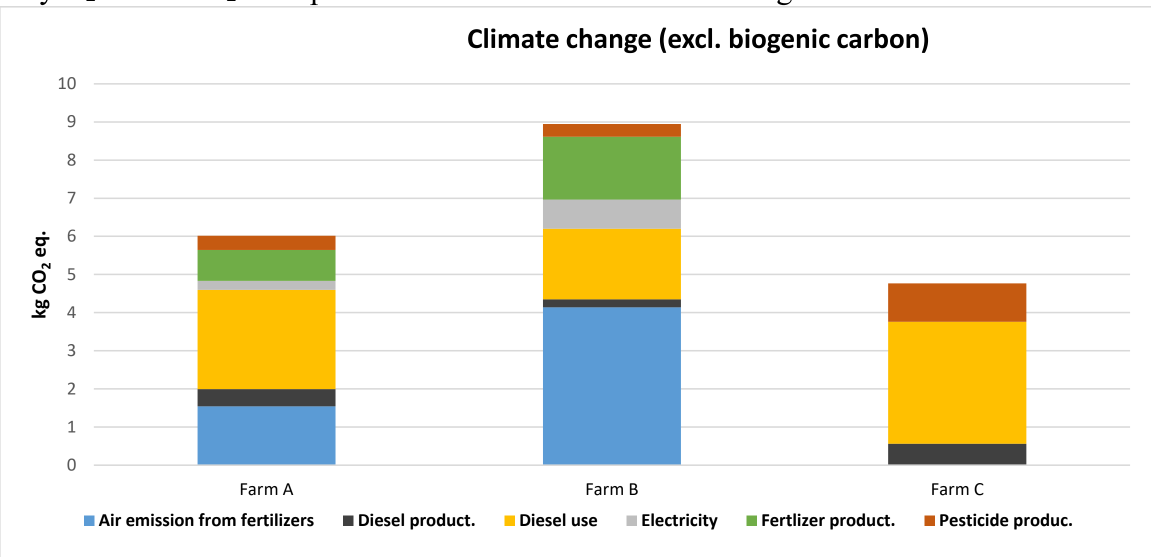

Figure 1. Contribution to GHG emissions of the cradle-to-gate life cycle processes of 100 kg of grapes.

Figure 2A shows SOC trends in the three vineyards during the 100-year RothC simulation. For each farm the most significant inter-row and under-row scenarios are shown. Although in each farm both inter-row and under-row spaces receive the same input of organic C from crop residues and organic fertilizers, in the inter-row SOC increases significantly (farm A and B) or at most decreases slightly (farm C), while in the under-row space, SOC decreases considerably in all farms. In fact, when considering bare soil in dry periods, RothC simulates less soil moisture loss by evapotranspiration allowing microbial biomass to mineralize more organic C (Farina et al., 2013) in the under-row. In farm A and B, also micro-irrigation promotes these conditions. As reported in Table 2, simulations came out as mean results a marked positive annual SOC variation (ΔSOC) for farm A (0.156 t C ha^{-1}) and slightly positive in farm B (0.002 t C ha^{-1}), while only in farm C the annual SOC variation is negative (-0.139 t C ha^{-1}). These trends are mainly related to the different annual C input for each farm. This trend in soil carbon translates into a different net emission of CO_2 (ΔCO_{2eq}) from soil, contributing for farm A and B with sequestration of 1.71 and 0.029 kg CO_2 eq. q^{-1} respectively, while for farm C to an emission of 10.17 kg CO_2 eq. q^{-1} (Table 2).

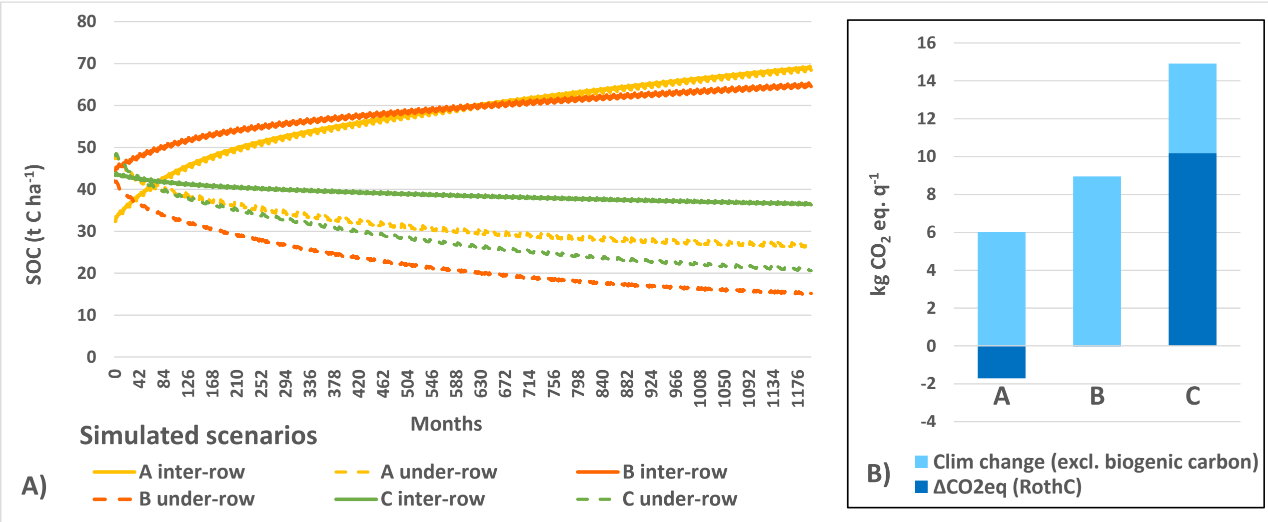

Figure 2. A) SOC trends in the three vineyards during the 100-year RothC simulation, for each farm the most significant inter-row (solid line) and under-row (dashed line) scenarios are shown. B) Climate change (excl. biogenic carbon) results integrated with the ΔCO_2 eq. results obtained through the RothC model.

Table 2. For each farm are shown: the number of RothC simulated scenarios, the initial and the final SOC, the annual variation in SOC, the equivalent CO_2 emitted from soil for producing 100 kg of grapes, the GWP and the GHG total emissions as CO_2 eq.

Farm	Simulated scenarios	SOC at 0 years	SOC at 100 years	ΔSOC	ΔCO_2 eq.		Climate change	GHG total emission
		Mean (1)	Mean (1)	Mean (1)	Mean (1)	St. dev. (1)		
	Number	t C ha^{-1}		t C ha^{-1} y^{-1}	kg CO_2 eq. q^{-1}		kg CO_2 eq. q^{-1}	
A	8	41.1	56.7	0.156	-1.71	2.51	6.02	4.31
B	6	44.1	45.6	0.002	-0.029	1.902	8.95	8.92
C	6	44.0	32.0	-0.139	10.17	5.38	4.75	14.92

(1): mean and standard deviation were weighted on the inter-row and under-row area into the vineyards

If LCA results of Climate Change are integrated with the ΔCO_2 eq. results obtained via RothC modelling, outcomes change considerably in Farm A and C while it does not affect Farm B (figure 2B). Farm A presents the highest carbon sequestration, leading to a significant reduction of the overall emissions of CO_2 eq. Farm B exbibits a very limited carbon sequestration which does not change significantly the Climate Change result. Farm C has a totally different behavior: in this case soil considerably decreases its organic carbon content and therefore the overall emissions of CO_2 eq. increase notably.
Specifically, ignoring this integration would have resulted in a significant overestimation of total CO_2 eq. emitted by 40% for farm A, and a significant underestimation of total CO_2 eq. emitted by 68% for farm C.

In conclusion, this study indicates that evaluating the carbon dynamics in soil and integrating them with the GWP score of the LCA can represent a crucial aspect in determining the actual CO_2 emissions associated to the production of grapes. It is noteworthy that the use of the RothC model requires data and expertise in addition to that of the generic LCA analyst. Moreover, the integration of the RothC model in LCA studies needs of specific guidelines in order to avoid subjective choices.

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Rethinking N-fertiliser and greenhouse-gas balances in rainfed cropping systems

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Keywords: *Conservation agriculture; carbon-nitrogen cycle; carbon footprint; life-cycle assessment; dryland cropping.*

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This study investigated the effect of cropping practices, including nitrogen, tillage and stubble management, on the cradle-to-farm-gate carbon footprint (CFP) of a dryland grain production system in Australia including measured soil carbon change. Data from agronomic simulations were also used to evaluate the effect of nitrogen management more generally across all Australian cropping regions.

Activity data for the CFP assessments were sourced from a long-term agronomic experiment conducted on a commercial farm in south-eastern Australia near the town of Harden (Kirkegaard et al. 1994). The experiment, conducted between 1990 and 2020, assessed the effects of tillage and stubble management on soil fertility, and growth and yield of wheat in a continuous, annually cropped system, as reported previously (Kirkby et al., 2016; Kirkegaard et al., 2020; Kirkegaard et al., 1994). In this study, six separate treatments were evaluated for the effect on CFP of the grains produced. The continuity of treatments and long-term records of field operations, nutrient application, crop protection, crop yield and soil organic carbon measurements provided a unique opportunity to assess the impact of agronomic practices on the CFP of this farm using a lifecycle assessment (LCA) approach.

The farm activity data were structured into annual accounts of inputs and outputs. Nitrogen rates (kg N/ha) were established using known nitrogen contents for the various fertiliser types used. All direct and indirect emissions that are part of the IPCC "agricultural soils" category were calculated applying methods and default values as used in Australia's national inventory (NIR 2019). For fuel and embedded emissions, process data from the Australian Life Cycle Inventory (AusLCI) was used. Greenhouse-gas (GHG) balances included the net emissions of soil-carbon change based on measurements, for three soil depths. For the reference assessment the 0-30cm soil layer was used, and in addition 0-90cm and 0-150cm were used by way of sensitivity assessment.

In addition to those based on real-farm data, GHG accounts were constructed using recent modelling of grain production across all Australian cropping regions (Sevenster et al. 2022a) with the Agricultural Production Systems sIMulator (APSIM, Holzworth et al. 2014). Direct emissions of nitrous oxide, indirect emissions from leaching, as well as changes in soil organic carbon (0-30cm) were calculated using 30-year average simulation results. Indirect emissions from volatilization were derived from simulation results. Other emission sources including embedded emissions were calculated using life cycle inventory data (AusLCI). For details on methodology, see Sevenster et al. (2022b). The GHG accounts for the Harden experiments and those derived from the simulations cover the same emission sources. They use the same background data and inventory calculations, except for the emission sources that are simulated by APSIM.

Results for the farm GHG accounts indicate that losses of soil carbon may double carbon footprints when accounted for in the calculations. Low rates of N application may suggest low traditional carbon footprints but can also lead to "N-mining" linked to a considerable loss of soil carbon. On the other hand, the results for the higher-N treatment, with rates calculated to maximise humification of the C-rich crop residue (Kirkby et al. 2016), decreased the carbon footprint of the grains produced in these Australian dryland conditions by increasing soil organic carbon sequestration. The additional nitrous oxide emissions due to higher nitrogen application were more than offset by the carbon dioxide removed through sequestration in the soil.

While the high-N treatment did not result in significantly higher yield in the Harden experiment, in general in the Australian grains industry, insufficient N application is considered to be the largest cause of the gap between potential (water-limited) yield and yields achieved by farmers (Hochman et al. 2016; Hochman and Horan 2018). In the simulations reported in Sevenster et al. (2022a), applying nitrogen fertilizer to meet full nitrogen demand of the crop growing maximally with available water (rain) resulted in an increase in total production across the Australian cropping region of around 50% compared to the baseline definition (Figure 1). This scenario also led to increased absolute total GHG emissions (~30%), but near-constant on-farm emissions and a decrease in GHG intensity per tonne of grain produced. The increase in field emissions of nitrous oxide, plus carbon dioxide due to application of urea, is almost exactly offset by a decrease in soil carbon losses, in some regions resulting in net sequestration. The increase in total emissions is due to the embedded emissions of fertilisers and crop protection products.

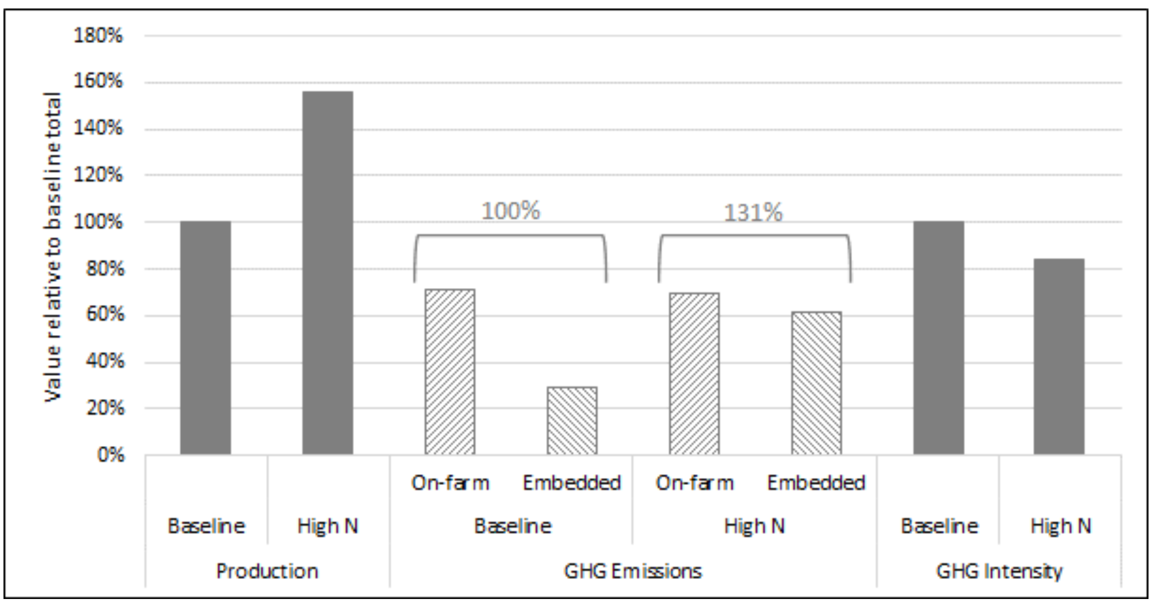

Figure 1 Results for two simulated scenarios (baseline and baseline with full nitrogen demand "high N" met) showing the change in production, total GHG emissions divided in on-farm and embedded, and the resulting GHG intensity in kg CO2-equivalent per tonne of grain (source: Sevenster et al. 2022a).

The farm data and the simulations resulted in the same finding that increasing nitrogen application in these rainfed cropping systems is likely to result in a decrease in net GHG emissions intensity. Based on a 40-year trial in Southern Queensland, Wang and Dalal (2015) find a similar trend, with higher nitrogen application resulting in considerable decrease in soil carbon losses in experiments with residue retained. The net GHG intensity is not reduced with higher nitrogen application according to Wang and Dalal (2015), but there are a number of differences between that study and the Harden experiments which limit comparability of the overall results.

There are also some crucial differences between the Harden experiments and the grain cropping simulations, in that the farm experiments showed little to no yield effect but a much stronger effect on reducing soil carbon losses. The simulations cover a wide variety of soil and climate types, while the experiments were in one location only, but the main factor is likely to be the difference in timing of application of additional nitrogen. In the farm experiment, the additional nitrogen was applied after harvest and aimed at improving humification of the crop residue, further aided by mechanical incorporation. This is not a common strategy applied in real grain farming. In the simulations, additional nitrogen application was modelled to take place throughout the growing season. This also resulted in a much higher overall increase in nitrogen application rate in the simulations, with around a factor 3 compared to approximately 1.5 in the farm experiments.

To conclude, N-mining in dryland cropping may lead to losses in soil carbon that have a significant contribution to the carbon footprints of grains. Ignoring these effects of "N-mining" in GHG assessments could lead to perverse incentives, with international market players increasingly orienting procurement toward low-GHG products. Emissions and removals due to soil carbon change should be included in LCA, preferably using soil layers of at least 100cm depth, although there is still some debate about the best way to do this in absolute CFP (see e.g. Sevenster et al. 2019). It is also important to recognize the role of nitrogen in certain environments in enhancing soil natural capital (soil carbon stocks, e.g. Sevenster et al. 2020) and in lowering net GHG emissions, at least during the transition to that higher natural capital state. Improved fertiliser application can result in a decrease in GHG intensity per tonne grain of up to 20%. Hence, incentives to de-risk nitrogen management decisions in the Australian low-rain environment will have double positive effect of increasing both yield and soil carbon stocks.

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Why does crop rotation entail environmental benefits in terms of yield, nitrogen and water use in the cultivation of lupin, wheat and potato?

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1. Introduction

Diversification of agricultural systems is a key policy to respond to challenges such as soil degradation, food security and climate change. The intensification of agriculture activities and their high input consumption leads to multiple environmental issues, such as depletion of non-renewable energy resources, biodiversity reduction, water pollution, and greenhouse gas emissions (González-García et al., 2021). The introduction of legumes into cereal-based rotation systems has been presented as an environmentally sustainable strategy to improve soil nutrient levels and reduce the environmental impacts of agricultural systems. Legumes can fix atmospheric nitrogen, reducing the need for this nutrient for the next crop in the rotation (Schwenke et al., 2015). Moreover, they can increase the yield and protein content of the following cereal crop, improving the rheological behaviour of the dough in bread production (MacWilliam et al., 2014).

In Galicia (North-Western Spain), native wheat grain can be classified into the "Caveeiro" and "Callobre" varieties with more starch and less gluten compared to durum wheat. Galician autochthonous wheat grain is the source of the bread product, a national quality reference for its flavour, texture, and aroma, whose production is expected to double in the coming years (Câmara-Salim et al., 2020). The relevance of evaluating the introduction of a legume, such as the lupin crop, in Galician winter wheat rotation systems is to determine new environmentally friendly alternatives for fodder production, avoiding dependence on imported soybeans. In addition, organic production of native wheat faces problems related to weed control due to the impossibility of using herbicides, which can be addressed by introducing a legume. Thus, this study aims to evaluate and compare the environmental performance of two wheat-based rotation systems in conventional (RC) and organic (RE) regimes.

2. Methodology

The life cycle assessment (LCA) methodology (ISO 14040, 2006) was used to estimate the environmental impacts of the rotation systems over a six-year period. The rotation systems consider the Galician winter wheat as the main product, while potato and lupin crops represent co-products. Therefore, the sequence in both rotations is lupin → potato → wheat.

2.1. Crops cultivation under organic regimen

The organic cultivation of wheat follows a strict dose application of mineral fertilisers and synthetic pesticides. The cultivation starts with a chisel ploughing, followed by organic fertilisation with poultry manure (5 $m^3 \cdot ha^{-1}$). Then, a combined tillage with sowing (150 kg seeds$\cdot ha^{-1}$) is performed. A mechanical treatment is applied to reduce weeds, subsequently, a foliar fertilisation (*Nitromyel* 30-0-0, 3 $L \cdot ha^{-1}$) is supplied to the leaves of the plants, which is allowed in organic regime. Finally, the grain is harvested (2.7 $t \cdot ha^{-1}$), leaving all the straw in the field.

Regarding lupin cultivation, the process starts with mouldboard ploughing, followed by mineral fertilisation (*Physalg*® 0-8-15), which is authorised in organic regime (CAAE, 2020). Then, a combined tillage and sowing (150 kg seeds·ha^{-1}) are performed, and lupin is harvested with a yield of 2.7 t·ha^{-1}, leaving the straw completely in the field. On the other hand, the potato cultivation starts with mouldboard and chisel ploughing, followed by organic and mineral fertilisation. The potato is harvested with a yield of 20 t·ha^{-1}.

2.2. Crops cultivation under conventional regimen

To compare the organic regime, information concerning the conventional rotation is obtained from Rebolledo-Leiva et al. (2022). Briefly, the wheat cultivation starts with mouldboard ploughing and milling before sowing (150 kg seeds·ha^{-1}). This is followed by agrochemical application and harvesting. Potato crop involves multiple soil preparation activities, the application of mineral fertilisers and other agrochemicals. Finally, lupin cultivation starts with mouldboard ploughing followed by combined tillage and sowing (120 kg seed·ha^{-1}). Subsequently, phosphate and potassium fertilisers as well as a pre-emergence herbicide treatment are employed. Lupin seeds are harvested (3.5 t·ha^{-1}) and all straw is left in the field as a nutrient supplier for the next rotation crop.

2.3. Life Cycle Inventory

The system boundaries of the crop cultivation consider a cradle to farm-gate approach. Moreover, the life cycle inventory is derived from primary data (i.e., farmer surveys) and secondary data for the background processes from the Ecoinvent® database 3.6v (Wernet et al., 2016). As suggested by Goglio et al. (2018), the rotation systems should be considered as a complete cropping system. Thus, the comparison of the environmental profiles of the rotations was based on a land management approach. The functional unit (FU) was defined in terms of ha (i.e., 1 ha). Field direct and indirect emissions from the agrochemical applications were considered for the environmental assessment where applicable. Thus, dinitrogen monoxide emissions were estimated according to the Intergovernmental Panel on Climate Change (IPCC, 2019). Nitrogen dioxide and ammonia emissions were determined according to the European Monitoring and Evaluation Program and the European Environmental Agency (EMEP/EEA, 2019). In addition, phosphorus leaching and runoff (Prasuhn, 2006), as well as, nitrate leaching (Faist Emmenegger et al., 2009) were considered. Pesticides emissions were estimated based on the Product Environmental Footprint Category Rule (European Commission, 2018).

2.4. Life Cycle Impact Assessment

The environmental impact categories were obtained following the ReCiPe 2016 v1.04 Hierarchist midpoint world method (Huijbregts et al., 2016). Therefore, the impact categories evaluated were global warming (GW), freshwater eutrophication (FE), marine eutrophication (ME), terrestrial ecotoxicity (TET), freshwater ecotoxicity (FET), fossil resource scarcity (FRS), and water consumption (WC). The Simapro® software version 9.1. (PRé Consultants, 2020) was used to model the rotation systems.

3. Results and Discussion

The environmental profiles of both rotation systems are presented in Table 1. The results show that the conventional regime presents the highest environmental impacts in six out of the seven categories evaluated. The organic regime shows a 55% reduction in the GW category compared to the conventional regime. A notable difference occurs in the toxicity-related categories, where an average reduction of about 89% is obtained. In the FRS category, the impacts of the organic regime are half those of the conventional system and 60% less in water consumption. The exception occurs in FE category due to the fertilisation activities (poultry manure and mineral fertiliser).

Table 1: Environmental profiles of RC and RE systems (based on FU: 1 ha)

Impact category	Unit	RC system	RE system
GW	kg CO_2 eq	6,991	3,119
FE	kg P eq	2.8	3.4
ME	kg N eq	124	38
TET	kg 1,4-DCB	54,657	6,990
FET	kg 1,4-DCB	359	35
FRS	kg oil eq	1,274	633
WC	m^3	72	29

Regarding crops contribution in the rotations evaluated (see Fig. 1), the potato is the key crop that represent the highest contribution in all impact categories of both systems. This is mainly due to the field emissions, as consequence of the high consumption of agrochemicals. In the GW category, this crop accounts for 67% and 56% of the total impacts in the RC and RE systems, respectively. Meanwhile, a contribution of around 80% and 57% is obtained in the toxicity-related categories and water consumption in both regimes. Otherwise, wheat and lupin crops do not play a significant role in the impacts, with exception of wheat for FE and lupin in WC in organic regimen, which represent about 51% and 40%, respectively. Moreover, lupin represents an environmental credit in the ME category due to nitrogen fixation.

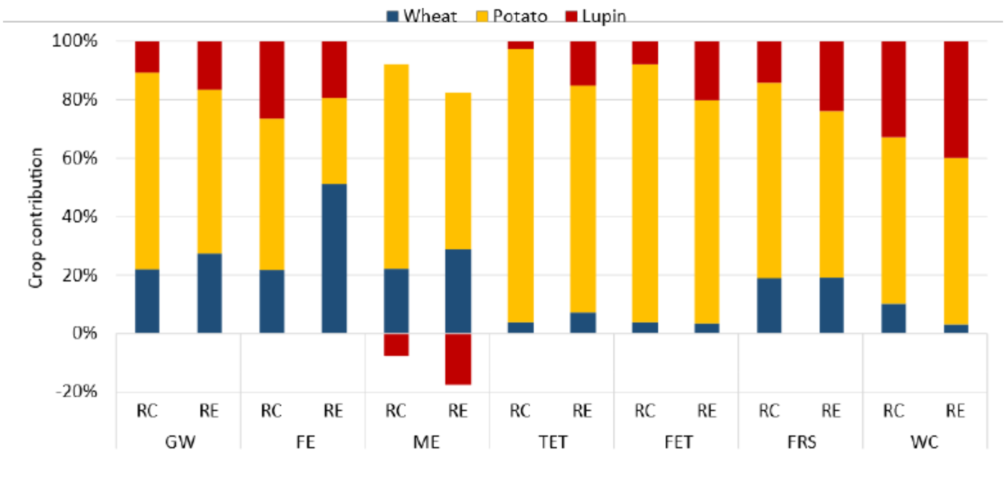

Figure 1. Crops contribution in the rotation system evaluated

4. Conclusions

Introducing lupin in an organic rotation system led to a better environmental performance than a conventional regimen. Moreover, it is relevant to define a crop sequence that allows reducing nutrient demand in those crops with higher requirements (e.g., potatoes in this study). In addition, it is important to note that the FU could plays a crucial role in identifying the best farming system in the decision-making process, considering that biomass yields are considerably reduced in the organic regime.

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Economic and environmental assessment of small-scale Haber-Bosch and plasma-assisted nitrogen fertilizers production pathways

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Ammonia (NH_3), the main compound for nitrogen-based fertilizers, is synthesized by the Haber-Bosch (HB) process. Yet, this process requires a lot of energy and releases carbon emissions since the hydrogen input is mainly obtained by steam methane reforming. In addition, given that this process highly depends on non-expensive natural gas, ammonia production is concentrated in a few countries at large-scale plants, adding emissions due to transportation. Distributed plants next to farmers can reduce these impacts, as well as reduce large storage needs, shortage risks, and price volatility of imported fertilizers. Mini HB plants have been proposed for local production, but they still need high pressure and heat, mainly produced by fossil sources. A proposed alternative is a non-thermal (NT) plasma reactor operating under ambient conditions, using only electricity. The feasibility of these emerging technologies can be promoted by the internalization of the environmental benefits of its products' life cycles in their economic analyses. In this sense, a life cycle assessment of different ammonia production pathways is performed to quantify, from cradle-to-site, credits of by-products utilization and reduced emissions in the production, storage, and transportation phases. Different scenarios are analyzed for centralized and distributed ammonia production in Australia for the conventional large-scale HB process, alternatives using mini-HB reactor supplied by hydrogen from water electrolysis and thermal plasma methane pyrolysis, and the NT plasma-assisted synthesis supplied by water electrolysis, using different renewable energy sources. Monetary valuation coefficients to internalize the impacts of climate change, ozone depletion, particulate matter, photochemical oxidant formation, and acidification were applied. Most of the external impacts were allocated to the carbon emissions of conventional plants and the thermal plasma plants due to the use of fossil-based electricity. However, the high external costs associated with the photochemical oxidant formation and particulate matter affected to a higher extent thermal plasma and non-thermal plasma plants, costing in total 9,500 and 4,200 \$/t NH_3, respectively, due to the impact of the manufacturing of solar panel. In contrast, electrolyzer-HB plants with rates of 114 \$/t NH_3 because of the high energy efficiency and oxygen sales. However, is important to know that the HB process has reached its efficiency limits, while the NTP process still has room for improvement, as well as, its production costs are lower at local-scale plants, which would bring additional socio-economic benefits from distributed fertilizers production.

Introduction

Ammonia (NH_3) is an indispensable fertilizer feedstock to sustain global food production. Over 90% of NH_3 is produced from hydrogen (H_2) and nitrogen (N_2) through the Haber−Bosch (HB) process (Fúnez-Guerra et al., 2020)), mainly using natural gas (NG) (Parkinson et al., 2018). This energy-intensive process has a carbon footprint of about 1.6 t CO_2/t NH_3, contributing to 1.8% of the global carbon emissions (The Royal Society, 2020). This dependency on energy feedstock has concentrated the NH_3 production in a few countries where non-expensive NG is available, increasing the carbon footprint when delivering NH_3 to different continents. Moreover, volatility of NG prices has revealed the unsustainability of conventional fertilizers production. The rise in NG prices by the end of 2021 increased the cost of each NH_3 tonne in Europe from US$ 300 up to US$ 810 (Durisin, 2021). The recent trade disruptions related to the pandemic lockdowns have also increased international shipping costs and time. Additionally, the NH_3 offer curtailment due to the Russia-Ukraine conflict has escalated NH_3 prices in March 2022 reaching peaks of US$ 1,625 in Tampa (Agroberichten Buitenland, 2022). The food security of countries with a high dependency of imported fertilizers have been affected in a greater extent. For example, in Peru, the 68.5%, 97.4%, and 50.9% of NH_3 derived fertilizers such as urea, ammonium nitrate, and ammonium sulphate, were imported from Russia last year, respectively (Gobierno del Perú, 2022). These factors have generated a local shortage of fertilizers and tripling their prices, triggering protests of farmers and inflation because fertilizers usually share about 27% of the total production costs of basic food product such as rice (Adepia, 2022; Agencia Agraria de Noticias, 2022).

These drawbacks have made us aware of the need to move towards an economic model based on a resilient and self-sufficient local production. Different plant configurations have been proposed to produce cleaner NH_3 than the conventional NG-based plants which produce "grey NH_3", such as the "turquoise NH_3" plants that also use NG but through high temperature plasma (HTP) pyrolysis for the H_2 production which does not release CO_2 (Long et al., 2021; Sarafraz et al., 2021), or "green NH_3" plants that use electricity from renewable sources to produce H_2 through water electrolysis to be used in all electric HB plants (Fasihi et al., 2021; Morgan, 2013) or in novel non-thermal plasma (NTP) reactors (Anastasopoulou et al., 2020b; Osorio-Tejada et al., 2022). NTP systems have been recently proposed as promissory alternative because they can be turned off and on quickly due to low thermal inertia (Snoeckx and Bogaerts, 2017), in contrast to the HB systems, which ideally run continuously, that is, they take many hours to reach a steady state process (Muelaner, 2020), which does not interface with the intermittency of renewable energies. The feasibility of these emerging technologies can be promoted by the internalization of the environmental benefits. Monetization of environmental impacts represents the weight of an impact category in monetary value based on the costs for preventing or repairing the damage or how much society is willing to pay to prevent these impacts (Durão et al., 2019). However, hitherto there is no consensus in the scientific community on the most suitable monetization method (Canaj et al., 2021; Thi et al., 2016). This is given the high uncertainty due to factors involved in the estimation of monetary valuation coefficients (MVC),

In brief, we propose in this study to perform a techno-economic analysis (TEA) of different ammonia production pathways to estimate the NH_3 cost at farm in Australia, considering credits of by-products utilization and reduced emissions in the production stage, as well as the impacts of storage, and transport phases. Moreover, life cycle assessment (LCA) results are monetized and internalized using different methods to identify the most cost-effective configuration when environmental aspects other than carbon credits are considered.

Methodology

The environmental analysis of the different NH_3 production pathways were estimated according to the standard ISO 14044 (ISO, 2006) for LCA studies. The unitary cost of production (UCOP) and the cost of storage and transport were estimated to provide insights into the economic performance of the conventional and alternative pathways for NH_3 production. We estimated the external costs of the NH_3 production and we internalized them in the economic analysis of each NH_3 supply chain.

*Goal and scope definition***.** The aim of this study is to analyze the extent in which cleaner alternative NH_3 production pathways can be cost-effective when environmental benefits are internalized in the economics of the supply chain in a cradle-to-site evaluation in Australia, in comparison to the conventional large-scale HB plants based on steam methane reforming (SMR) process.

Pathway (1) is a SMR-HB national-scale plant to supply an annual demand of 1.6 million tonnes (t) NH_3 (Nghiep Tran et al., 2021) up to 4,800 km away. For regional supply, plants with a capacity of 320,000 t NH_3, up to 800 away from farms, were considered. For these regional-scale plants, two plausible options for this production volume were compared: pathway (2) using conventional SMR-HB plants and pathway (3) using HTP-HB plants. Pathway (4) is for electrolyzer-HB county-scale plants with capacity of 106,500 t NH_3 per year, up to 300 km away from farms. And for the local-scale production, the feasible options are electrolyzer-HB plants (pathway 5) or electrolyzer-NTP plants (pathway 6) at farmers' cooperatives with capacity of 10,650 t NH_3 per year, around 30 km away from farms. Given the high energy demand of the national- and regional-scale plants, fossil NG and electricity from the Australian grid were used in pathways (1), (2), and (3). Despite the potential use of solar photovoltaic electricity or methane from biomass residues in Australia, these energy sources were not considered for the national and regional pathways because they would require large extensions of land (in the case of solar energy) and large quantities of biomass, which are not always available due to its seasonal nature. In the case of the county- and cooperative-scale plants, due to the lower energy demand of these all-electric

The defined functional unit was 1 tonne of anhydrous NH_3. The pathways were analyzed with the approach of the "avoided burden" or system expansion (Azapagic and Clift, 1999) because each pathway generates co-products (carbon black (CB) from the HTP process or oxygen from the electrolysis process) and by-products (heat or steam from the HB process).

Life cycle inventory analysis. Specific modelling for the production, storage and transport phases was performed. Inventories were created and adapted to the specific energy datasets available for Australia in Ecoinvent 3.8 (ETH, 2022) Cut-off approach. For the TEA, we assumed a cost of \$50/MWh for grid electricity and \$40/MWh for onsite photovoltaic electricity generation based on Fasihi et al., (2021). Other utilities cost were estimated according to the Ulrich 2006 method (Ulrich and Vasudevan, 2006) based on the natural gas cost under average conditions of 4 \$/MMBTU. Regarding co-products, the sale price for CB from the HTP section was assumed 1,000 \$/t CB (ChemAnalyst, 2021). For the price of pure O_2 from electrolyzers, we have assumed an average sale price of 0.55 \$/kg O_2. The unitary internal cost of NH_3 production was estimated considering the Opex plus the Capex based on the annualized capital cost (ACC) method (Towler and Sinnott, 2013), using an annual capital charge ratio (ACCR) with a 10% interest rate and a 15-year lifespan. For storage, we estimated costs of 8.6, 12.7, 9.9, and 19.1 \$/t NH_3 stored for the national, regional, county, and cooperative storage, respectively, at plant gate. For transportation, we estimated rates of 0.12, 0.21, and 0.30 \$/tkm for NH_3 transport by articulated tanker truck, bobtail 3 axle, and bobtail 2 axle, respectively. In the case of rail transport, the cost was 0.03 \$/tkm, based on NH_3 transport in diesel-electric train (Bruce et al., 2018). NH_3 sale prices delivered at farms were calculated based on an expected net profit margin of 5%, after a corporate tax of 30% for large companies and 25% for small and medium companies (Australian Government, 2022).

Life cycle impacts assessment and monetization methods. The selection of impact categories and life cycle impacts assessment (LCIA) method was constrained by the monetization methods. We utilized the maximum and minimum MVC for five impact categories (i.e., climate change, ozone depletion, particulate matter, photochemical ozone formation, and acidification) presented by de Bruyn et al., (2010), Schneider-Marin and Lang, (2020), Alberici et al., (2014), de Bruyn et al., (2018), and Ponsioen et al., (2020). Most these impact categories are included in ReCiPe 2016 (Huijbregts et al., 2017). We obtained the LCIA characterization results using SimaPro 9.3 (PRé Consultants, 2022), based on the ReCiPe hierarchical perspective, excluding long-term emissions. For the impact categories of particulate matter and photochemical oxidant formation, ReCiPe 2008 was utilized because most of the available MVC for these categories are presented in the units used in this version.

Results and discussion

The estimated cost for each delivered tonne of NH_3 at farms, i.e., the sale prices by considering the different production pathways for pathways (1), (2), (3), (4), (5), and (6) were: 590; 587; 837; 766; 1,325; and 2,404 \$/t NH_3, respectively. Despite the higher production costs of the conventional plant at regional scale, they are compensated with the lower storage and transportation costs. The alternative pathways produce NH_3 at more than twice the cost of the conventional pathways, but these costs are partially compensated by the lower transport and storage costs and the credits sales. Due to the high quantity of O_2 credits, the electrolyzer-HB plant at county-scale had the lowest sale price. Yet, this pathway 4, given the use of the HB process, it is highly affected when the production scale is reduced. Nevertheless, the alternative pathways presented environmental benefits when supplied by solar photovoltaic energy, Fig 1.

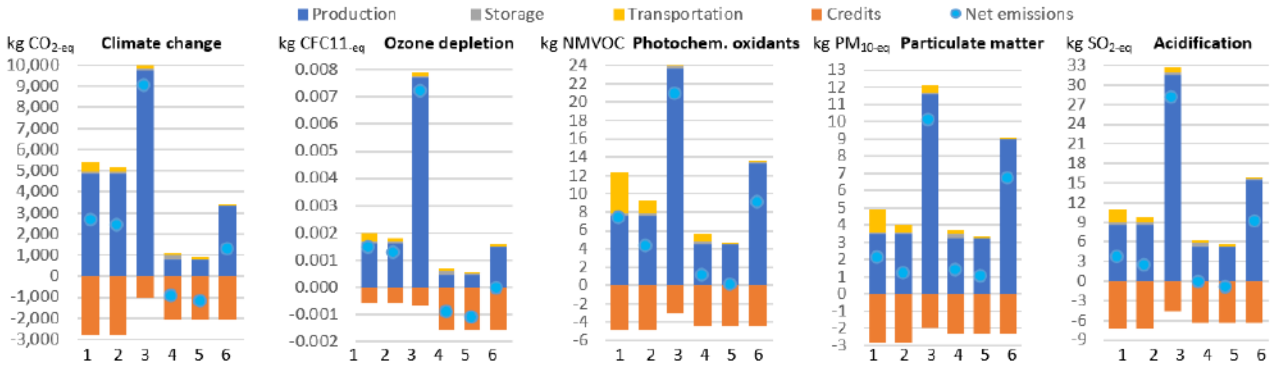

Fig 1 Environmental impacts of ammonia production in different pathways.

Despite the benefits of steam credits, the conventional pathways had worse environmental performance than the alternatives using solar energy. The regional plant using HTP technology had the worst performance because these plants consume more electricity and NG than SMR-based plants. In these HTP plants, the highest impact was the electricity because it is mostly generated coal power plants in Australia. For this reason, when solar energy is used, the environmental impacts are highly reduced, especially in the climate change impact category. This emissions reduction was also promoted by the O_2 sales because the traditional O_2 production consumes a lot of grid electricity. The environmental benefits were internalized in the NH_3 production costs in Fig 2.

MVC per impact category	Max / Min [$2020]
Climate change	0.788
[kg $CO_{2\text{-eq}}$]	0.034
Ozone depletion	132.30
[kg CFC-11 $_{eq}$]	36.81
Photochem. oxidants	15.99
[kg NMVOC $_{eq}$]	0.003
Particulate matter	69.83
[kg $PM_{10\ eq}$]	18.64
Acidification	18.29
[kg $SO_{2\text{-eq}}$]	0.247

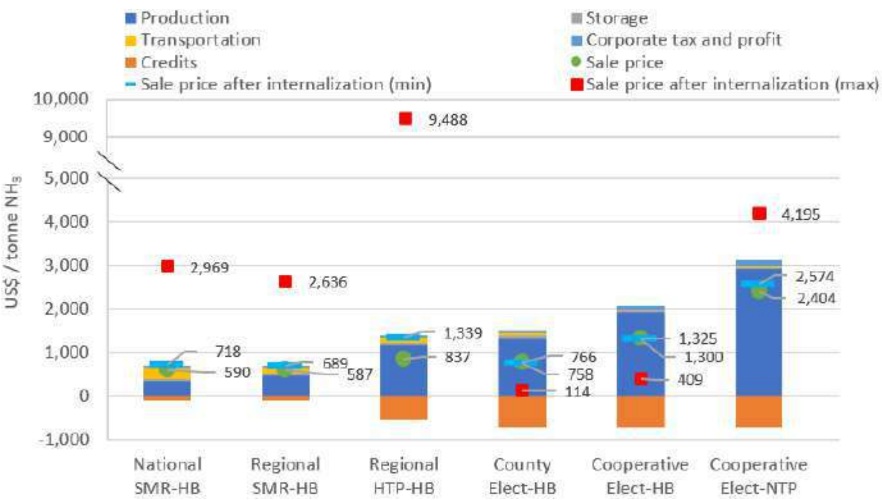

Fig 2 Internalization of environmental impacts of ammonia production of different pathways in the sale price.
Note: only the most relevant co-product in each pathway is shown as credit, i.e., steam, carbon black, and oxygen for the SMR-HB, HTP-HB, and electrolyzer-based plants, respectively. Other less relevant credits, such as heat, CO_2, hydrogen sulfide, N_2, H_2, and NG are already discounted in the production cost.

According to the MCV, the highest external costs per kg of emission are for CFC-11-eq (photochemical oxidant formation) and $PM_{10\ eq}$ (particulate matter). For this reason, the pathways that release the highest quantities of these emissions were more affected by the internalization of environmental impacts, such as the HTP-HB regional plant and the electrolyzer-NTP local plant, costing in total 9,500 and 4,200 \$/t NH_3. The NTP-assisted plant, despite being all electric and supplied by renewable energy, did not obtain the expected improvements because the solar photovoltaic electricity has relevant environmental impacts in its life cycle, mainly related to the manufacturing of solar panels, whose minerals require energy intensive and pollutant processes. Pathways in which the emissions balances were inverted due to the higher environmental relevance of the sold credits, they had further NH_3 cost reduction by assuming that they would have received a bonus due to emissions reduction. In this sense, the pathways considering the electrolyzer-HB processes overperformed the novel NTP-assisted plants, obtained costs final sale prices 114 \$/t NH_3.

Conclusions

The use of monetary valuation coefficients in environmental and economic assessments, besides being useful to aggregate all the environmental impacts in a single monetary unit to be added to the calculated internal cost to compare the total cost (internal and external) of the different NH_3 pathways, monetizing the environmental impact are useful to analyze and find out which of the different impacts are the "worst" or the "most severe" in the NH_3 supply chains, in monetary terms. Alternative pathways have become attractive for small and distributed NH^3 production because the traditional SMR-HB process is more cost-effective at large-scales, increasing the negative impacts of centralized production and environmental impacts and costs related to storage and transportation.

After the internalization of environmental impacts, the electrolyzer-HB plants show lower NH_3 sale prices than the novel NTP-assisted synthesis and the conventional SMR-HB. These later plants would have to sell NH_3 at prices over 2,636 \$/t NH_3, while the electrolyzer-HB plant reach rates of 114 \$/t NH_3. This is due to use the optimized energy usage of the HB processes, which is much higher than the NTP process. However, is important to know that the HB process has reached its efficiency limits, while the NTP process still has room for improvement, as well as its production costs are lower at local-scale plants. In this sense, further research is necessary on this technology, ever more if we consider that the theoretical maximum energy efficiency can make to reduce the electricity usage in more than 20 times the current consumption (i.e., from 28 to 1.11 MWh/t NH_3) (Rouwenhorst and Lefferts, 2020). For this reason, future research could include additional sensitivity analyses by considering the different current and expected energy efficiencies of the NTP, as well as variation in the prices of utilities and credits, which are very relevant such as the CB and O_2 credits. Moreover, given that in most of the Australian regions can potentially be used wind sources for electricity generation, albeit at slightly higher costs (Fasihi et al., 2021). It would be worthy to consider an additional scenario to analyze the economic and environmental performances of the use of another source of renewable energies, locally generated, to improve the competitiveness of local and distributed NH_3 production.

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Embedding soil carbon sequestration in greenhouse gas calculations of ruminant systems and possibilities to offset enteric methane emissions

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Rationale and objective

Ruminant production has been identified as the largest contributor to anthropogenic methane (CH_4) emissions from the livestock sector through enteric fermentation (Opio et al., 2013). There is an urgent need for the ruminant sector to control its greenhouse gas (GHG) emissions and to lower its contribution to global warming. Carbon sequestration (C-seq) in grassland soils has been proposed as a promising strategy to remove carbon dioxide (CO_2) from the atmosphere and to (partly) offset the climate impact of ruminant systems (Godde et al., 2020). However, in carbon footprint studies of ruminants, soil C equilibrium is often assumed for the sake of simplicity or because of a lack of data. Some studies have assessed the impact of soil C-seq on GHG mitigation by estimating a C-seq rate, expressed as the amount of sequestrated C per hectare per year (e.g., Ricard and Viglizzo, 2020). Such an approach, however, hides the evidence that soil C-seq is time-limited in most situations (Godde et al., 2020), whereas CH_4 emissions are continuous as long as the system exists.

Moreover, there are time-effects and intrinsic differences in climate impacts between long-lived CO_2 and short-lived CH_4, which cannot be reflected by the current widely used GHG metric, i.e., global warming potentials over a 100-year time horizon (GWP_{100}) (Allen et al., 2018). Comparing the impact behaviors of CO_2 and CH_4, shows that on a unit basis, CH_4 has a much higher impact on radiative forcing than CO_2 (i.e., 120 times higher in year one), and a much shorter perturbation lifetime (12 years for CH_4 and millennia for CO_2) (Persson et al., 2015). To address this issue, a new metric named GWP* was introduced, which relates the climate impact of a one-off release of CO_2 to a change in the rate of emissions of CH_4 (Allen et al., 2016; 2018). GWP*, however, is criticized for its ignorance of historical emissions (Rogelj & Schleussner, 2019; Meinshausen and Nicholls, 2022). In a situation that livestock numbers and associated CH_4 emissions are stable, GWP* is zero (without considering the delayed response of stock) (Cain et al., 2019). While a constant level of CH_4 emissions may not lead to additional warming, however, it is still warming the planet (Rogelj and Schleussner, 2019). Both GWP and GWP* results are, furthermore, annual base and fail to reflect the long-term (cumulative) climate effect of GHG emissions and removals. To provide a more nuanced understanding of the climate benefits of C-seq in ruminant systems, the difference in climate impact behaviors of CO_2 and CH_4 need to be accounted for, and we need to go beyond currently used metrics (Pierrehumbert and Eshel, 2015; Allen et al., 2018; Ridoutt, 2021).

This study proposes a new approach to include soil C-seq in GHG accounting of ruminant systems, for situations where soil C-seq can be considered a finite process, and the differences in the behaviors between CO_2 and CH_4, based on a simple climate model. By equating the climate benefits of soil C-seq and a continuous flow of enteric CH_4 emissions related to the Dutch dairy sector, we illustrate the method and how it can be used to assess the potential of soil C-seq in GHG mitigation in ruminant systems.

Approach and methodology

Model. This paper uses a simple climate model (GHG metric parametrization) to analyze the combined climate effects of C-seq and a continues flow of enteric CH_4 emissions from ruminant production over time, as an alternative to GWP_{100} and GWP*. The original functions, which are based on the same set of assumptions regarding the radiative efficiency and perturbation lifetimes of the GHGs as used by IPCC AR5, can be found in Persson et al. (2015). Those functions allow us to evaluate the climate impact of not only a pulse of emission, but also a continuous flow of the emission over a flexible time frame. Radiative forcing, which measures the energy input to the atmosphere-ocean system, is used in this study to indicate the climate impact of GHGs. For modelling purposes, the total sum of C-seq was translated into a 'one-time' removal of CO_2 at year one. Subsequently, the model was used to assess the (foregone) radiative forcing of that one-time removal of CO_2, and that of a continuous and constant flow of CH_4.

Case study. To illustrate the method, and the evaluate the potential of C-seq in grassland soils to offset enteric CH_4 emissions from ruminants, we used the Dutch dairy sector, one of the leading milk producers across the globe, as a case study. In the Netherlands, there were 1,593 k heads of dairy cows in 2019, occupying 8,996 k ha of grassland (ZuivelNL, 2020). The average CH_4 production of Dutch lactating cows was 437 g cow^{-1} day^{-1}, varying from 186 to 738 g cow^{-1} day^{-1} (Koning et al., 2020). For C-seq, it was assumed that the difference between C storage in grasslands (60 years old, 80 tonnes C ha^{-1}) and arable land (full tillage, 41 tonnes C ha^{-1}) can be assigned to ruminant systems. Therefore, a total C-seq of 39 tonnes C ha^{-1} was adopted in this study (Van Middelaar et al., 2013). This value is a positive estimation of the C-seq potential in ruminant systems by comparing two land-use systems (grassland vs arable land). Given the uncertainties in such an assumption, a change of ± 50% was applied in the result, leading to a C-seq of 20-59 tonnes C ha^{-1}. By multiplying those values with the area of grassland occupied by dairy farms in the Netherlands, we (roughly) estimated the C-seq potential of the grassland of Dutch dairy sector.

Three scenarios were developed based on the above data, namely, 1) the average scenario (437 g CH_4 emission cow^{-1} day^{-1} and 39 tonnes C-seq ha^{-1}); 2) the optimistic scenario (186 g CH_4 emission cow^{-1} day^{-1} and 59 tonnes C-seq ha^{-1}); 3) the pessimistic scenario (738 g CH_4 emission cow^{-1} day^{-1} and 20 tonnes C-seq ha^{-1}).

Main results and discussion

Equating C-seq and enteric CH_4 emission. Model results show that the climate effect of a continues flow of CH_4 finds equilibrium over time. After a few decades, the radiative forcing of a yearly emission of CH_4 stabilizes at 2.72 nW m^{-2} ton^{-1}. The avoided radiative forcing of a pulse of CO_2 is 0.00072 nW m^{-2} ton^{-1}, 100 years after emission. Based on these figures, the amount of C-seq needed to compensate the radiative forcing of a continuous flow of one ton of CH_4 equals 3,8 k tons CO_2 (i.e., 2.72/0.00072 =3778), which is comparable with the finding by Lauder et al. (2013), i.e., 3.5-4.0 k tons CO_2 per ton of a continuous flow of CH_4. For a dairy cow releasing 437 g CH_4 per day, for instance, this would mean that about 164 tonnes of C are required to be (permanently) sequestrated in the soil, in order to offset the climate impact of the continuous flow of CH_4.

The potential of soil C-seq to off-set methane emissions from the Dutch dairy sector. For the average scenario, the total amount of enteric CH_4 emissions from the Dutch dairy sector was found to be 254 kilotonnes per year. To off-set the climate impact of this emission flow, 262 kilotonnes of C needs to be sequestered (Figure 1). Based on aforementioned assumptions, however, the C-seq potential of grassland soils occupied by the Dutch dairy sector was estimated to be 35 kilotonnes. Based on those estimates, soil C-seq of current dairy systems in the Netherlands could offset about 13% of the climate impact of a continuous flow of enteric CH_4 emissions. This value is increased to 48% under the optimistic scenario, when the minimum CH_4 emission and the highest C-seq potential were adopted. This scenario, however, shows the extreme optimistic situation and cannot be treated as representative for the current system. In the pessimistic case, when the CH_4 emission is at the higher end of the range of estimates, and the C-seq at the lower end, only 4% of climate impact from emissions could be offset by C-seq. The significant difference between the scenarios indicates that combining strategies to safeguard soil carbon while at the same time reducing CH_4 emissions offers a pathway to significantly reduce the climate impact of the Dutch dairy sector.

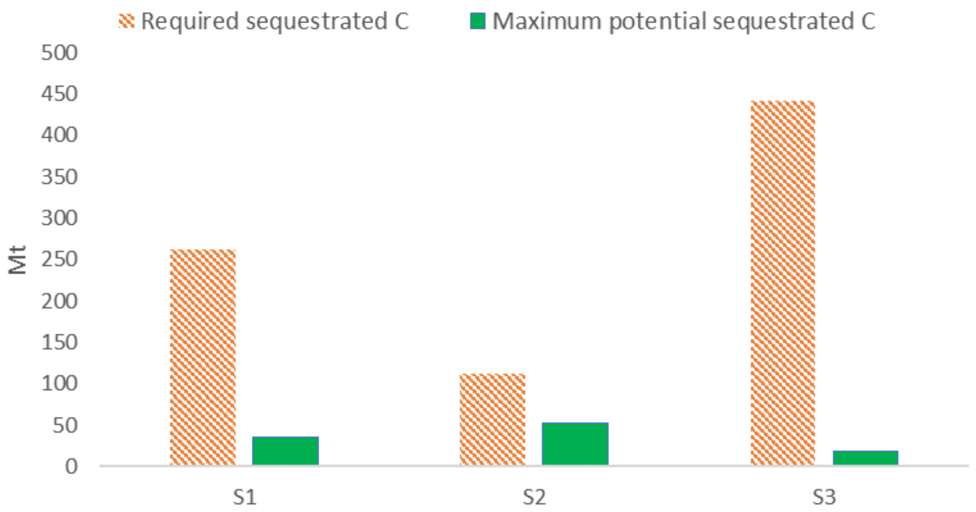

Figure 1. The potential of soil carbon (C) sequestration in grasslands to offset enteric methane emissions from the Dutch dairy sector. The three scenarios (S1-S3) represent the average, the optimistic and the pessimistic case. Details about assumptions and the design of scenarios could be found in Approach and methodology.

The results demonstrate that, even under the most optimistic case, grassland soils occupied by the Dutch dairy sector cannot completely offset the climate impact of CH_4 emissions. The results of this study only cover the emission of enteric CH_4, whereas other emission sources, e.g., manure management and feed production, were excluded. The inclusion of those sources would further increase the contribution of the current systems to global warming. Moreover, the assumption regarding C-seq potential (difference between soil C stocks in arable land and grassland) is an optimistic estimation in favor of C-seq. For instance, in the situation were C-stocks in grassland would be compared to those in natural forest, the net contribution of ruminants to C-seq might be negative. Taken into account these considerations, it seems evident that in the current system, soil C-seq cannot offset the climate impact of ruminant emissions.

Conclusion

This study proposes a novel approach to incorporate soil C-seq in GHG accounting of ruminant systems while considering the finiteness of soil C-seq, and the time-effects and intrinsic differences between CO_2 and CH_4. Our approach allows to calculate the amount of C required to be sequestrated to compensate for the climate impact of CH_4 emissions and can serve to set clear targets for both C storage in agricultural land, as well as the mitigation of CH_4 emissions. Based on preliminary calculations, it seems inevitable that in case of the Dutch dairy sector, the climate benefit of soil C-seq is too limited to offset the continuous CH_4 emission given the current production system.

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Including Negative and Positive Effects in LCA when evaluating Salinity variations on Aquatic Environments

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Keywords: Biodiversity, Climate Change, Ecotoxicity, Life Cycle Impact Assessment (LCIA), Salinity, Species Sensitivity Distribution, Transitional Waters

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Introduction

Salinity is changing in aquatic systems due to anthropogenic activities (like irrigation or dam management) and climate change. In fact, direct relationships between anthropogenic CO_2 release and alterations in the water cycle which result into salinity variations have been already established [1]. These impacts can be even more uncertain in transitional waters such as estuaries, deltas, or coastal lagoons.
Although there are studies on the effects of salinity variations on individual species, little is known about the effects on overall ecosystems. The few works that addressed this topic in life cycle-based approaches such as life cycle assessment (LCA) have considered these impacts using ecotoxicity models. But these models state that an increase in the concentration of a pollutant generates an increase in the impacts. However, the impact of salinity is not only linked to concentration increases, but also to concentration decreases (systems can become saltier or fresher). Moreover, salt is not a toxic, but an essential element. Hence, ecotoxic models might not be valid to describe its behaviour, and a critical improvement of these methodologies is necessary. Therefore, the goal of this study is to provide a methodological framework to improve how salinity is addressed in LCA, including both negative and positive effects of salt emissions on ecosystems.

Methodology

Impacts linked to chemical releases are measured in LCA as in Eq. (1), where IS is the impact score, CF is the characterization factor, and M is the mass of substance (here salts) emitted. The CF is calculated considering the principal cause-effect chains linking the emission M to the environmental consequences through the modelling of fate, exposure, and effect factors (FF, XF and EF, respectively), according to Eq. (2) [2].

$$\boldsymbol{IS = CF \cdot M} \qquad (1)$$

$$\boldsymbol{CF = FF \cdot XF \cdot EF} \qquad (2)$$

CFs addressing impacts on ecosystem quality at the endpoint level have units of potentially disappeared fraction of species (PDF)·m^3·time/kg. As M in Eq. (1) is in kilograms, IS has units of PDF·m3·time[2]. FF is expressed in units of time (it represents the mass of a chemical in the environment resulting after an emission flow, so units are kg/(kg/day)), XF is dimensionless, and EF is expressed as PDF·m3/kg. The XF represents the availability of the released chemical in a system, which can be considered as 1 for salt as it is fully dissolved. In the present work, XF and FF are modelled as in conventional methodologies. Therefore, the novelty of this work is in the EF modelling. Here, the classic methods used to define the effect factor (linked to the behaviour of the pollutant in the ecosystem) are expanded to include negative effects linked to a decrease in the concentration of salt, and positive effects linked to salinity increases, acknowledging the specific features of salinity, that is not a pollutant, bus an essential substance (Figure 1) [3].

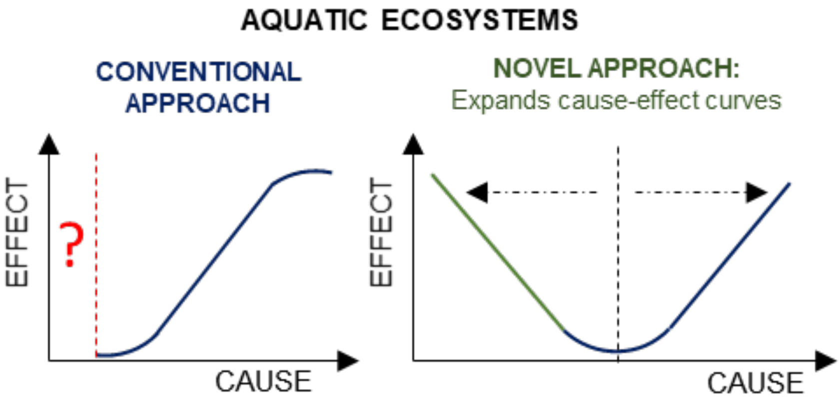

Figure 1: Scheme of the cause-effect curves defining the effect of salinity variations in aquatic ecosystems.

Results and discussion.

Development of Effect Factors for salinity variations in aquatic environments

The proposed approach is based on the premise that the species in an ecosystem have an optimal range of salinity for living, and that detrimental effects will be observed if it varies below or above it. Therefore, there must be an optimal concentration of salt at which no impact occurs (i.e., PDF = 0). Then, negative effects will occur if salinity increases above the optimal range or decreases below it. Moreover, positive impacts will occur for increments in the salt concentration for environmental concentrations below the optimal, and vice versa [3].

The first step is then to define the optimal salt concentration range by gathering data of chronic effects for the species of the ecosystem regarding salinity. After defining the optimal region, there are now two EFs: EF_{LOW} and EF_{HIGH}, both in PDF·m^3/kg. They represent the amount of a substance that generates a certain effect on the ecosystem, where the EF is the slope of the concentration-response curve.

Application of the methodology to a case study

To calculate the Effect Factors, data of chronic effects were gathered. Then, the collected data were represented together to find the ecosystem optimal (environmental) salt concentration. Therefore, EC50 concentrations are calculated for each species at high and low range considering the estimated cut-off point. As the Fate Factor (see Eq. (1)) was calculated seasonally, six Characterization Factors were obtained (Table 1) [3].

Table 1: Characterization factors modeling the effects of salinity variations in Arousa ría. The results are expressed as average ± standard deviation, and as the confidence interval (between brackets), where negative values truncated to zero

Characterization Factors for low range of concentration (CF_{LOW})			Characterization Factors for high range of concentration (CF_{HIGH})		
Dry	Wet	Annual	Dry	Wet	Annual
0.27 ± 0.21	0.16 ± 0.14	0.18 ± 0.15	0.08 ± 0.04	0.05 ± 0.03	0.05 ± 0.03
[0, 0.89]	[0, 0.57]	[0, 0.62]	[0, 0.20]	[0, 0.13]	[0, 0.14]

Conclusions

This research work addresses for the first time the potential effects on the environment derived from a decrease in the concentration of essential substances, where the effects of an emission can also generate positive impacts. Moreover, it is expected that the framework can also be applied to model environmental impacts of other essential substances in LCA, such as metals and macronutrients. According to the obtained results, salinity cannot be modelled using classic ecotoxic models, which address the issue considering salt as a pollutant and only show one side of the coin (negative effects liked to salinisation) and disregards, for example, negative effects of freshening or positive effects of salinity increase in transitional waters. Therefore, the present study opens a new pathway to model how essential substances are modeled in the environment.

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Why regionalization matters - Provision of GIS-based characterization factors for groundwater regeneration

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Keywords: land use impact assessment; LCA; LANCA®; forestry; soil quality index; groundwater regeneration; regionalization

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Purpose

Land use change is at the heart of the environmental impacts of agriculture and food systems. However, some land use types such as forests are still insufficiently considered in the impact assessment in an LCA. In LANCA®, for example, only one default value is assigned to all forest types. Furthermore, there is a need for geographic resolutions as well as broader applications of sealing factors (UNEP 2019) in order to receive more appropriate impact result values. The approach described in Bos et al. (2020) is further refined here and used to update the LANCA® framework based on regionalized geospecific maps. This study reports on the update of LANCA® with a focus on the indicator groundwater regeneration and on forestry. These improvements intend to update the characterization factors within the Soil Quality Index (SQI) in LANCA® on Environmental Footprint (EF) by the European Commission.

Method

Following the recommendations of UNEP (2019) and Horn et al. (2022) and based on the conceptual framework of Bos et al. (2019; 2020), the LANCA® model (Beck et al., 2010; Bos et al. 2016) was improved by applying higher resolution data, updating and including the sealing factor and using a new averaging approach. In this study, the LANCA® update approach for the groundwater regeneration indicator is presented. New sealing factors were calculated based on the data from Elvidge et al. (2007). The sealing factor now also feeds into the calculation of groundwater regeneration, which was previously missing for this LANCA® indicator.

Based on these input data, spatially refined maps for the characterization factors (CFs) of groundwater regeneration are calculated with a resolution of 1 km for all land use flows using the calculation framework of Bos et al. (2020). In a further step, the revised weighting approach (Maier et al. 2019) was applied, where all areas not classified as a specific land use type, e.g., forest, were excluded from the CF calculations. 58 CF maps were calculated for each land use flow in the EF flow list. Country averages were then calculated for 212 countries and all land use flows. The new CFs for specific geo-locations for intensive and extensive forest management are examined in more detail. The CFs resulting from the updated maps and the revised weighting method are compared with the country averages developed by Horn and Maier (2018), which are currently used in LANCA®.

Results and discussion

Exemplary results are presented for the land use flows forests and the CFs for groundwater regeneration. Maps are presented as well as country average results. The updated values are compared to the CF values in the previous LANCA® version. Herein, it can be shown that the inclusion of grid-cell based information on land use, soil properties and slope information for the development of the CFs for groundwater regeneration improves upon the limitations of using only country average values. As shown in Bos et al. (2020), by using regionalized CFs, it is possible to obtain more robust results, notably in large countries. This could also be verified for the newly developed CF maps for groundwater regeneration.

Conclusions

From the presented regionalization, enhancing sealing factors, and revised weighting of LANCA® indicator, a requirement to method refinement for forestry land use type is fulfilled.

It is explicitly important to improve reliability and robustness consistently as products from renewable resources such as wood or other biomass often tend to have a large land use impact with the corresponding large spreads in the results. Therefore, the SQI still requires to be revised taking into consideration all five LANCA® indicators as well as the improvements regarding the individual soil quality indicators. Similarly, a weighting depending on the distinctive land use type and the respective levels of scales should be applied for each soil quality indicator contributing to the SQI.

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Towards Biodiversity Impact Assessment in Freshwater Ecosystems: First steps, thoughts and research gaps

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Keywords: *biodiversity; life cycle assessment; freshwater biodiversity; pressures; ecosystem services; food systems.*

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Purpose: Nature contributes to human-wellbeing in various forms especially by providing and conserving ecosystem services (ES) (MEA, 2005). The degree of biological diversity plays a crucial role for both the quality of life on earth and global economy. Biodiversity loss, the degradation of ES and human well-being are strongly interconnected. The intactness of ES and biological diversity are essential to guarantee food security (e.g. via provisioning ES) (Crenna et al., 2019) and increasingly get subject to economic valuation (OECD, 2019). Although the importance of preserving terrestrial and aquatic biological diversity experiences increasing attention (Beck-O'Brien & Bringezu, 2021), biodiversity is currently declining at unrivaled rates (IPBES, 2019). Freshwater ecosystems, in particular inland waters, are considered sensitive indicator systems for changes in the environment. The population of vertebrates in freshwaters has declined by more than 80 % in the last 50 years (WWF, 2016) and wetlands declined by 35% between 1970 and 2015 (OECD, 2019). The sharp decline in freshwater biodiversity is perceived as a 'global biodiversity crisis' and can be traced back to human activity (Albert et al., 2021) (IPBES, 2019). Drivers of biodiversity loss have accelerated during the past 50 years with a rate that is unprecedented in human history. Impacts related to land/sea-use and land/sea-use change concurrently with unsustainable consumption and production patterns are identified as the main drivers for biodiversity loss threatening global food supply (IPBES, 2019). While food production uses around 50% of habitable land and 4% of sea area and accounts for 70% of global freshwater withdrawal, the food industry needs appropriate measures to identify and regulate "impact-hotspots" along the value chain. To systematically and holistically analyze the environmental performance of products, processes or services, life cycle assessment (LCA) has been a proven tool for years. The inclusion of biodiversity impacts in life cycle impact assessment (LCIA) is explored for more than 20 years (Winter et al., 2017). Several methodological approaches aiming to assess land-use based impacts on terrestrial biodiversity exist (Crenna et al., 2020). However, approaches to assess impacts on freshwater biodiversity in LCIA are only sparsely addressed by single impact pathways or via single impact categories such as freshwater ecotoxicity (Crenna et al., 2019). As constituted by several scientists, research addressing impact pathways on freshwater biodiversity is urgently needed (Mazor et al., 2018). A dedicated approach to comprehensively assess biodiversity impacts related to freshwater ecosystems - similar to existing terrestrial land-use related biodiversity impact assessments - and associated drivers and pressures is currently not available. The following paper aims to take first steps to pave the way towards a biodiversity impact indicator for freshwater biodiversity applicable in LCA-studies.

Method: Firstly, relevant pressures on freshwater biodiversity are compiled and grouped into five categories. In the next step state-of-the-art LCIA methods which strive freshwater biodiversity are reviewed in terms of impact pathways and level of biodiversity. In a third step it is analyzed how relevant pressures for freshwater biodiversity are covered by existing LCIA methods. Lastly,

recommendations and suggestions are made on which pressures should be included in an impact assessment method and initial thoughts on how they could be included are discussed.

Results: The analysis of threats to freshwater biodiversity revealed a set of 18 ecosystem disturbance variables which are likely to contribute to freshwater biodiversity loss depending on occurrence, intensity, duration, and frequency of disturbance. Only pressures and threats mainly caused by anthropogenic influence are considered. All 18 pressures were grouped into one of five categories (physical, mechanical, chemical, biological, other) depending on their prevailing type of ecosystem impact. Notably, many pressures and threats are interconnected and influence each other by reinforcing magnitudes of impacts (e.g. increase in water temperature, nutrient loading and occurrence of harmful algal blooms) and/or originate from different activities but lead to the same or similar freshwater ecosystem disturbance (e.g. emissions of organic substances and nutrient loading both lead to increased oxygen demands and negatively affect freshwater biodiversity).

Along with the main freshwater biodiversity threats identified by IPBES (2019) (sea use change, direct exploitation, pollution, climate change and invasive non-native species), emerging threats such as freshwater salinization, light, noise, and the degradation and surface sealing of riparian zones were identified (Kaushal et al., 2021, Williams-Subiza & Epele, 2021). A complete list of identified threats can be found in the supplementary material.

While a contribution ranking of threats was not part of this study, IPBES (2019) ranks sea use change as the major contributor to freshwater biodiversity decline followed by direct exploitation, pollution, climate change and invasive species. Sea use change threats in the IPBES (2019) report refer in this study to mechanical disturbance variables, which lead to fragmentation impacts, alteration in water flows, loss and degradation of habitats, water bodies, sea and water banks.

To assess the coverage of freshwater biodiversity threats in current LCA practice the impact pathways of the most widely used LCIA methodologies integrating biodiversity, namely LC-Impact (Verones et al., 2020), ReCiPe 2016 (Huijbregts et al., 2017), Impact World+ (Bulle et al., 2019), Ecoscarcity (BAFU, 2021) and Stepwise (Weidema et al. 2008), were analyzed. The present study shows, that 8 (44%) of 18 identified freshwater biodiversity threats are at least partly addressed in current LCIA-methodologies. 10 of the identified threats are not covered yet (for details see supplementary).

Comparably well-known are freshwater biodiversity impacts associated with toxic substances, acidifying substances, eutrophication impacts, water consumption and decreased discharge due to global warming. Current LCIA-methods do not cover impacts associated with lateral and longitudinal fragmentation, change in water flow regimes, freshwater salinization, invasive species, overfishing, microplastics, degradation of riparian zones and light and noise pollution. For some of the rarely addressed threats, first approaches and characterization factors (CF) have been proposed for the use in LCA (e.g. Salieri et al. (2021) for microplastics or Hanafiah et al. (2013) for invasive species).

Considering impacts on freshwater biodiversity several weaknesses were identified in the well-established LCIA-methods. Eutrophication impact assessment in current methods mainly considers secondary oxygen consumption stressing the potential contribution of phosphorus (P) or nitrogen (N) to biomass production. Primary oxygen consumption due to increased emission of organic material to freshwaters (e.g. wastewater of cellulose industry) is often neglected. A current study shows, that a *traditional* LCA of a wastewater treatment plant generates abnormal results for eutrophication impacts which can be reasonablized when introducing chemical oxygen demand (COD) impacts (Zhao et al., 2018). Ecoscarcity is found to be the only impact assessment method considering BOD/COD impacts. Notably, the ecological scarcity model does not include areas of protection which aggregate to freshwater biodiversity impacts. The comparison to other LCIA methods is therefore limited.

Climate change impacts on freshwater biodiversity in state-of-the-art LCIA models face several shortcomings. In current impact assessment models, a fish species-river discharge relationship is developed (based on Hanafiah et al. (2011)). It is expected that global warming leads to a decrease in river water discharge which is related to a potential decline in fish-species. However, current research shows that freshwater fish species are more severely threatened by water temperature alterations than alterations in water flow (Barbarossa et al. 2021). Biodiversity impacts associated with thermal water pollution from the discharge of cooling water is included in Impact World+ only. Impact assessment models to calculate the impacts of cooling water discharge on freshwater species were developed by Verones et al. (2010) and Pfister and Suh (2015). Impacts of temperature increase due to global warming are not considered. LCIA models which account for extreme water temperature alterations due to climate change are lacking.

Overfishing was found to be a relevant biodiversity threat, and several LCA approaches exist (e.g. Langlois et al. 2014a, Emanuelsson et al. 2014, Woods et al. 2016, Frischknecht et al. 2021, Bach et al. 2022). However, among the assessed LCIA methods biodiversity impacts from overfishing are not covered.

Another major threat to freshwater biodiversity which is not covered in current LCIA methods was found to be invasive species (IPBES, 2019). Few LCA approaches addressing invasive species threats exist. Hanafiah et al. 2013 developed CFs for freshwater biodiversity impacts of invasive species based on potentially disappeared fraction of endemic freshwater species in Rhine and Danube per kilogram transported good. A reason why it is not included in current LCIA methods might be the lacking possibility to globalize impacts. Hanafiah et al. (2013) also claim the high relevancy to include the introduction of exotic species in LCA frameworks.

Freshwater biodiversity impacts resulting from habitat destruction and change in water flow, such as fragmentation impacts (e.g. through dams, hydroelectric power stations) or impacts on benthic communities (e.g. through water maintenance measures) are not covered in current LCIA methods. Although, these impacts are found to be of high relevancy only a few approaches which quantify biodiversity impacts through hydroelectric power stations exist. Gracey & Verones (2016) provide an extensive review and recommendations for further development, such as a fragmentation index. Turgeon et al. (2021) developed empirically derived CFs for hydropower production represented in PDF for fish species. However, other causes of flow alteration and habitat degradation are not yet considered in these approaches which provides potential for further developments.

Although freshwater salinization is found to be a relevant threat to freshwater biodiversity, none of the assessed LCIA methods cover salinization impacts (Kaushal et al., 2021). Payen et al. (2016) provide a review and first steps to integrate salinization impacts in LCA while Núñez and Finkbeiner (2020) provide CFs for soil salinization. Operational LCA approaches dedicated to salinization impacts on freshwater biodiversity could not be found.

Riparian zones are known to be important ecosystems mitigating terrestrial land-use impacts such as agricultural nutrient input to freshwater ecosystems. By degrading these buffer zones, habitat alteration impacts, increased soil erosion impacts and river/sea edge impacts negatively affecting freshwater biodiversity occur. These impacts originate e.g. from unsustainable use and transformation of freshwater banks such as clearing, building of urban promenades and harbors or frequent recreational activities. The degradation of riparian zones and freshwater banks and resulting impacts on freshwater biodiversity is not reflected in current LCIA-methodologies.

Most current LCIA-methodologies develop characterization factors based on estimations of potential species (diversity) loss. To capture all dimensions of biodiversity (species diversity, genetic diversity, ecosystem diversity), metrics also incorporating ecosystem diversity and genetic diversity should be considered.

Conclusion: Currently, freshwater biodiversity impacts are mostly modelled based on impacts resulting from terrestrial processes, such as impacts from agricultural nutrient leaching. The impacts of human activities in freshwaters on freshwater environments are poorly addressed. Similar to the concept of land use classes for terrestrial environments (e.g. Lindner et. al (2019)) or sea use classes for marine environments (e.g. Langlois et al. (2015)) we propose the introduction of freshwater use classes for freshwater environments. As first ideas, we propose freshwater use classes for large rivers and lakes for (1) water transport, (2) power generation, (3) recreational activities and (4) fishery &

aquaculture (full list in supplementary). By further characterization of these classes with reasonable biodiversity contribution parameters and functions (e.g. fragmentation [no. of transverse structures /km] for the use class power generation in rivers, or fairway quotient [m/m] for the use class water transport) first approaches for integrating impact assessments on freshwater biodiversity can be developed and tested using the adaptable biodiversity impact assessment method presented by Lindner et al. (2019). A first set of characterization indicators can be found in the supplementary. Existing important impact pathways such as decreased river discharge, or ecotoxicity and eutrophication impacts can be included and further refined. Existing approaches which are currently not considered in state-of-the-art LCIA methods can be included by the definition of appropriate contribution functions based on recent findings, characterization factors, and cause-effect relationships. This is especially the case for impact pathways associated with overfishing, invasive species, fragmentation or microplastics for which frameworks targeted to be used in LCA were already proposed. As climate change impacts and resulting temperature extremes account for a strong influence on freshwater biodiversity these impact pathways should be further refined and included. The same appears to be true for fragmentation impacts (e.g. from hydropower plants) and degradation of riparian zones, lake/river banks and water bottoms.
The present analysis shows that current LCIA methods address freshwater biodiversity only sparsely. While single biodiversity pressures such as eutrophication, freshwater withdrawal or ecotoxicity are in general covered, a large number of threats are not included (e.g. habitat fragmentation, acoustic and visual disturbances, morphological alterations, structural diversity). The present study reveals that further research to comprehensively account for freshwater biodiversity in a life cycle assessment context is required. Impact pathways have to be further examined and developed and missing pressures have to be included. Methodological structures need to be adapted to better match the characteristics of freshwater ecosystems. First thoughts on how to achieve comprehensive biodiversity impact assessments in freshwater ecosystems are outlined.

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Land use-specific characterization factors to assess biodiversity of conventional and organic woody perennial and annual arable crops in the European Mediterranean Biome

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Keywords: *Life cycle assessment; biodiversity; characterization factors; organic agriculture, conventional agriculture*
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1. Introduction

Agriculture is among the main drivers causing biodiversity loss across the globe. Organic agriculture is often seen as one possible solution to reduce this loss. Life cycle assessment (LCA) can be a useful tool to address the complexity of biodiversity assessments using characterization factors (CFs) that predict the potential disappeared fraction (PDF) of organisms in specific land use types and intensities. However, all LCA literature studies aimed at biodiversity on organic farms were limited to the temperate and mixed forest biomes in Europe. The Mediterranean is the most plant biodiverse biome in the world outside of the tropics, hence the importance in measuring and identifying important on-field drivers. Moreover, no biodiversity CFs are available for permanent organic crops in this biome. To fill these gaps, new midpoint occupation CFs expressing PDF of vascular plant species in the Mediterranean biome were calculated using the methods described in Knudsen et al. (2017) and secondary plant richness data from organic and conventional farms across four European countries.

2. Materials and methods

Vascular plant species richness data for organic and conventional cropland in the Mediterranean were collected from four studies for the following country and crop combinations: Spanish olives, French cereals, and Italian vineyards (Lüscher et al., 2016), Spanish vineyards (Puig-Montserrat et al., 2017), Spanish cereals (Caballero-López et al., 2010), and Greek olives (Solomou and Sfougaris, 2011). These data were used to develop characterization factors for the potential plant species richness loss relative to a baseline scenario, expressed as PDF/m^2, using the framework described in Knudsen et al. (2017). Woodland forest was chosen to be the baseline land use type, data for this was gathered from (Lüscher et al., 2016) in Spain and France. This study only looked at midpoint impacts and did not go further into endpoint, since the main objective was to look at the impacts of land use occupation on species richness. Endpoint would require the inclusion of other impact categories like climate change and their related flows like CO_2, which was not in the scope of this study.

3. Results and discussion

The CFs for arable crops were able to distinguish between management practices (organic and conventional) due to differing herbicide and nitrogen input. However, CFs could not be differentiated by management practice in permanent crops using species richness data from (Lüscher et al., 2016), since they were highly dependent on practice intensity. Specifically, CFs for organic and conventional Spanish olives and Italian vineyards were not significantly different due to the extensive management practiced in the conventional farms. In other words, the practices (e.g., pesticide, N input, tillage) were similar between organic and conventional farming. Whereas CFs for Spanish vineyards (using data from Puig-Montserrat et al., 2017) and Greek olive production (data from Solomou and Sfougaris, 2011) could be differentiated between organic and conventional farming due to intensive practices in the conventional farms sampled. The CFs for Greek olive production did not fall within the range of the other crop land use types, but were in fact much lower. This may be due to the baseline species richness count used; it may be useful for Spain, France and Italy, but possibly not for Greece.

Therefore, binary land use management types like organic and conventional may not be sufficient to fully account for biodiversity loss in perennial farms. The CFs may be more useful if non-binary variables were used to account for more levels of intensity. For example, Solomou and Sfougaris (2011) monitored plant species richness in conventional olive fields sprayed with herbicide and conventional not sprayed with herbicide, which resulted in significantly different species richness values. Additionally, tillage intensity has also been found to be an important factor for plant species richness in woody crops (Rey et al., 2019). Thus, till or no-till could also be further land use sub-classes to include.

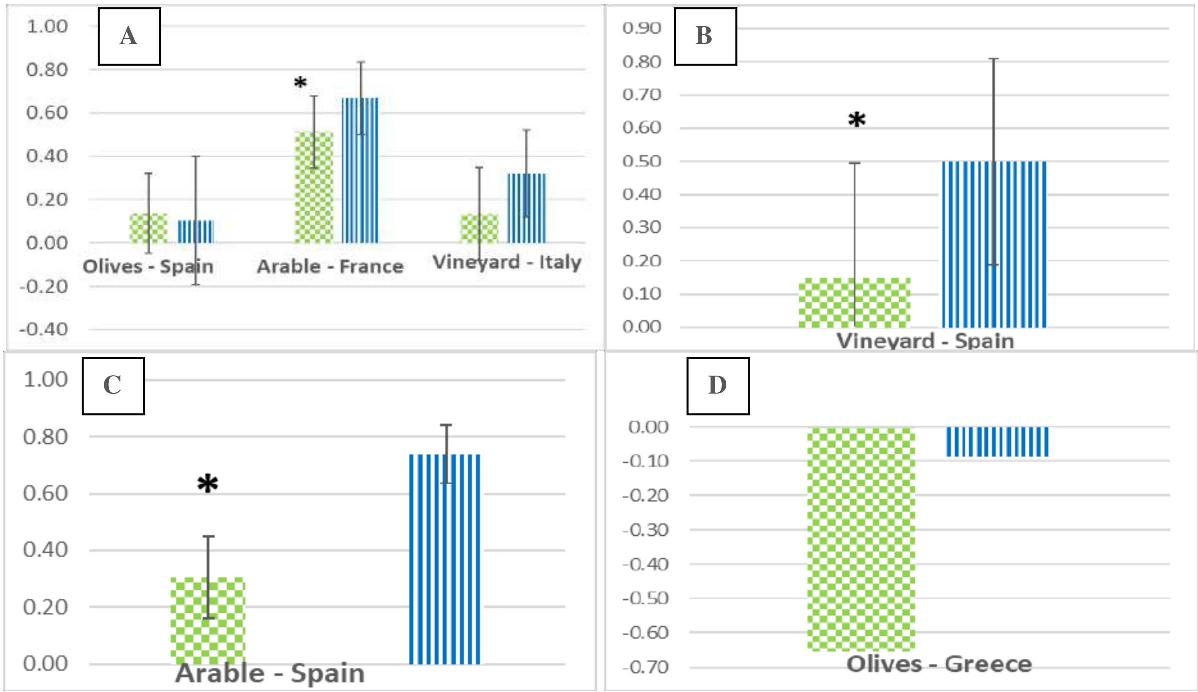

***Figure 1**. Characterization factors in PDF/m² for organic (green checker) and conventional (blue lines) crop production, in studies Lüscher et al. (2016) for A, Puig-Montserrat et al. (2017) for B, Caballero-López et al. (2010) for C, Solomou and Sfougaris (2011) for D. The * means it is significantly different.*

4. Conclusions

Impact of organic vs conventional farming on local plant biodiversity in the Mediterranean can be differentiated in arable crop systems, but cannot be consistently differentiated in permanent crops, based on the available studies. Further, land-use sub-classes for conventional practices may be needed to fully account for biodiversity losses in perennial crops. CFs derived, from real field measurements of species richness ensures higher certainty of the results, and given that more data on biodiversity is becoming available, further CFs can be calculated using this method.

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Using agent-based modeling to embed disruptive impacts in the sustainability assessment of supply networks: a proof of concept on the Peruvian fish-meal industry

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Keywords: *fishmeal, anchoveta, agent-based modeling, multi-agent, resilience, disruption*

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1. Introduction and objectives

Global supply networks (SN) are now more complex than ever due to the high interconnection of nodes and the macro behavior that arises from agents' individual motivations. This complexity is not evident when the system performs in average or stable conditions, as it is usually considered when building life cycle inventories, but it gains notoriety when a SN experiments disruptions or sudden changes. In this sense, understanding properties such as the system's restoring capacity (resilience) becomes significantly relevant when analyzing a SN. The recent disturbances in global logistics and production generated by the COVID-19 pandemic have shown how food systems need to re-adapt in order to maintain the supply and still generate value. While this kind of affectations can be directly measured in terms of economic losses, there is still a gap in the understanding of these consequences from a sustainability point of view. In this manner, we propose the use of a complexity driven approach that relies on agent-based modeling (ABM) to simulate explicitly changes in the system.

Fishmeal (FM) is a brown powder that is valuable due to its high protein content. It is mainly obtained from small pelagic fish, such as anchoveta (i.e., *engraulis ringens*) in a process of cooking, drying and grinding. FM is used as an important component in the production of animal feed which is mostly destined for aquaculture and swine production. Peru is the biggest worldwide exporter of FM and its anchoveta mono-species fishery is the largest in the world (Avadi et al., 2014). The associated SN (i.e., extraction, production, trading, and delivery) is composed by multiple agents that assume different roles and consider distinct strategies when doing business. FM industry is not only susceptible to the impacts of natural disruptions (e.g., ENSO phenomenon), but also to the affectations of extreme demand variations (e.g., pandemics). We selected the Peruvian FM sector as a case of study because 1) its importance in other supply chains, 2) the involvement of heterogeneus stakeholders, and 3) the role of Peru as a leading country in the supply of this product. In this manner, the objective of this study is to understand the impacts that disruptions may have in the sustainability of Peruvian FM industry by relying on ABM as the core modeling tool.

2. Materials and methods

The approach considered for this study follows the four *principles of a complexity-driven* *sustainability assessment* proposed by Larrea-Gallegos et al. (2022). In this sense, the study does not focus on finding optimal configurations, but on exploring the likelihood of the system to remain inside a sustainability region during the pre- and post-disruption periods. We defined a sustainability region as the space where the collective SN state (i.e., the aggregation of nodes' states) is considered tolerable to the society and/or specific stakeholders. Resilience oriented targets were introduced as short-term impacts (i.e., added value in USD), in addition to the long-term impacts commonly considered (i.e., climate change). This change of perspective allowed to understand the effects that perturbations can have over SN on different dimensions of sustainability during different time spans while observing the network re-adaptation in the process.

2.1. Computational workflow

In order to describe agent's operational configuration in a computational and systematic manner, we proposed a novel Algebraic Framework for RepresentIng Computational Agents (AFRICA). This framework is inspired in the Stochastic Technology-of-Choice model (Kätelhön et al., 2016) and it provides a mathematical structure to computational agents so they can solve common business-related problems. More specifically, AFRICA is designed to allow agents to solve a sourcing decision problem (*sourcing problem* hereafter) considering current agent's beliefs of reality, current objectives, and the possible actions to be taken. AFRICA follows a rationale compatible with the beliefs, desires and intentions model of agency (Rao and Georgeff, 1995) and it provides a set of mathematical objects in the form of matrices and vectors. For a given time step *t*, AFRICA establishes that every agent must posses an intention matrix $\mathbf{A}_{nxm}$, a factors matrix $\mathbf{F}_{oxm}$, a price vector $\mathbf{k}_o$, a constrains vector $\mathbf{c}_o$, and a money availability variable $\mathbf{z}$. Here, *n*, *m* and *o* are the number of products, processes and factors, respectively, involved in the sourcing problem of every agent.

When a given demand of products, y_n, is imposed, agents' will try to determine a supply vector s_m. This vector correspond to the quantities of each process *m* required to satisfy y_n. Similarly to Kätelhön et al. (2016), we assume that agents will aim to minimize the monetary cost of a decision. In this sense, solving a sourcing problem implies minimizing an objective cost function, depicted in Eq. (1), where *M* is a big scalar (i.e., big M method), and x_n is a vector of missing products when y_n cannot be fully satisfied.

$$\begin{aligned} \min \quad & Z = k^T \; Fs + Mx \qquad (1) \\ \text{s.t.} \quad & k^T \; Fs \leq z \\ & As + y_s^T \leq y \\ & Fs \leq c \\ & As \geq 0 \\ & x \geq 0 \\ & s > 0 \end{aligned}$$

To simulate the SN, we developed a computational software, PACHA, fully programmed in python v3.8. This library gives the user the resources to model markets, companies, organizations, and individuals as computational agents thanks to methods specifically designed for the SN context. PACHA uses a python implementation of the mathematical elements and operations defined by AFRICA. Moreover, PACHA provides a simulation environment that lets agents interact in daily time-steps while accounting for all transactions, emissions and consumption in the system. Relying on AFRICA, different decision mechanisms (e.g., sourcing and production) can be explicitly defined. Moreover, strategies and rules for agents can be programmed leveraging Python OOP paradigm. Figure 1 shows the different stages of the modeling exercise where AFRICA and PACHA sub-modules intervene.

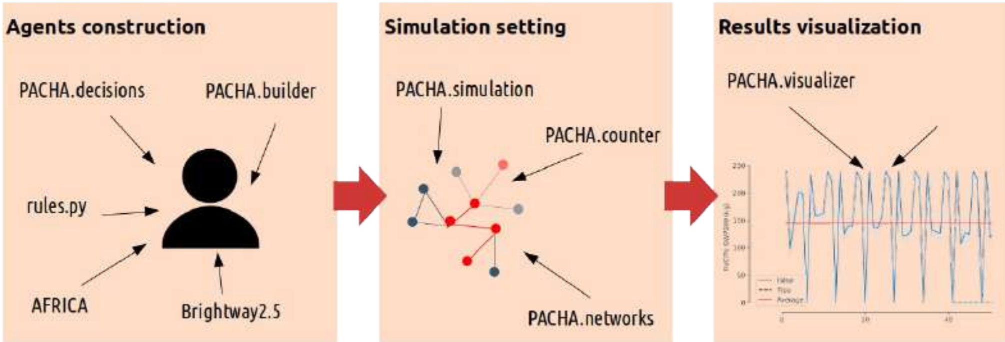

Figure 1. Computational workflow of the study and usage of AFRICA and PACHA sub-modules during the modeling.

2.2 Supply network modeling

The modeled system, depicted in figure 1, represents the upper segment of the full FM life-cycle (i.e., cradle-to-gate) and it was composed by four main type of agents: *fishers, vessel owners, fish-meal producers, and traders. Fishers* are agents that represent humans working in a vessel during the fishing activity that only have their own labor as output. *Vessel owners* are the representation of fishing companies that hire fishers, consume fuel, equipment, and they deliver fresh fish as an output. *FM producers* are companies that may or may not own vessels and they consume fresh fish, fuel and equipment to deliver FM in an industrialized process. Finally, *traders* are companies or individuals that manage to buy and sell FM to other agents in the SN or to a global market. This system is driven by the demand imposed by a proxy-agent representing the aggregation of the global FM market. In figure 2, one-sided arrows represent flows in one direction, while double-sided ones indicate bidirectional flows.

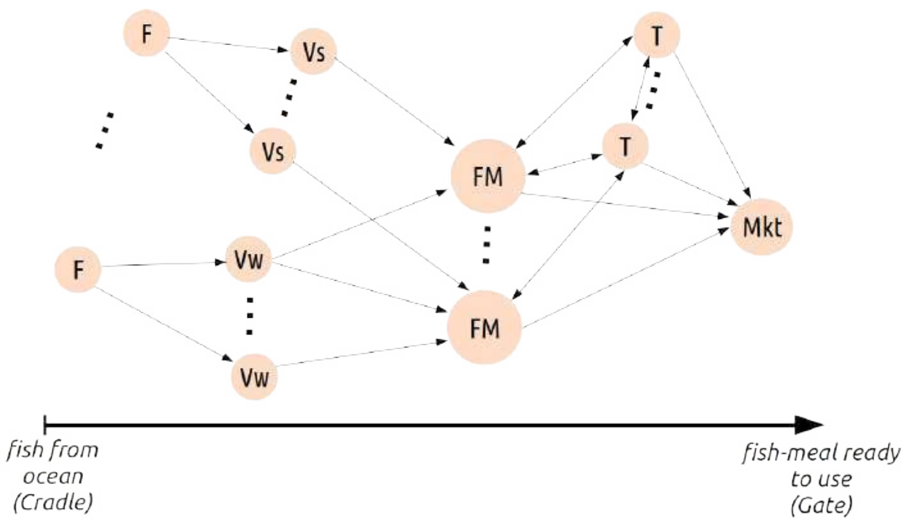

Figure 2. Representation of types of agents considered in fish-meal supply network. *F:* Fisher, *Vs:* vessel owner (steel), *Vw:* vessel owner (wooden), *FM:* fish-meal producer, *T:* trader, and *Mkt:* global fish-meal market.

Agents are initialized using the framework presented above. Agents' behaviors were elicited from primary sources (e.g., fishers, FM producers, vessel owners) following the approach presented by Elsawah et al. (2015). Finally, secondary data (i.e., trading data, national statistics) were used to provide context to the simulation. Since it was not feasible to model every actor of the FM value chain, flows of the rest of products (e.g., gas, heat, electricity, chemicals) were obtained from proxy market agents using data derived from ecoinvent 3.6 (Wernet et al., 2016) and using brightway2.3 as LCA calculation package (Christopher Mutel, 2016). Disruptions were introduced as stochastic events that explicitly affect network parameters or configuration. In this study we focused on the disruptive malfunction of certain agents, mimicking

3. Results and discussions

Results show that the final configuration is highly sensitive to the initial topology (i.e., degree centrality) when there is a low likelihood of finding new suppliers. Nevertheless, when these probability increases, network topology converges to a stable configuration, and indicators eventually show cyclic patterns regardless of the initialization (i.e., stochastic or deterministic). Preliminary results indicate that, when deleting nodes, highly connected FM producer nodes are is less prone to fail in returning to its initial condition most of the times (see Figure 3a). This occurs due to its high negotiation power among the other type of agents. Moreover, when fishers or vessels owners are removed, their likelihood to stabilise depends on the FM producer's final state just before the disruption.

Regarding the emission profiles, the preliminary figures indicate that the system tends to stabilise when the induced disruptions are temporal. While this may not seem relevant from some environmental indicators (i.e., climate change), the short-term variations are critical when other indicators are evaluated (i.e., job losses, added value) (see Figure 3b). This demonstrate that necessity of including temporality and short-term impacts in the sustainability assessment exercise. Different negotiation strategies are currently being evaluated to determine optimal initial conditions to reach a sustainable SN.

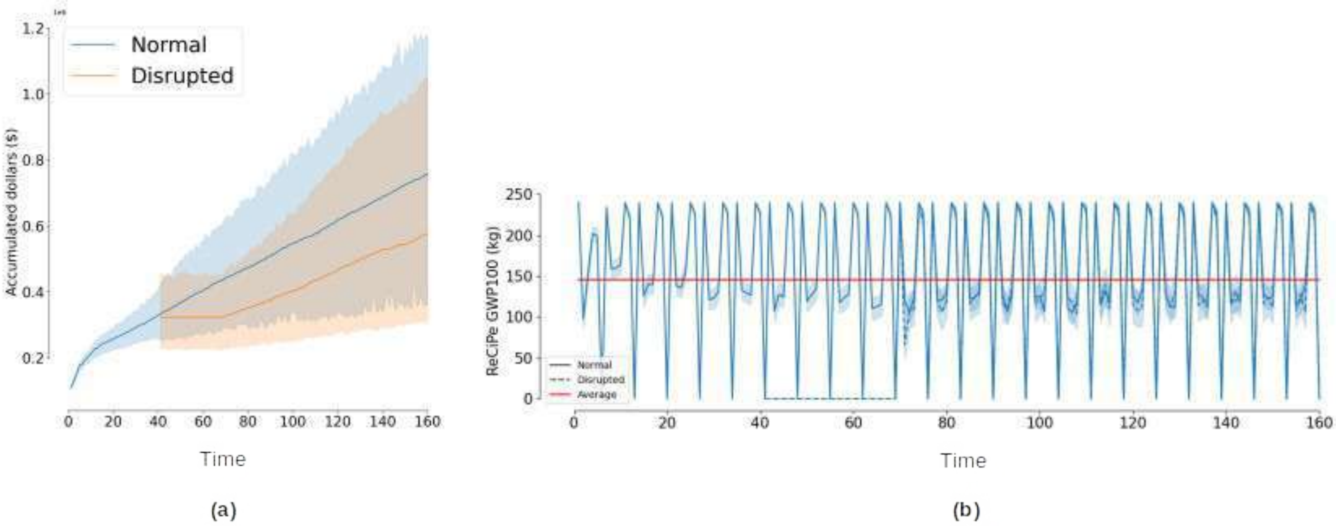

Figure 3. System evolution in terms of accumulated added value (USD) after the introduction of the induced disruptions (a). Daily Global Warming Potential (GWP) for normal and disrupted agents (blue continuous and disrupted lines, respectively) and average impact (red line).

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Environmental performance comparison of polylactic acid and fossil-based bioplastics: a literature review in feed and food packaging

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Keywords: Bioplastics, LCA, lignocellulosic biomass, food loses, bioactive compounds

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Rational: The growth of the global population combined with the covid-19 pandemic has increased production of single-serve packaging systems for agri-food systems. In July 2021, the 2019 European Plastics Directive put an end to most single-use plastics which are mostly made by polymers of fossil origin, such as polyethylene terefthalate (PET) or polypropylene (PP). The development of biodegradable bio-based plastics or bioplastics as an alternative to conventional fossil-based plastics gives hope that such problems can be solved with an additional advantage of reducing the use of fossil resources (Changwichan et al., 2018). Polylactic acid (PLA), a biodegradable bioplastic, is taking a relevant place in the plastic market. Several Life-cycle assessment (LCA) studies have characterized and compared the environmental performance of fossil-based plastics and biobased plastics for agri-food systems. Nevertheless, the results obtained vary considerably and are difficult to compare due to different system boundary definitions, functional units, multifunctionality approaches used in each study.

Objective: The main objective of this work was to carry out a systematic literature review and to use a normalization approach that allow comparing the main environmental impacts between PLA and fossil-based plastics along their value chain.

Approach and methodology: An online search of articles published (since 2002) with LCA studies of PLA and/or PLA packaging was conducted and detailed information on the methodology, assessment assumptions and data screened. A total of 40 studies were assessed, 50% published in 2021. More of 38% of the studies analysed were conducted in Europe. In all the studies analysed, maize was the biomass feedstock for the production of PLA. Whenever possible, for each article, the impact values were collected for each category of environmental impact identified for PLA and other polymers of fossil origin [Polypropylene (PP), Polyethylene terefthalate (PET), high density polyethylene (HDPE), low density polyethylene (LDPE) and Polystyrene (PS)]. Special attention was also paid to articles that constituted comparative analyses of LCA between PLA and other conventional polymers of fossil origin (PP, PET, PS, LDPH, HDPH), whenever the studies returned this type of results. Due to the heterogeneity of functional units identified in the analysis of the evaluated articles, functional units were converted to 1kg of polymer, whenever possible this conversion. The values of original impact categories were normalized to 1kg of polymer, allowing the comparison of impacts between the different articles and polymers.

Results and discussion: The comparison between the different polymers showed, based on the analysed articles, that PET, PS and PP polymers have higher impacts than PLA in the following environmental impact categories: "climate change", "ozone depletion", "acidification" and "eutrophication". However, PLA was the polymer with the highest impact and contribution to the categories of "freshwater eutrophication", "marine eutrophication" and "human toxicity", followed by PET polymer. The production of PLA from maize may be one the reason that explain the higher impacts on the different environmental impact categories, and explain the higher average impacts compared to the other fossil-based polymers observed in some studies, namely for the impact categories "freshwater eutrophication", "marine eutrophication" and "human toxicity".

Indeed, nowadays main biomass feedstock for bioplastic are food or food derivatives. With the increasing demand for biodegradable bioplastics, competition by land and inputs between food production and other uses. Thus there are still three major problems that need to be solved to overcome this biomass scarcity barrier: i) first, sufficient biomass needs to be produced while ensuring that resources are not overexploited and do not enter into direct competition with the food sector; ii) second, greenhouse gas emissions caused by biomass production and its associated land use must inevitably be reduced; and iii) third, biomass production pathways must be economically competitive (Bussa et al., 2019).

Conclusions: The use of alternative biomass sources, such as lignocellulosic residues from forest and marginal land, could be a key option for biobased materials production applied for food/feed sector, with lower environmental and socioeconomic impacts. Thus, there is necessary to invest in the development of new non-seasonal raw-material sources for the production of bioplastics and new equipment that allow to maximize the added functions and value of these biobased advanced materials, as proposed in the Circular Economy projects BeirInov and FLUI. In these projects, biofunctional bioplastic films will be developed for sustainable functional packaging of agri-food products. The matrix of the film to be developed will be composed of PLA from lignocellulosic residues recovery and its biofunctionality conferred by the extraction of bioactive compounds extracted from agroindustry waste. Main results of environmental performance of these innovative films will be also presented and discussed.

Acknowledgments

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Plastic Pollution as a result of the Peruvian Fishing Industry

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Keywords: Abandoned, lost or otherwise discarded fishing gear (ALDFG); commercial fishing; hull scraping; marine plastic pollution; MFA; plastic packaging

Abstract

The Peruvian fishing industry, despite being the third most important in the world in terms of landings, remains highly informal. The informality and lack of documentation in this industry is closely related to a considerable amount of mismanaged waste, including plastics entering the ocean. This study presents a material flow analysis (MFA) of the plastic waste generated in the country's fishing industry, with the aim of quantifying the stocks and flows of plastic and identify the most relevant sources of its emissions towards the Peruvian ocean. Special focus is given to abandoned, lost or otherwise discarded fishing gear; plastic polymers emissions from the vessels hull's antifouling coating; and plastic packaging consumed onboard while performing fishing activities. In 2018, the fishing gear plastic stock amounted 41,773 metric tons and leaked 2,989 metric tons yearly towards the ocean. The plastic polymer stock from antifouling coating was 232 metric tons, emitting a total of 14 metric tons annually. The general waste leaked from plastic packaging ranged from 50 to 128 metric tons per year in the best- and worst-case scenarios, respectively. These results can serve as a stepping stone to a better understanding of the plastic flows in the Peruvian fishing industry towards the ocean, as well as identifying key points for a better assessment and management to reduce plastic emissions from marine-based sources.

1. Introduction

In recent years, ocean plastic pollution has become of major concern to our society, due to its potential impacts on marine biota and human health. Although the main source of plastic waste reaching the marine environment is land-based, ocean-based sources account for up to 20% of all plastic waste in the ocean (Li et al., 2016), generating multiple threats for marine ecosystems. The Peruvian fishing industry, despite being the third most important in the world in terms of landings, only surpassed by the Chinese and Indonesian fleets (FAO, 2020), remains mainly highly informal. Hence, reports of flows and stocks linked to fishing gear (FG), antifouling coating and general plastic waste consumed on board are not easily retrieved.

The Peruvian fishing fleet is divided according to the cargo hold capacity and the distance to land of the fishing activities. The artisanal fleet is made up of vessels with a maximum cargo hold capacity of 10 m^3, operating no more than 5 nautical miles (NM) from the coast; the small-scale fleet has a cargo hold capacity of over 10 m^3 up to 32.6 m^3, working within 5 NM from the coast as well. The largest fleet, in terms of landings, is the industrial fleet; it has a cargo hold capacity of over 32.6 m^3 and operates outside of the 5NM from land, which is reserved for artisanal and small-scale fishing only. Furthermore, the industrial fleet is divided in two: 'Vikings' (wooden hull vessels) and industrial (naval steel vessels) (PRODUCE, 2021).

The commercial fishing industry is identified as the main contributor to marine plastic waste release and abandoned, lost, or otherwise discarded fishing gear (ALDFG) comprising approximately 10% of all marine plastic litter (Macfadyen et al., 2009). Moreover, ALDFG cannot only lead to animal entanglement but also cause physical effects in the digestive system due to the ingestion of macroplastics. In addition, plastic waste can further break down into microplastics, thus increasing the potential impacts affecting all the levels of the trophic chain, and also human health due to the consumption of seafood (Walkinshaw et al., 2020). Antifouling coating losses due to hull scraping, weathering, and maintenance jobs also release microplastics to the ocean. Unfortunately, however, their flows and impacts to the marine environment are still an understudied field (Bray, 2019). Finally, packaging waste from food and other activities on board also have the potential of generating the release of a variable amount of macro- and microplastic residues. In this context, the main objective of this study is to analyze and estimate the stock and flows of plastic pollution to the ocean as a result of the Peruvian commercial fishing industry. For this, the release by littering, loss or dissipation of the following on board activities were assessed: ALDFG, plastic polymers from antifouling coating and plastic packaging consumed on board.

2. Materials and Methodology

2.1. Material Flow Analysis

Material flow analysis (MFA) is a well-established methodology to quantify stocks and analyze the flows of multiple materials through the technosphere (Kahhat & Williams, 2012; Dworak et al., 2021). Furthermore, MFA uses the mass conservation principle to evaluate the input and output flows in all of the phases of the material studied (Ciacci et al., 2017). MFA has been used for the development of several studies mainly considering commercially valuable commodities, such as metals, minerals, and chemicals (Gottschalk et al., 2010; Chen & Graedel, 2012). More recently, it has been used to understand the fate and dynamics between the several stages of plastic polymers and plastic packaging, mainly in Europe (Laner *et al*., 2016; Kawecki, et al., 2018; Cimpan, et al., 2021). In this study, MFA is used as the main methodology to determine the flows of marine plastic pollution from ocean-based sources; taking into account the inflow and outflows of plastics to the Peruvian Fishing industry. The system boundary considered was the Peruvian Exclusive Economic Zone (EEZ), which accounts for the first 200 NM from the coast. The reference year considered was 2018.

2.2. Data Acquisition and modelling

In order to estimate the stocks of plastics in the Peruvian fishing industry and their flows into the Pacific Ocean, different data sources have been used to build the MFA. For instance, information regarding technical characteristics of vessels in Peru was collected, including fleet type (i.e., artisanal, small-scale, 'Vikings' and industrial vessels), length, beam, cargo hold capacity, and fishing methods used by each vessel (PRODUCE, 2021). The vessels were then grouped by fishing method and cargo hold capacity, in order to estimate the stock of FG. Based on available literature related to the loss of FG into the ocean, the amount of ALDFG was estimated (Richardson, et al., 2019; Macfadyen, et al., 2009), as seen in Table 1.

Table 1. Fishing gear losses by method

Fishing method	Loss (%)	Reference
Longline	3.0	Macfayden et al.
Purse seine	7.0	Richardson et al.
Trawls	18.0	Richardson et al.
Gillnets	6.6	Richardson et al.
Traps/pots	20.0	Macfayden et al.

To estimate the stock of antifouling coating in the Peruvian fishing fleet, data regarding the length and beam of all identified vessels were divided and clustered accordingly. The average beam and length for each group were calculated and used to estimate the underwater area considering a fully loaded vessel. The artisanal fleet was grouped in 2-meter intervals, due to the small size of their vessels (the largest is <15m); the remaining fleets were clustered in 5-meter intervals. The amount of antifouling used and its plastic content was taken from the literature and common coating products used in the Peruvian marine sector (Pinturas Jet, 2021). Using the OECD (2009) antifouling emission estimates to the environment, the plastic emitted due to weathering and maintenance was calculated. These emissions were determined considering an annual maintenance regime; however, in Peru, hull maintenance is performed every 2 years, by law, with some applying for special permits to extend it up to 2.5 years.

General waste (GW) was considered as all the plastic packaging generated while fishing with the potential of being thrown overboard. Time spent at sea was estimated using different common Peruvian fishing fleet regimes, taking into account the duration and frequency of fishing activities. However, due to the high variability of fishing activities in terms of duration and frequency, which depends on multiple factors, different scenarios regarding the time aboard were analyzed. It is worth noting that the artisanal and small-scale fleets do not have fishing seasons, and are allowed to work all year-round. Moreover, the high variability of fishing jobs, combined with a vast informal artisanal sector, translates into high uncertainties when estimating the plastic consumed (and released) while at sea. Using information from ENAPREF (2012), the diet of the fishermen was calculated and used to estimate the plastic packaging consumed on board. It is important to mention that no reports regarding the amount of waste thrown overboard have been identified. However, littering is a common practice in the artisanal and small-scale fisheries, and floating debris from fishing vessels is frequently detected. Despite this significant limitation, different littering overboard scenarios were considered (35%, 50%, and 90% of all plastic consumed). The number of fishermen considered was obtained by the 'First national census of marine artisanal fishing' (INEI, 2013). However, the GW emissions to the ocean cannot be distinguished between these two fishing fleets, because the National Institute of Statistics and Computing (INEI in Spanish) aggregates artisanal and small-scale fishermen into the same category. Finally, the industrial and "Viking" fleets were not included in the calculation of GW because these are highly controlled by Peruvian authorities and are expected to unload their waste with each landing. However, it should be noted that a certain amount of direct leakage of this waste may occur, as well as indirectly, due to the abundance of open dumps along the Peruvian coastline.

3. Results and discussion

The MFA brought to light that the total plastic emitted towards the Peruvian EEZ from its fishing industry ranged from 3053 to 3131 metric tons in the year 2018. It can be noted that ALDFG has the highest contribution, of 96% and 98%, in the best- and worst-case scenarios respectively. The antifouling coating has the lowest share, up to 0.5%. Meanwhile, GW proportion ranged between 2% to 4%. Figure 1 illustrates the flows and stocks of plastic in the Peruvian fishing industry. It is worth noticing that GW as a stock is not considered as it is defined as the plastic packaging that can flow into Peruvian waters from commercial fishing activities. Hence, there is no permanent GW stock is not in the fishing industry.

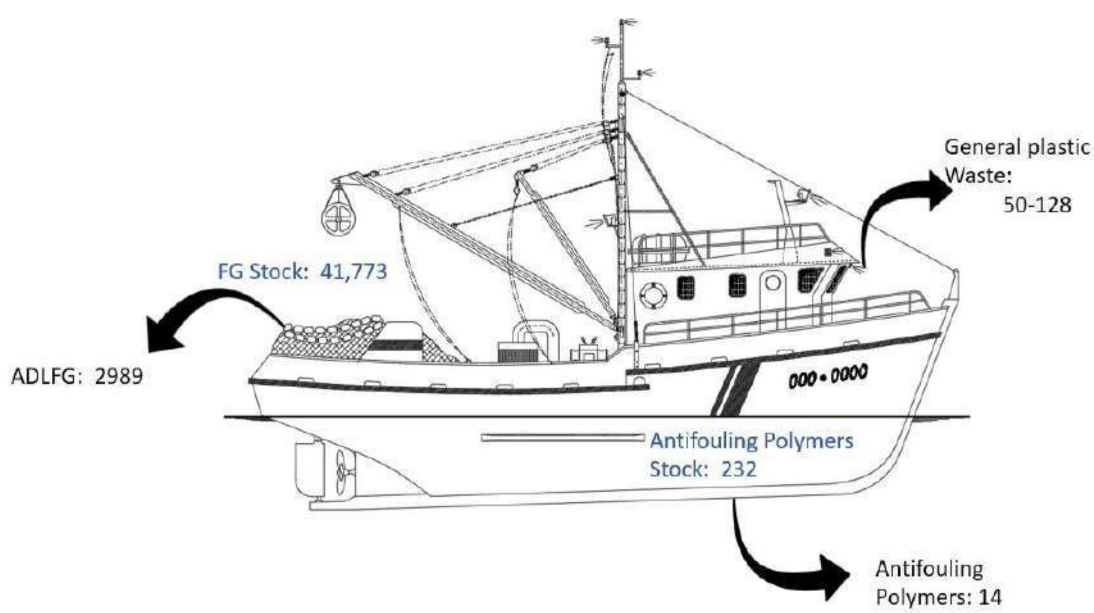

Figure 1. Peruvian fishing industry plastic stocks and flows. In metric tons

As seen in Figure 1, the total amount of FG stock in Peru is 41,773 metric tons, meaning that approximately 7% of all the FG is lost to the ocean yearly. Furthermore, it is estimated that around 232 metric tons of plastic polymers are found in the antifouling coating of all the fishing fleet, considering a two-layer application. In regards to GW, the high variability of fishing activities explained meant an important difference of 78 metric tons between the best- and worst-case scenarios. Table 2 presents the results of all the plastic flows towards the EEZ. It can be observed that the most polluting fleets are the industrial and "Vikings" fleet. The naval-steel fleet accounted for 44% of all the plastic emissions to the ocean, followed by "Vikings" (37%).

Table 2. Peruvian fishing fleet plastic waste flows to the ocean

<table>
<tr><th colspan="2">Fleet type</th><th>Artisanal</th><th>Small Scale</th><th>Vikings</th><th>Industrial</th></tr>
<tr><td colspan="2">Fleet (#)</td><td>12415</td><td>1490</td><td>804</td><td>821</td></tr>
<tr><td colspan="2">ALDFG (t/yr)</td><td>301.6</td><td>286.7</td><td>1095.1</td><td>1305.5</td></tr>
<tr><td colspan="2">Antifouling polymers emission (t/yr)</td><td>6.1</td><td>1.8</td><td>1.7</td><td>4.3</td></tr>
<tr><td colspan="2">Subtotal (t/yr)</td><td>307.7</td><td>288.4</td><td>1096.9</td><td>1309.8</td></tr>
<tr><td colspan="2">Contribution</td><td>10.2%</td><td>9.6%</td><td>36.5%</td><td>43.6%</td></tr>
<tr><td colspan="2">Plastic emission/vessel/yr (t)</td><td>0.02</td><td>0.19</td><td>1.36</td><td>1.60</td></tr>
<tr><td rowspan="3">General Waste (t/yr)</td><td>35%</td><td colspan="2">50</td><td colspan="2" rowspan="3">No direct leakage considered</td></tr>
<tr><td>50%</td><td colspan="2">68</td></tr>
<tr><td>90%</td><td colspan="2">128</td></tr>
</table>

ADLFG: Abandoned, lost, or otherwise discarded fishing gear

In spite of having smaller fleets (in terms of numbers of vessels) both industrial and "Viking" fleets have a much higher stock of plastic in both FG and antifouling polymers, as shown in Table 3. This is due to having a considerably greater average cargo hold capacity. Thus, the vessels in both fleets are on average, bigger than those in the artisanal and small-scale fleets, meaning that they have a superior underwater area and have to carry larger FG weights. On the one hand, it can be seen in both tables that the artisanal fleet has the lowest emission and stock per vessel. Despite having on average smaller vessels, it has the largest number of vessels, roughly ten-fold higher than the rest of the fleets; hence, it also has a higher total contribution than the second-largest fleet: the small-scale fleet, which has a substantially larger plastic stock per vessel. On the other hand, both "Viking" and industrial vessels have, on average, a substantially higher FG weight on board. Furthermore, the industrial fleet has a far greater polymer content, of 87.5 kg, in the underwater hull area, compared to the others. It is interesting when comparing it to the Vikings fleet, as they have a similar FG weight on board, yet the industrial fleet has on average more than two times the underwater area. This may be explained because naval steel vessels are more modern and have more and better equipment, technology, and facilities on board, which in turn results in bigger vessels regardless of the same relative cargo hold capacity.

Table 3. Peruvian fishing fleet plastic stock

Stock				
Fleet	Fishing Gear (t)	Fishing gear/vessel (t)	Polymers (t)	Plastic polymers/vessel (kg)
Artisanal	4773	0.38	101.5	8.18
Small Scale	3390	2.28	29.6	19.87
Vikings	16344	20.33	28.6	35.56
Industrial	17266	21.03	71.8	87.49
Total	**41773**	**--**	**231.5**	**--**

4. Conclusions

There is an important difference in the FG plastic stock per vessel between the "Vikings" and industrial fleets as compared to the artisanal and small-scale fleets. The weight of FG carried on board, which solely depends on the cargo hold capacity, is of higher importance than the numbers of vessels, regarding plastic emissions to the ocean. The industrial fleet, despite being less than a tenth of the size of the artisanal fleet (in number of vessels) emits 4 times more plastic in terms of FG and antifouling polymers. Furthermore, ADLFG comprises roughly 96% of all the plastic emissions towards the Peruvian ocean from the fishing industry, which demonstrates the importance of better control and management of FG.

The Peruvian fishing industry directly contributes between 3% to 7% of the total plastic waste flowing to the EEZ, from both land-and marine-based sources (Ita-Nagy, et al., 2021). Nonetheless, these estimates have uncertainties, which sheds light on the need to address the lack of documentation and informality; and promote fieldwork and the implementation of methodologies to characterize and quantify plastic stocks and waste flows to the marine environment from ocean-based commercial fishing activities in Peru. Moreover, understanding plastic flows derived from the Peruvian fishing industry will help decision-makers to recognize and tackle this problem in a sustainable manner, considering a holistic approach. A critical first step is to raise awareness among all levels of fisheries' stakeholders about the effects of litter, ALDFG, and vessel maintenance have on fishing resources, both economically and biologically, as well as on the livelihood of fishermen and fishing communities.

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Development of simplified characterization factors for the assessment of marine microplastic emissions and application on food packaging case studies

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Keywords: *life cycle impact assessment; microplastics; marine litter impacts; food packaging; characterization factors; MarILCA.*

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Introduction: Although plastic litter is a growing environmental concern, so far, there is no life cycle assessment (LCA) methodology to assess the potential impacts of plastic litter on the environment or human health. To tackle this shortcoming of LCA, the international scientific workgroup MarILCA (MARine Impacts in LCA, marilca.org) was formed in 2018, supported by FSLCI and the Life Cycle Initiative, with the goal to propose a methodology for assessing potential (macro-, micro, nano-) plastic litter impacts in LCA. Within the MarILCA framework, the new impact category *physical effects on biota* aims at capturing the physical impacts of plastic litter on organisms, both through internal (ingestion) and external (entanglement, smothering) pathways (Woods, Verones, Jolliet, Vázquez-Rowe, & Boulay, 2021). To provide characterization factors (CFs) for *physical effects on biota*, the following sub-factors are developed, following a common structure in emission-based LCA (Jolliet et al., 2006):

$$\textit{Characterization factor} = \textit{Fate factor} * \textit{Exposure factor} * \textit{Effect factor} \quad (1)$$

Lavoie et al. (2021) already proposed a combined exposure and effect factor for assessing the impacts of microplastics on aquatic (freshwater and marine) species. Recent work proposed simplified fate factors, which were combined with Lavoie et al.'s (2021) factor to obtain simplified CFs for modelling the impacts of two types of microplastics – expanded polystyrene (EPS) and tire and road wear particles (TRWP) – in the marine environment (Corella-Puertas et al., 2022). As a continuation of Corella-Puertas et al. (2022), this study aims at providing additional simplified fate and CFs for assessing potential physical effects on biota impacts and associated damages on ecosystem quality, for different types of microplastic emissions (polypropylene, PP; high-density polyethylene, HDPE; low-density polyethylene, LDPE; polyethylene terephthalate, PET; polyvinyl chloride, PVC; polylactic acid, PLA).

The resulting CFs are included in case studies within the UNEP LCA meta-study on supermarket food packaging (comparing single-use plastic options and their alternatives) (UNEP, n.d.), as well as a case study on grocery bags within the upcoming Springer Handbook of Circular Plastics Economy (Maga et al., n.d.). Specifically, the developed CFs are used to include impacts of marine litter in existing LCA studies which had not included those impacts yet. The goal is to add the new category of *physical effects on biota* to the existing impact assessment results, allowing to compare the relative magnitude of marine microplastic litter impacts on biota to other potential impacts.

Methodology: Simplified fate factors are developed for different microplastic types (PP, HDPE, LDPE, PET, PVC, PLA) following the fate modelling steps proposed by USEtox (Fantke et al., 2018) (Fantke et al., 2018). This work tests microplastic removal mechanisms via degradation and sedimentation in the marine environment. Degradation rates are proposed using literature data, based on the structure proposed by Chamas et al. (2020) and modified by Corella-Puertas et al. (2022):

$$r_d = SSDR * \rho * SSA \quad (2)$$

With the polymer degradation rate r_d in $kg_{mass\ loss}/(kg_{in\ compartment}*year)$, the specific surface degradation rate *SSDR* in µm/year, the polymer density ρ in kg/m^3, and the specific surface area *SSA* in m^2/kg. As an update to the work of Corella-Puertas et al. (2022), in this work, the SSA varies as a function of the microplastic size. Different microplastic size scenarios are assessed. Sedimentation rates are estimated based on buoyancy, assuming first-order kinetics. Since there is uncertainty in the experimental data on degradation and sedimentation rates, best, average and worst-case scenarios are tested. The degradation and sedimentation rates are integrated into fate factors and ultimately CFs, following the methodology proposed by Corella-Puertas et al. (2022).

The CFs are tested in LCA studies, such as the one comparing single-use bags used to package fresh-cut lettuce, considered in the UNEP LCA meta-study on supermarket food packaging. This exemplary case study is based on the work of Vigil et al. (2020), which compared the potential impacts of PP (3.97 g) and PLA (4.14 g) bags containing 130 g of fresh-cut lettuce, used in Italy. Vigil et al. (2020) calculated various impact categories based on the ReCiPe life cycle impact assessment method, but did not include impacts of microplastic emissions. In order to calculate marine microplastic litter impacts, the first step is to quantify marine (micro)plastic emissions using the Plastic Leak Project guidelines (Peano et al., 2020). Different fragmentation rates of macro- into microplastics are tested within the plastic inventory. The microplastic emissions are multiplied by the proposed polymer-specific CFs to calculate the potential impacts of *physical effects on biota* on ecosystem quality.

Results and discussion: To assess the magnitude of potential impacts associated with *physical effects on biota*, the resulting CFs were compared to *marine ecotoxicity* CFs from ImpactWorld+ (Fig. 1). Polymers with densities (TRWP, PLA) higher than seawater are expected to sediment quickly and thus result in CFs on the lower end of the spectrum in Fig. 1. In those cases, sedimentation occurs quickly enough that degradation within the marine water column barely affects the results. For polymers with densities close to seawater (HDPE, LDPE, PP), degradation becomes relevant. There is high uncertainty associated with the degradation and sedimentation rates. The highest uncertainty is obtained for EPS CFs, and is associated both to degradation and sedimentation rates. Since EPS is positively buoyant, EPS microparticles are only expected to sink if biofouling occurs, as it generally increases the overall particle density. Currently, there is still high uncertainty associated to EPS biofouling and sedimentation rates. Overall, the CFs for different polymers span over several orders of magnitude. This highlights the need to develop polymer-specific CFs, as well as continue research efforts to reduce CF uncertainty. The development of CFs for PET and PVC will be also presented.

The CFs are applied in a case study on single-use lettuce bags (Fig. 2). Although the microplastic emissions are estimated to be similar for both PLA and PP bags, the higher *physical effects on biota* CF of PP leads to higher potential *physical effects on biota* impacts from the PP bag. Nevertheless, even in the worst-case scenario of *physical effects on biota* impacts, the contribution to the overall impacts on ecosystem quality remains very small compared to other impact categories. Particularly, climate change has the largest contribution for both lettuce bags. This exemplary case study shows the importance of performing comprehensive LCAs to understand the relative significance of different impact categories, and avoid burden-shifting when making environmental decisions.

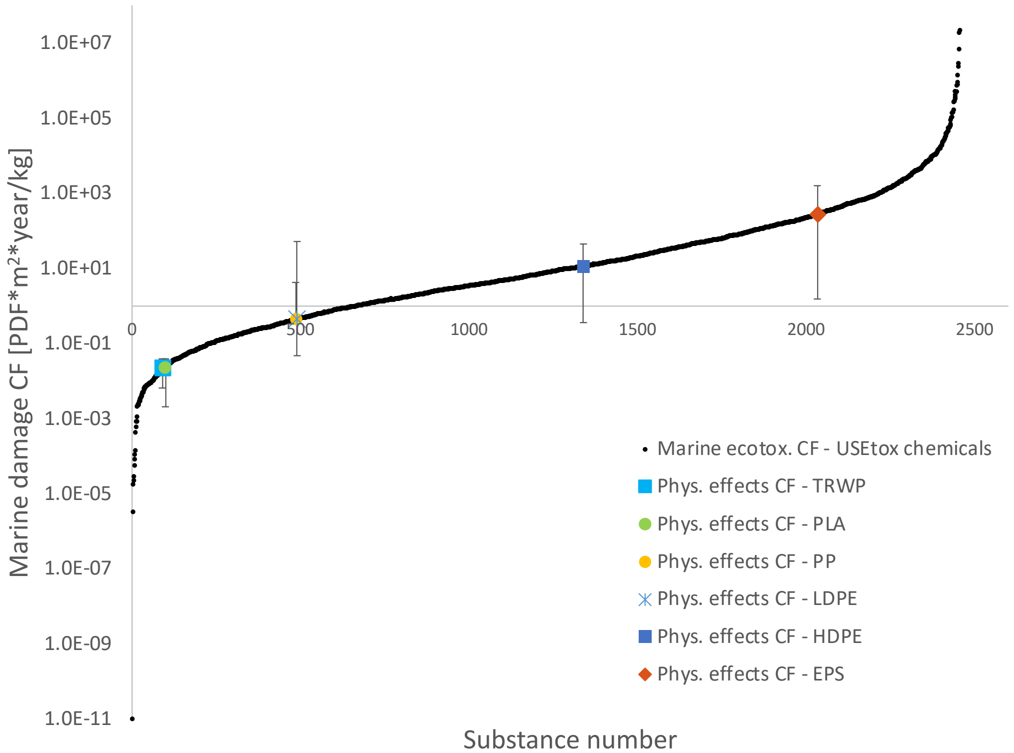

Figure 1: Values of the endpoint CFs for *physical effects on biota* of microplastics in the marine compartment compared to endpoint CFs for *marine ecotoxicity* for all organic chemicals represented in USEtox. For *physical effects on biota*, the markers represent average-case scenarios, whereas the error bars show the range between the best and worst-case scenarios. EPS and TRWP CFs come from Corella-Puertas et al. (2022), whereas other *physical effects on biota* CFs were calculated in this work.

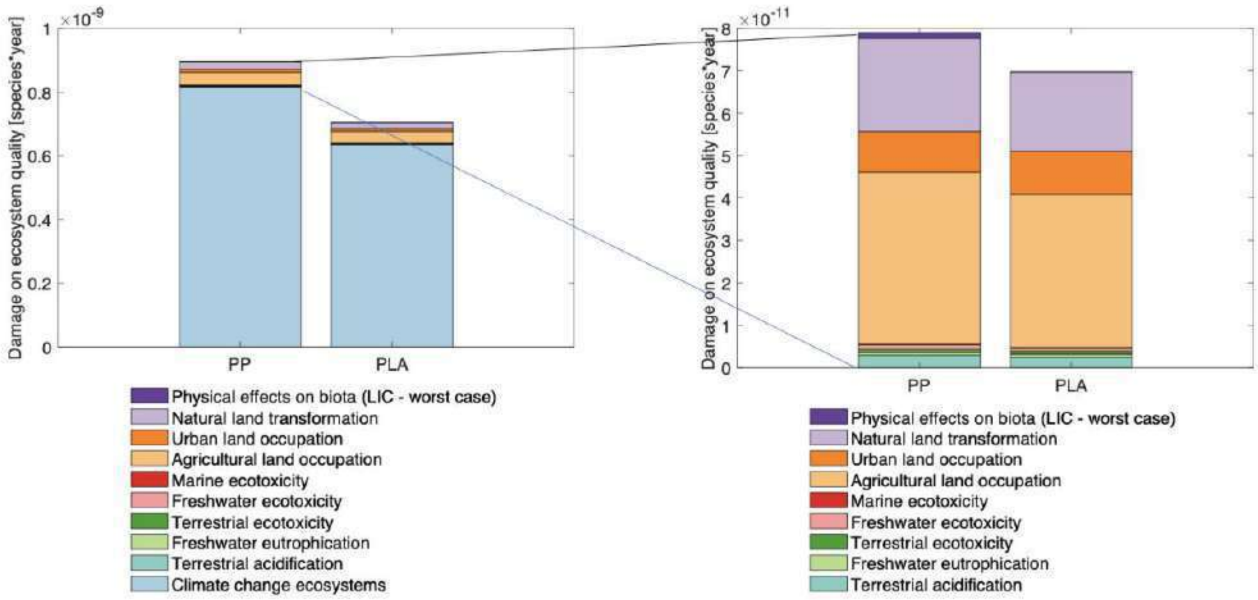

Figure 2: Ecosystem quality results for a case study on single-use lettuce bags made of PP or PLA. Left: Impact categories calculated by Vigil et al. (2020) with the addition of *physical effects on biota* (worst-case scenario) (UNEP, n.d.). Right: Climate change impacts removed for illustration purposes. These images and results are published as part of the UNEP LCA Meta-analysis on supermarket food packaging (UNEP, n.d.), Annex C.

Conclusions: This exploratory work provides simplified *physical effects on biota* CFs for different types of microplastic emissions. The results confirmed the need for developing physical effects on biota CFs specific to different plastics, since sedimentation and degradation rates vary from one plastic type to another and thus influence the microplastic fate. Testing the proposed CFs in existing LCA case studies of food packaging and grocery bags will help to assess the relative importance of microplastic impacts compared to the rest of the life cycle. The insights gained will provide information which will assist environmental decisions based on comprehensive LCAs. Note that the CFs presented in this work only cover part of the complexity of the potential impacts of plastic emissions. Further impact categories related to plastic emissions are currently developed by the MarILCA workgroup (physical effects on biota of macroplastics, invasive species, ecotoxicity of plastic additives, etc.) and will allow for a more comprehensive assessment of the plastic impacts on the environment.

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Developing characterization factors to quantify the environmental impacts of plastic waste in the ocean

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1. Introduction

During recent years, marine litter, especially plastic, has become a major concern, affecting an increasing number of coastal and marine areas, including multiple ecosystems, with multiple negative consequences, physical, chemical, or biological, on the habitat affected, including its effects on the food chain and human risk toxicity or ingestion. Plastic materials take centuries to completely degrade, however, when disposed in nature and due to different weather triggers (e.g., UV radiation, temperatures, mechanical abrasion), some plastics will break down into microplastics (Lassen et al., 2012). These microplastics are then more easily ingested or absorbed by species and transported upwards the trophic chain, where they are more likely to end up back again in the technosphere as part of our food chain (Vazquez-Rowe et al., 2021). Increased awareness on the matter has also been observed in academia, where researchers are constantly trying to estimate the amount of waste entering the oceans and their consequences in the environment and human health.

Life cycle assessment (LCA) is a well-known tool used to evaluate the environmental impacts of a product system, from a holistic perspective. Even though LCA is broadly used to support decision making by analysing a variety of environmental impacts, marine impacts are still generally lacking or in early stages of development (Boulay et al., 2021; Woods et al., 2021). More specifically, it can be noted that most studies are oriented towards quantifying the environmental impacts related to chemical (toxicity) or physical (entanglement) impacts across different trophic levels, leaving aside other still important issues, as for example the economic impact of unrecoverable materials. Waste entering the ocean can be considered as unrecoverable materials, conforming a mostly inaccessible stock accumulated in the environment. Also, during the impact assessment of waste, specifically mismanaged or dissipated waste, the methodology currently lacks an adequate route to include these environmental impacts and damage within the metrics. Thus, it is important to include those resources that are capable of being recirculated in the technosphere but are, instead, mismanaged and making their reclamation unfeasible.

Most plastics are made of oil or natural gas, as part of the by-products in the refining processes. Even though the main purpose of fossil fuel extraction is the production of energy, an approximate of 9% is used for plastic production (Nielsen et al., 2020), considering both feedstock and energy use. When fossil fuel is used for energy production, the final disposal is mainly considered as dissipation. However, when used as feedstock to produce a material, like plastic products, fossil fuels become a stock in the technosphere that could be recirculated into the production chain.

Plastic dissipation occurs once the material is released from the economic production chain into the environment, either by accident or as a consequence of poor waste management. The fate of dissipated plastics is affected by different factors, including the compartment where it is firstly disposed, the physico-chemical properties of the material and the characteristics of the environment along their possible path towards a final sink. Considering the slow degradation of plastics, it is expected that they will have the ability to be transported longer distances before experiencing greater transformation and degradation processes (Lecher 2018).

Nowadays, the main objective of international organizations, governments, NGOs and academia relies on the development of strategies to diminish the amount of waste in the ocean; however, it is also important to analyse the environmental impacts of these releases in different areas of protection, including resource depletion. Thus, the main objective of this study is to develop a methodology to identify and quantify the environmental impacts of plastic waste entering and accumulating in the ocean, from a resource dissipation perspective. The case study involves the environmental evaluation of a beverage packaging from a cradle to grave perspective, in order to assess the introduction of this new evaluation.

2. Methodology

To develop a methodology to evaluate the environmental impacts, under an LCA perspective, of solid (mismanaged) waste, specifically plastic waste, ending up in the ocean, the starting point includes the identification of their main hotspots and their mobility towards the ocean. From that point onwards, characterization factors (CF) for plastic materials are being developed, to assess the marine circularity loss (MCL) of mismanaged ocean plastics.

Two impact assessment (IA) methodologies focused on resource depletion are chosen to be used as the base for the development of CF in MCL. The first one, the environmental dissipation (ED) (van Oers et al., 2020) which is developed following the abiotic depletion (AD) method in CML2001 (van Oers et al., 2002), measures resource scarcity as the decrease in the accessibility of the total stock, considering present use of resources. The second one, fossil energy use (FEU) method in Impact World+ (Bulle et al., 2019) builds the CF following the extraction-consumption-competition-adaptation approach, which describes the impacts of resource consumption as a decrease in the availability for current or future users (Bulle et al., 2019). In both cases, fossil fuel consumption is linked to energy supply, leaving aside the fraction not dissipated and accumulated as anthropogenic stocks in the technosphere and nature.

In this study, the mid-point CF are developed considering the most used plastic polymers (polyethylene-PE, polypropylene-PP, polystyrene-PS, expanded-polystyrene-EPS, polyethylene terephthalate-PET) during the production of commodity materials following the concentration of refined fossil fuels employed during production, as a way to quantify the stock of fossil fuels in each material. Thus, the CF are not intended to quantify the amount of extracted fossil fuels from nature, but the amount existing as an anthropogenic stock on the material and their potentially lost in the ocean.

It is important to mention that, currently, adequate inventory data related to mismanaged or littered waste is still incomplete despite advances in recent years, which is an additional hurdle during an impact assessment. Our estimations are based on global available percentages of waste entering the ocean to cover these gaps. However, improved inventory data are necessary, not only for this methodology but also for those quantifying other impact pathways of marine plastics (Woods et al., 2021).

3. Results and Discussion

The development of a framework to assess the impacts of marine plastics attempts to connect mismanaged waste dissipation leaked to the marine compartment and the socio-economic assets as the Area of Protection. The evaluation follows the concept of resource accessibility decrease on a global level, considering resources accessible in both the environment and technosphere (van Oers et al. 2020).

The environmental impact category developed considers the accumulation of plastic waste in the ocean, as the final sink compartment. Characterization factors of MCL are developed following the existing relationship between materials in the technosphere and their likelihood to end up as ocean litter. The evaluation of impacts is intended to analyse future effects caused by present mismanagement of waste regarding their availability in both the environment and technosphere.

The methodology is intended to complement existing impact assessment categories focussed on resource depletion to quantify the effects of plastic materials incorrectly disposed in nature. Its implementation will allow practitioners to also include the impacts during the material's end-of-life, additionally to the depletion potential given by the dissipation as energy, which is the current state-of-the-art in the evaluated impact categories (ED and FEU). The CF developed per plastic polymer during production of goods will tackle some of the most commonly found plastic materials in the ocean: bottle caps, straws, cutlery, single use bags and beverage bottles (Ocean Conservancy 2021), as a starting point. Thus, knowing their polymer composition and likelihood to be mismanaged and enter the ocean, the amount of resource dissipated in nature can be estimated and added as part of the IA evaluation.

The developed CFs are compared to the existing impact assessment categories to evaluate their implications during life cycle IA, considering a specific case study: a 1 L water bottle. During the development of the case study, the use of the original impact categories and the modified categories are intended to give a better understanding of the relevance of dissipation of plastic materials, when considering the whole life cycle of a good.

4. Concluding remarks

An inadequate final disposal of all kinds of waste generates not only environmental consequences, but also economic ones, as for example costs expended for clean-up plans and remediation techniques, diminish of tourism affecting local businesses, or damage of existing man-made infrastructure and services (ten Brink et al. 2016). In addition to these well-known consequences of littering, mismanaged waste also reduces the possibility of circularity in the economy, making recyclable materials unavailable for the future. Thus, impacts of marine litter as part of a resource depletion model, may help impulse the generation of stricter policies to increase circular economy, avoiding the transport of waste back to nature where extraction in the future may not be feasible.

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LCA of two West African fisheries value chains: mapping and assessing eco-efficiency indicators to identify priorities for improvement

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Keywords: *artisanal fisheries; fuel use intensity; functional analysis; value chain mapping; West Africa.*

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One of the main challenges for improving the sustainability of value chains is understanding their functioning and interactions among actors. Mapping (i.e. thoroughly describing) them, is a useful tool to be used as a basis for analyses, which implies the creation of a typology of actors and activities, generalisations and extrapolations.

We mapped fisheries-based value chains (Figure 1) in two contrasted countries. In both cases, these value chains belong to very important sectors for a large percentage of the population: The Gambia, where marine fisheries dominate, and Mali, with inland fisheries (Acosta-Alba et al., 2022).

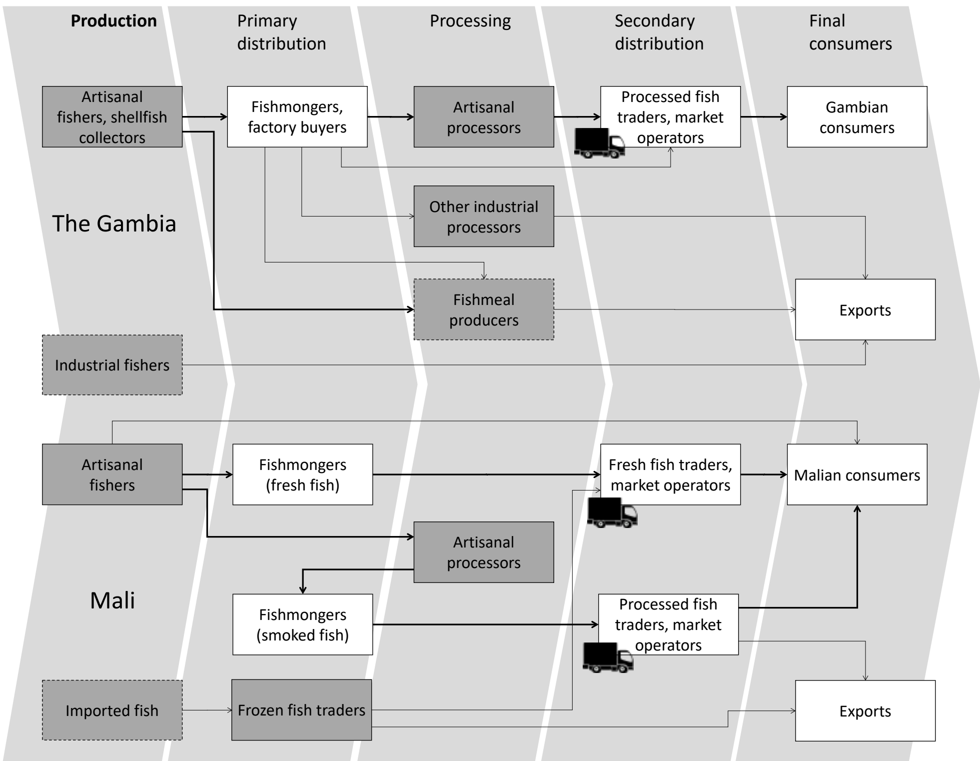

Figure 1. Simplified value chain schemes of the Gambian fisheries and the Malian continental fisheries value chains

We explored, quantitatively and qualitatively, the geographical distribution, organisation, technical performance and exploited ecosystems associated with these value chains, as a means to facilitate their sustainability assessment. We applied an approach, Value Chain Analysis for Development (Dabat et al., 2018), developed by policy makers and implemented by scientists within time constrains, in scarce data contexts, to monitor how development actions contribute to sustainable development goals. Such exercise allowed us to discuss the challenges of mapping fisheries value chains and provide recommendations for improving value chains analyses.

The Gambian and Malian fisheries and fish processing value chains are predominantly artisanal and represent a key source of protein and livelihoods, yet their eco-efficiency has not been studied to date. After mapping those value chains, LCA was used to estimate the environmental impacts associated to inform eco-efficiency indicators, which relate technical efficiencies to environmental impacts (Avadí & Acosta-Alba, 2021):

- Fuel use intensity (FUI), namely the ratio between landed fish and fuel consumed to catch and land the fish, is widely used as an indicator of fisheries efficiency in LCA, as it captures both the actual fishing effort as well as other components of the fishing activity such as the fuel consumption associated with travel to and from fishing areas, and even fuel saving strategies and other skipper behaviour (Avadí et al., 2018).
- Other indicators have been used to assess eco-efficiency of fisheries and other seafood systems, such as energy return on investment (EROI) (Vázquez-Rowe et al., 2014) and protein-per-impact (PPI) (Laso et al., 2018). The former refers to the ratio of energy embedded in a fish product to the industrial energy (CED) required to produce said product (expressed for instance with respect to its edible yield), while the latter represents the ratio of protein (as a proxy for nutritional value) delivered by a product to the environmental impacts (e.g. as a single score) associated to the production system (Avadí & Fréon, 2014).

The results showed that industrial Gambian fleets' fuel use efficiency is rather low as compared with the global mean fuel use intensity (landed fish/consumed fuel) for both small pelagics and demersal fish. In Mali, the fuel use intensity of motorised artisanal fisheries is lower than the mean values for artisanal inland fisheries in developing countries, but the important increase of frozen imported fish from fish farming multiplies the estimated impacts of the value chains by four. The least energy-intensive fisheries (cast nets and stow nets in Gambia and opportunistic fishers in Mali) feature better eco-efficiency scores (Figure 2).

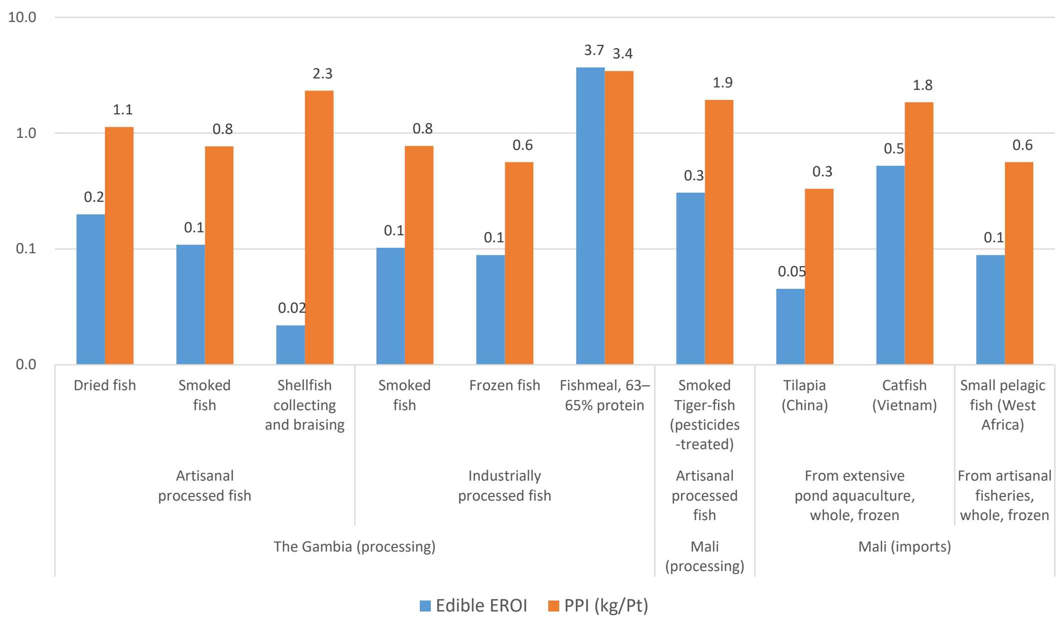

Figure 2. Edible energy return on investment (EROI) and protein-per-impact (PPI) of Gambian and Malian processed fish products

The efficiency of Gambian and Malian fisheries, as well as the eco-efficiency of said fisheries and fish processing, were quantified by means of LCA-derived indicators. Both metrics are relatively lower than equivalent global processes and products, except for Malian inland fisheries. The main reasons for such performance include the type of fisheries organisation and governance prevailing in these countries, which determines a continuous race for poorly regulated common-access resources. Moreover, migratory and/or high mobility fishing strategies increase fuel consumption. Improvements in infrastructure and energy efficiency of fishing and processing units would likely contribute to improve the eco-efficiency of the fisheries-based value chain in both countries.

Based on the identified sources of inefficiencies, we suggest improvements in the landing/processing infrastructure and fishing units' engines, coupled with technical and business training and improved processing methods, to ameliorate seafood eco-efficiency and a stronger recognition of the importance of the artisanal fisheries subsector to overcome challenges and improving re-source management.

This work has been recently published as Avadí & Acosta-Alba (2021) and Acosta-Alba et al., (2022).

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Integrating epistemic uncertainty quantification into life cycle assessment to visualize the influence of environmental standards and labels

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Keywords: *Monte Carlo simulation; knowledge management; scenario uncertainty; land use change; prospective LCA*

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1. Introduction

Environmental standards and labels (hereafter, ecolabels) are expected to induce pro-environmental consumer behavior through stakeholder interactions (Lambin and Thorlakson, 2018) and their positive effects on increased sustainable food selection and consumption have been reported (Potter et al., 2021). To understand the effects of ecolabels on consumer behavior, the specification of consumer preferences is an indispensable process; Tobler et al. (2011) identified inconsistencies between the assessment of environmental friendliness by consumers and the results of the life cycle assessment (LCA).

Although these research trends indicate the necessity of further ecolabel studies on the relationship between consumers' behavioral changes and environmental effects, they also indicate the necessity of clarifying the process of calculation of LCA in the context of ecolabel effects, especially in the case of type III ecolabels. Accurate assessment scenarios can be difficult to determine when performing life cycle inventory (LCI) analysis for ecolabels. In interactions involving multiple stakeholders, a downstream player does not necessarily know the details of the production of upstream players; for example, in the Mass Balance model of RSPO certification, production details like deforestation are not made available to the buyer, because both certified and non-certified palm oil are mixed during distribution. Deforestation in product supply chains is generally difficult to monitor, which is why strategies such as the use of satellite data for detecting deforestation are mentioned in action plans such as the EU Biodiversity Strategy for 2030.

The existence of indeterminacy in assessment scenarios implies that there are scenario uncertainties in LCI data constructed using imperfect information (Hayashi et al., 2014). Although many studies have been conducted to cope with the uncertainties within LCA, with pedigree matrices being used to generate statistical distributions in LCI databases (Ciroth et al., 2016), what matters here is knowledge representation that can be linked to visualization in ecolabels rather than the data quality considered in the pedigree matrix.

Therefore, this study proposes a method to integrate epistemic uncertainty—a type of uncertainty that can be refined through knowledge acquisition and which is different from uncertainty based on data quality—into LCA, which demonstrates the usefulness of modeling imperfect knowledge in LCI analysis.

2. Methods

2.1 Use of epistemic uncertainty to assess ecolabels

In addition to the conventional classification into parameter, model, and scenario uncertainty (Huijbregts, 1998), the distinction between aleatory and epistemic uncertainty has been used in LCA. In contrast to aleatory, ontic, or stochastic uncertainty, which is characterized by intrinsic randomness, epistemic uncertainty is due to the lack of knowledge and can be reduced by gathering additional information (Kiureghian and Ditlevsen, 2009). Although the terminology of epistemic uncertainty has been widely found in the LCA literature, the concept has not yet been applied to the evaluation of ecolabels as a carrier of knowledge. This study focuses on land use change (deforestation); greenhouse gas (GHG) emissions from the unit process "Land use change, perennial crop, annualized on 20 years (WFLDB)/ID U" (Bengoa et al., 2020), which is referenced from the unit process for oil palm production in Indonesia, were assessed as a case study.

2.2 Uncertainty quantification

As a method to quantify both the parameter uncertainty (aleatory uncertainty; expressed as probability distributions) and the epistemic uncertainty that can be mitigated by ecolabels, the Monte Carlo method was integrated with the formulation of a knowledge domain or a feasible region (Fig. 1). In Fig. 1, the area for land use change from primary forest to agricultural land, for example, is zero if environmental labels guarantee that there is no deforestation owing to production. Since LCA software such as SimaPro cannot solve the problem (constrained Monte Carlo simulation), the RiskOptimizer in @Risk 8.0 was applied and the problem was formulated as a range maximization. Upstream uncertainties were estimated by Monte Carlo simulation in SimaPro 9.3 (1000 iterations) and were presumed to be normal distributions.

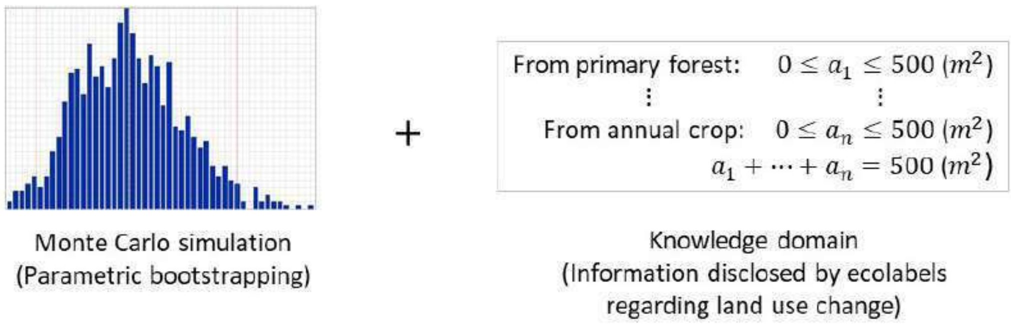

Fig. 1. Quantification of uncertainty with knowledge management.

2.3 Two comparisons

This study conducted two comparisons on density estimation of GHG emissions from land use change into perennial crop land in Indonesia. First, to confirm the effects of epistemic uncertainty quantification, the constrained Monte Carlo simulation—in which no *a priori* weights (measured as area) were determined for land use change categories—was compared with the conventional Monte Carlo simulation based on market process modeling (weighted averaging of land use change categories). Second, to visualize the influence of knowledge on deforestation, the no-deforestation case—in which knowledge on no-deforestation is disclosed by ecolabels and the reliability of the information is institutionally guaranteed—was compared with the above constrained Monte Carlo simulation.

3. Results

3.1 Influence of epistemic uncertainty quantification

The result of the comparison to estimate the influence of epistemic uncertainty quantification indicated that conventional Monte Carlo simulation based on market process modeling may underestimate the means and variances related to procurement (Fig. 2a).

3.2 Influence of knowledge acquisition

The result of the comparison to understand the effects of knowledge acquisition on deforestation showed that if ecolabels guarantee no deforestation in procurement, means and variances decrease drastically (Fig. 2b).

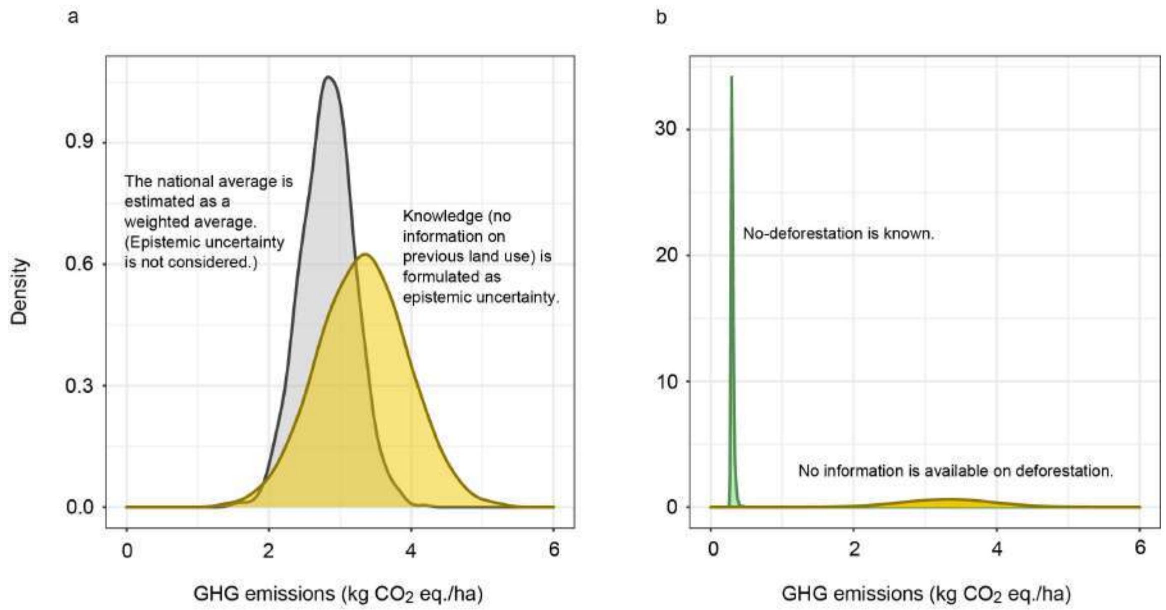

Fig. 2. Results of the density estimation of GHG emissions due to land use change into perennial crops in Indonesia. **a**, Influence of epistemic uncertainty quantification. **b**, Influence of knowledge about deforestation provided by environmental labels.

4. Discussion

4.1 Importance of introducing epistemic uncertainty quantification

The result that knowledge refinement (information acquisition through ecolabels) has a large influence on the distribution of estimated environmental impacts indicates the importance of introducing epistemic uncertainty quantification into LCI analysis. Although the estimation presumed that the information provided by ecolabels is completely reliable, it is possible to adjust for cases in which unreliability exists.

4.2 From market process modeling to knowledge management

The use of production areas (or volumes) for weighted averaging in market processes seems to be a viable procedure to construct an averaged unit process. However, it needs to be reconsidered from the perspective of epistemic uncertainty quantification, because market process modeling is equivalent to the case where the production information is known to the LCA analyst (Hayashi, 2020). The necessity of reconsideration of the market process concept implies that implementation of the calculation procedure in the LCA software is also necessary.

4.3 Further inclusion of conservation effects into inventories

Although much attention has been paid to the behavioral and preferential effects of ecolabels in previous studies, the environmental effects of ecolabels should be further studied, and they should be incorporated into LCI data, keeping in mind epistemic uncertainty quantification. For example, the conservation impacts of ecolabels (Milder et al., 2015) have demonstrated its utility in helping establish sustainable agricultural systems, especially in tropical areas, which are important production hubs for plantation crops. Sustainable procurement of these crops is an important research topic, and the conservation benefits brought about by sustainable practices can be formulated through LCI analysis supplemented with knowledge management.

4.4 Necessity of a wide range of categorical differentiation

In addition to deforestation, other categorical parameters should also be included in the quantification of epistemic uncertainty. For example, farm type is an important factor, because there are noticeable differences between large-scale plantations and small farms in terms of metrics like oil palm production. Although these considerations may reveal the ineffectiveness of current ecolabels (Meemken, 2020), the integration of the explicit formulation of the environmental effects of ecolabels and epistemic uncertainty quantification facilitates visualization and understanding of programs to establish sustainable agricultural systems.

5. Conclusions

This study proposed a method to integrate epistemic uncertainty quantification into LCI analysis and identified the influence of epistemic uncertainty quantification and knowledge acquisition. The results demonstrated the utility of modeling imperfect knowledge found in ecolabels. Although the primary focus of the case study was deforestation, it is important to widen the area of attention to varying metrics of sustainability assessment. For example, analytical extension to farm typology requires consideration of social issues and the epistemological assumptions behind them. Epistemic uncertainty quantification will also play an important role in the prospective LCA of future technologies, in which many types of epistemic uncertainties should be specified.

Acknowledgments

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Environmental and nutritional performance of fish and seafood: A friendly tool for producers and consumers

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Introduction

According to world projections, in the next decades fresh water, energy, and food demand will significantly increase in virtue of the pressure exerted by the growth and mobility of the population, economic development, international trade, urbanization, diversification of diets, cultural and technological changes, and climate change. Due to the close relationship between these challenges, meeting demand will be restricted by competitive needs for limited resources in many parts of the world (UNPAR, 2017; Fernández-Ríos, 2021).

During the last decade, among all sectors, food and, particularly, the European seafood and aquaculture sectors are facing important challenges in terms of environmental threats, social development, or economic growth, that will require the modernization of the pathway followed until today. These issues are forcing societies to take decisions to mitigate its consequences. Consequently, people, enterprises and governments habits and actions must be rethought and adapted. To do it, the international consensus rests on the Sustainable Development Goals (SDG, 2022) as the beacon that marks the route for the coming years with cross-cutting commitment being essential for their achievement. The interaction between climate change and wild fisheries may produce important fish stock migrations from/to colder waters doing fishermen journeys larger and harder (Leitão et al., 2018); the continuous pollution, i.e., marine debris, microplastics, ghost fishing, complicates life under oceans and seas already means a global threat crossing country border (Lusher et al., 2017; Vince and Stoett, 2018).

Stakeholders in productive sectors worldwide are increasingly making use of environmental certification standards, also named eco-labels, to reach consumers, and in the belief that these labels provide an increased value added to their products. In this context, life cycle assessment (LCA) has become a thriving methodology within environmental management to measure the environmental impacts of products and services. However, the former strength of LCA studies can also be interpreted as an important limitation when it comes to communicating the environmental profile of a product beyond the scientific community. Therefore, while the utility of broad LCA studies is evident, stakeholders prefer to make use of single indicators as way of communicating a specific environmental standard to their customers (Vázquez-Rowe, 2016). To overcome this situation, the

Interreg Atlantic Area NEPTUNUS project (EAPA_576/2018)[1] has developed a methodology to perform environmental footprints studies of the seafood products in a harmonized and consistent manner, under a life cycle perspective. The project aims to pursue a new transnational clustering concept approach to review, examine and harness key eco-labelling and key enabling eco-innovations. This add-value and cross-cut sea food-water-energy domains to address barriers and to strengthen these sectors regionally and across jurisdictions in the Atlantic region. NEPTUNUS includes, as a scientific and methodological innovation, the introduction of the Water-Energy-Food NEXUS (WEF) variable in the decision-making process related to the circular economy of seafood, in addition to the typical economic, environmental, and social variables. Such WEF methodology has been implemented in a friendly tool for producers and consumers. In this work, the development, interface, and preliminary results of the developed tool are presented.

Eco-labels and recommendations are created as "abstract systems" of communication, to create trust and security for consumers in production systems that are removed from their daily experience and that are too complex and incomprehensible to communicate in full detail (Roheim et al., 2018). In this sense, eco-labels simplify consumers 'decision-making process and helps them to choose a "green" good or service (Thogersen et al., 2012). The proliferation of sustainable seafood certification has brought new challenges to achieve more sustainable fisheries and aquaculture production as, for example, sustainability criteria are imperfectly measured and open to interpretation (Roheim et al., 2018).

Methods

To be able to build the tool, first the NEPTUNUS consortium created and developed a WEF NEXUS methodology that it is described in the technical report "Methodology of Water, Energy, Carbon and Nutritional Footprint for seafood products", which is available online on the project website. Such technical document includes the guidelines for the calculation of the environmental footprints of seafood products within the European Atlantic Area framework and their integration in the NEXUS Energy-Food-Environment. In this sense, the scope of the guide includes seafood for human consumption from fisheries or aquaculture, which comprises fresh and preserved products with techniques such as refrigeration, freezing, brining, drying, salting, and smoking. The processing of seafood products to produce into canned and similar products is also included within the scope of this guide, provided that the final objective of the processing processes is to obtain products for human consumption. Therefore, this guide excludes the production of fish oil and/or fishmeal for feed production.

NEXUS Eco-label methodology

The NEXUS approach is the selected methodology for the integration of the footprints evaluated in this project (i.e., water, energy, carbon, and nutritional footprints) for each of the species considered. In this context, the term "NEXUS" implies that an action in one of the systems has also consequences on the others and it is for this reason why it is important to understand the synergies and trade-offs to develop response options to ensure a more sustainable environment (Laso et al., 2018). Therefore, the NEXUS index can be useful to develop strategies based on the circular economy approach in search of optimal management patterns that minimises water and energy consumption, as well as GHG emissions, while maximizing their nutrient content.

[1] https://neptunus-project.eu/

The WEF NEXUS calculation comprises the following stages (Benini et al, 2014; He and Gu, 2016):

1. Selection of product environmental footprints: Establishment of representative environmental footprints to be included within the NEXUS eco-label. In this case, the Water Footprint (WF), Energy Footprint (EF), Carbon Footprint (CF) and Nutritional Footprint (NF) were selected to be included.
2. Calculation: The assessment of the different footprints is carried out following the guidelines and procedures detailed in this guide.
3. Normalisation: Normalisation is used to express the indicator data in a way that could be compared among all types of product environmental footprints. Since the spectrum of species, fishing gears and processing analysed within the project are representative for the Atlantic Area, the results obtained in terms of each environmental footprint will be used as a model for linear normalisation, using the maximum and minimum footprint results considering the whole sample evaluated within the NEPTUNUS project (Sousa et al., 2021). In this way, whilst the product with the lowest footprint in terms of WF, EF and CF are assigned a score of 100, the rest of the products decrease the score in proportion, considering as score of 0 the highest footprint. Conversely, since the NF should be as good as possible, the product with the highest value will be assigned the value 100 and 0 will be assigned to the lowest value:
$$WF_{ni} = \frac{WF_{max} - WF_i}{WF_{max} - WF_{min}}$$
$$EF_{ni} = \frac{EF_{max} - EF_i}{EF_{max} - EF_{min}}$$
$$CF_{ni} = \frac{CF_{max} - CF_i}{CF_{max} - CF_{min}}$$
$$NF_{ni} = \frac{NF_i - NF_{min}}{NF_{max} - NF_{min}}$$
Where WF_{ni}, EF_{ni}, CF_{ni}, and NF_{ni} represent the score of the normalised footprints (water, energy, carbon and nutritional, respectively) for the analysed product (i). WF_i, EF_i, CF_i and NF_i represent the individual footprint value for the analysed product. WF_{min}, EF_{min}, CF_{min} and NF_{min} represent the minimum footprint value considering the whole sample evaluated within the project. WF_{max}, EF_{max}, CF_{max} and NF_{max} represent the maximum footprint value considering the whole sample evaluated. So that the final score for each footprint will be 0-100.
4. Weighting: Assign weights to the different types of product environmental footprints based on their perceived importance to emphasize the most important potential impacts with the consideration of design requirements. The resulting multi-criteria value of the NEXUS is obtained as follow
$$NEXUS_i = w_1 \cdot WFn_i + w_2 \cdot EFn_i + w_3 \cdot CFn_i + w_4 \cdot NFn_i$$
where w_1, w_2, w_3, and w_4 are the correlative weights of each indicator.

Results and discussion

The objective behind the development of the ecolabel lies in the importance of communicating the potential and usefulness of establishing a harmonized procedure for indicators of environmental sustainability and nutritional quality of seafood products. In this work, an easy-to-read image that follows a color range is proposed. To ensure market acceptance, it is necessary to consider both consumer understanding and acceptance, as retailers' interest in its application for seafood products. Therefore, the proposed design, shown in Figure 1, represents the nexus score as a percentage from 0% (worst) to 100% (best) along with a color scale that goes from red (worst) to green (best).

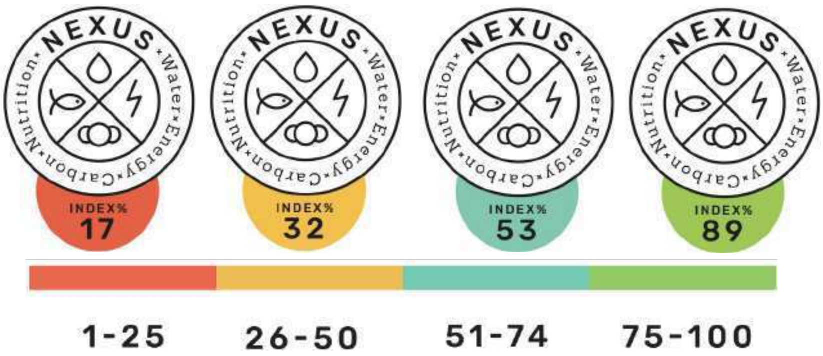

Figure 1. Ecolabel design proposed applied to four hypothetical case studies.

Thanks to this design, consumers will be able to recognize the environmental profile and sustainable commitment of seafood products bearing such a label. In terms of symbols, a drop represents the water footprint, a lightning the energy footprint, a CO_2 molecule the carbon footprint and a fish the nutritional footprint. In addition, the label includes the name of each footprint along with NEXUS.

Conclusions

The Water-Energy-Food (WEF) NEXUS approach has been promoted as a tool for sustainable management of resources through the interconnection of these three fundamental pillars. In this work, a flexible model has been implemented into a user-friendly tool for assisting seafood produced, municipalities, communities, and regions of the Atlantic area to easily obtaining LCA results on seafood production and consumption. Materials and energy inputs have been accounted to determine sustainability from an urban metabolic approach, as well as waste flows were assessed, and therefore, sustainability by means of closing materials flows. A tool and a set of seafood indicators has been developed to identify and measure the hotspots of seafood sector. The species have been selected based on statistical data for catches by Atlantic fishing area and reported production from aquaculture from the same area.

The development of the tool seeks to improve the information for producers and consumers giving them the opportunity to take decisions with a deeper knowledge. To do it, the LCA methodology was applied to European Atlantic fleets, canning and processing plants and aquaculture systems. In addition, the nutritional footprint of the marine products (fresh, smoked, canned, frozen) was also calculated. All inputs and results generated were compiled to contribute to build a solid Life Cycle Inventory database, being part of the software of a widget for public use. The developed tool will easily obtain LCA results on seafood production and consumption. Consequently, both producers (from fishermen to aquaculture and processing plants) and consumers will be able to improve their decisions in their activities and own lives.

Acknowledgements

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Management tool for monitoring the energy requirements of freezing chambers in seafood sector

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Keywords: freezing; energy consumption; life cycle inventory; frozen food; monitoring.

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Introduction

Due to population growth, the current consumption of food is increasing significantly during the last decades. Concretely, for the case of seafood, both wild catches and aquaculture production are increasing during the last years. In fact, it is expected that seafood demand increases in coming years.

Seafood supply chain is very complex in a globalized world, where fishing grounds, processing plants and retailers are far away to each other, so, generally, seafood travels large distances from fishing grounds or production site to consumers. In this context, freezing process and frozen storage facilities play a key role within the supply chain; on the one hand, it assures people's access to a fundamental source of protein, and, on the other hand, it prevents food losses. However, seafood supply chain is high energy intensive. Specifically, frozen storage facilities require a large amount of energy. In this regard, energy consumption of freezing chambers depends on: i) size of the facilities; insulation; climate parameters/weather; fishing campaigns and product rotation based on market fluctuations/demand.

The NEPTUNUS project aims to promote the sustainable development of the seafood sector in the Atlantic area. Hence, in the framework of this project, it is developed a management tool able to predict the energy requirements during frozen storage of food products and to detect the occurrence of any malfunction or inefficiency. The tool is developed to guide facilities managers and other seafood supply chain stakeholders (e.g., researchers, engineers, etc.) on how to predict and monitor the energy consumption of freezing chambers based on several variables: dimension; insulation type and thickness; indoor and outdoor temperature; and stored product and packaging. Likewise, it is useful for LCA practitioners when dealing with life cycle inventory data for freezing stages.

Methodology

The tool is based on the calculation of the energy consumption of the chamber. To obtain it, it is necessary to know, as a preliminary step, its thermal demand, being fully correlated both variables. Therefore, the development of the tool has been divided into two blocks (Figure 1). Block 1, in green, consists in obtaining the thermal demand of the chamber. This demand is highly related to the temperature inside and its variations. Block 2, in orange, allows calculating the energy consumption of the cooling circuit, based on the result of previous block.

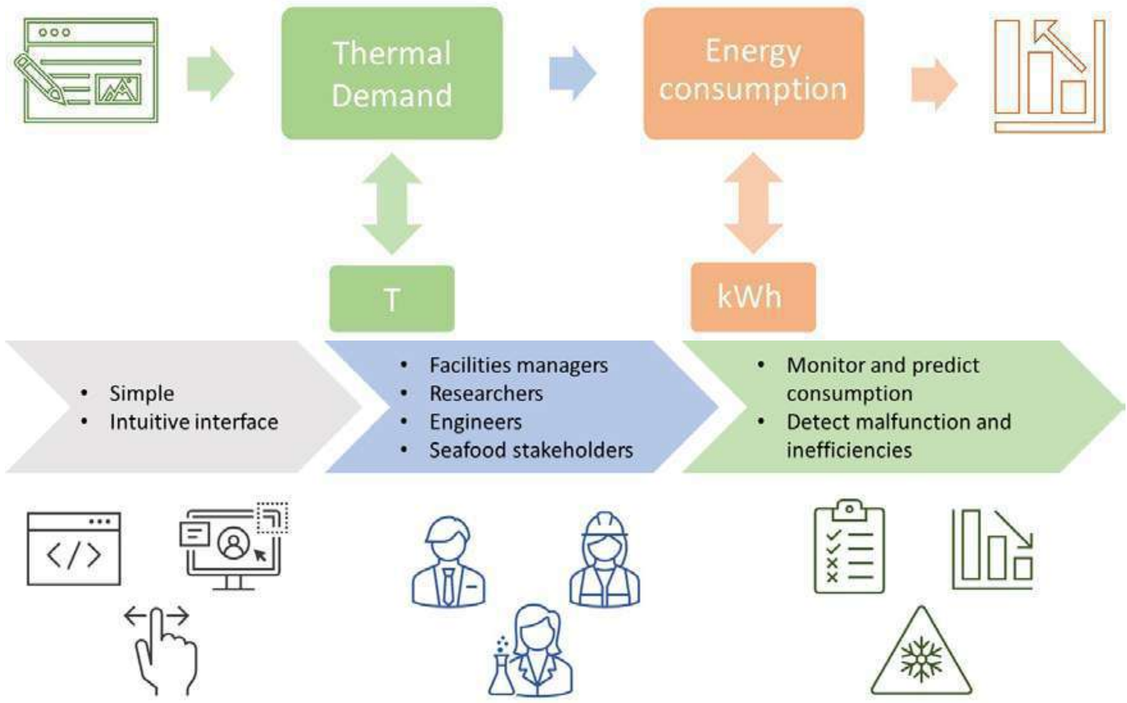

Figure 1. Conceptual framework to develop the tool.

Results

The developed tool allows to obtain either the global energy consumption of the entire circuit or the consumption of each individual unit or component, being able to:

- Detect the malfunction of any of the equipment when identifying large differences between the calculated and real consumption.
- Schedule the maintenance by means of the evolution of the energy consumption of the equipment.
- Predict the energy consumption required for certain operating conditions, for example if a certain amount of product is expected to enter.
- Be used to perform the life cycle inventory of freezing processes.

Life cycle assessment of oyster farming in Portugal

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Keywords: *aquaculture, bivalves, life cycle assessment, oyster production*

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Introduction and objective

Oysters production has increased rapidly in the last years and nowadays represents a relevant portion of the global aquaculture production dominated by China, who accounted for around 83% of global production (FAO, 2021). In Portugal, it represents about 25 % (by volume) of the aquaculture production (INE, 2020). Oysters produced in Portugal are exported to European markets such as France and Belgium, thus not being a 'short-chain typology', which would imply proximity between producers and consumers in order to mitigate environmental impacts.
The aim of this study was to apply life cycle assessment to evaluate the environmental impacts of oysters produced in 4 farms in Portugal (Table 1) and to identify hotspots. Oyster fattening is performed through extensive aquaculture systems, meaning that no feed is added. Carbon sequestration due to oyster shells growth and release due to calcification was also included.

Table 1. Oysters aquaculture farms characteristics.

	Aquaculture farms			
	1	**2**	**3**	**4**
Species	*Crassostrea gigas*	*Crassostrea gigas (90%)* and *Crassostrea angulata (10 %)*	*Crassostrea gigas*	*Ostrea edulis*
Common name	Pacific oyster	Pacific oyster and Portuguese oyster	Pacific oyster	European flat oyster
Spats production	Hatchery	Hatchery (90%) and wild collection (10%)	Hatchery	Wild collection
Spat origin	France	France and Portugal	France	France
Spats weight (g/spat)	0.35	0.21	0.20	0.20
Oyster grow-out period (months)	12	12	14	24
Mortality rate (%)	67	76	15	15
Final oyster weight (g/oyster)	60	65	85	40-150
Average oyster production (t/yr)	40	53	25	200

Material and methods

System boundaries encompass seed hatchery and spat production, transport of juveniles, fattening, and transport of the oysters to depuration in Portugal (farms 2, 3 – 10 % of oysters produced, and farm 4) and France (farm 1 and 3 – 90 % of oysters produced). For farms 1, 2 and 3, the spat oysters are transported from France maternities, while for farm 1 the spats are wild collected in Portugal. In addition, also spats from wild collection if France are transported to farm 4.
The carbon dioxide (CO_2) net sequestration per functional unit (production of 1 kg of fresh oysters (with shell) ready to go to the consumer market) was calculated by the balance between the CO_2 sequestrated via calcification and released during biogenic calcification (CO_2 released). Regarding the oyster's residues, the organic residues due to oyster mortality during grow-out and are left to biodegrade on the water, while the shells end up in a municipal sanitary landfill.
Depuration involves placing the oysters in tanks with water treated by ultraviolet to remove microorganisms accumulated in the oyster. The consumption of oysters and end-of-life were excluded from the system boundaries. The characterisation factors used in this study are those suggested for conducting a Product Environmental Footprint (Zampori and Pant, 2019). The functional unit is the production of 1 t of oyster delivered to depuration facilities in Portugal and France.

Results and conclusions

Results show that the depuration stage is in the case of this production the hotspot for most impact categories, mainly due to the electricity consumed during the depuration operations. Considering the transport of oyster to depuration plants, it was been observed that, when the depuration occurs in Portugal, the total impacts of transportation of oysters to depuration plus depuration operations are up to 20 % lower environmental impacts than in France, being relevant for climate change and resource use impact categories. Therefore, a 'short-chain typology' in farmed oyster production has should be further considered to contribute to the reduction of the total environmental impacts of these systems.
This study show that an environmental assessment of oysters' production should imply that its impacts do not compromise the environment at the local and global levels.

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Environmental assessment of common octopus (*Octopus vulgaris*) from pots and traps fishery in Portugal

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1. Introduction

Octopuses (*Octopodidae*) are muscular animals with four pairs of arms that spawn only once at the end of the life cycle, and live between 1 and 2 years (Sauer et al., 2021). Around twenty octopus species are harvested, but common octopus (*Octopus vulgaris*) is the most relevant (Josupeit, 2008). Typically, octopuses are caught worldwide by both industrial (e.g. trawlers) and small-scale artisanal fleets (Pita et al., 2021). The European market is very important for cephalopods, especially in southern Europe due to dietary traditions and small-scale fisheries activity (ICES, 2018). Common octopus is the species with the highest economic revenue in Portugal (INE, 2021), with Portuguese consumers revealing the second highest octopus per capita consumption in the world (Josupeit, 2008). In 2020, 5,227 tonnes of octopus were caught by the Portuguese fishing fleet, from which 96.4% came from the artisanal polyvalent fleet, 3.3% from industrial trawling and 0.3% from purse-seining (INE, 2021). Portugal is an important market for octopus, with exports mainly to Spain and USA (Pita et al., 2021). The Algarve region, in the south of Portugal, has a specific fleet dedicated to octopus fishery, with landings representing, in 2020, 54% of octopus production in Portugal (INE, 2021). The common octopus is the main species caught with pots and traps accounting for around 90% of octopus landing volume in Algarve (Moreno et al., 2014). In 2019, 358 vessels were licensed in Algarve region for traps or pots (326 trap and 189 pot licenses, as vessels can carry more than one gear), employing 1,501 fishermen (Pita et al., 2021). Small-scale octopus' fishery uses traps made by a metal framed covered with hard plastic netting and pots made by plastic and concrete that are replacing ceramic pots in the last years. Unlike pots, traps are baited with fish. Both traps and pots are deployed in ropes with several hundred units. The loss of gears is very common, as nets with traps and pots are often deployed without signalling and for long periods, making it easier that other gears entangle, and fishers or bad weather break up the lines (Erzini et al., 2008; Loulad et al., 2017). It has been estimated that 52,604 traps were lost in Algarve waters, corresponding to a rate loss of 24% for traps (Erzini et al., 2008). In fact, 50% of the marine debris collected in the southern Atlantic coast of Morocco was plastic, being 94% from lost pots to capture octopus (Loulad et al., 2017).

A wide range of LCA studies on fisheries products have been performed in recent years, yet only one study assessed an octopus fishing with trawling in Mauritania waters, including onboard processing operations to produce frozen octopus products (Ruiz-Salmón et al., 2021; Vázquez-Rowe et al., 2012). Due to the global importance of this resource and diversity of production methods, including different fishing gears and degrees of industrialization, it is of foremost interest to assess small-scale fisheries. The overall aim of the study was to assess environmental impacts of common octopus' fishery with traps and pots in the Algarve by including standard Life Cycle Assessment (LCA) impact categories and fishery-specific impact categories to determine trade-offs and to find if significant differences exist between traps and pots.

2. Methods

The functional unit (FU) selected is 1 kg of octopus and the study is a 'cradle to gate' system, including all inputs and outputs from fishing operations until the product is landed at the harbor. The scope includes: a) inputs as gears' materials (HDPE, concrete, iron, ceramic), bait, fuel, ice, materials needed for vessels' maintenance (paint and zinc); and b) outputs as landings and emissions to the air derived from the combustion of diesel and lubricant oils and emissions to the water derived from the paints, as well as gears lost to the environment. Primary data was obtained by face-to-face questionnaires performed in 22 vessels. The bait used was small pelagic fish species (e.g. sardine, Atlantic chub mackerel) caught by purse seine fishing vessels. The background data for bait and ice production was obtained from a LCA study about purse seine fishery in Portugal from Almeida et al. (2014). Background data for diesel, lubricant oil, gears' materials, paint, and end-of-life (EoL) of gears' materials were obtained from Ecoinvent 3.7.1 database (Moreno et al., 2018).
The average of all inputs and outputs identified was calculated for all vessels sampled, and for vessels using only pots or only traps (*Table 1*). The life cycle impact assessment step was carried out using the ReCiPe 2016 v1.1 in Hierarchist perspective methodology at the midpoint level (Huijbregts et al., 2017). Eight conventional impact categories were selected and analysed according to the type of impacts more frequently applied in seafood LCA studies (Ruiz-Salmón et al., 2021): global warming (GW) and stratospheric ozone depletion (SOD) to establish the impacts on the atmosphere; freshwater eutrophication (FE), marine eutrophication (ME), freshwater ecotoxicity (FET) and marine ecotoxicity (MET) to quantify the impacts on fresh and marine water; and mineral (MRS) and fossil resource scarcity (FRS) to establish a link with minerals used in the gears and fuel consumption. SimaPro v9.2 (PRé Consultants, 2021) was the software used to lead the computational implementation of life cycle inventories. To capture biological impacts not included in conventional LCA impact categories, fisheries-specific impacts categories were applied: 1) stock assessment and management, 2) by-catch and discards, 3) seafloor disturbance, 4) mean trophic level (MTL) based on species trophic level and their proportion in the total catch (Hornborg et al., 2013; Torres et al., 2013), and 5) primary production required (PPR) estimation based in Pauly and Christensen (1995).

Table 1. Inventory data for octopus fishing with pots and traps (average values per FU = 1 kg of octopus for overall vessels (n = 22) and vessels only with pots (n = 6) or with traps (n = 9)).

INPUTS		**Unit**	**Overall**	**Pots**	**Traps**
Fishing gears	Polyethylene from pots and traps	kg	0.025	0.019	0.027
	Concrete from pots	kg	0.027	0.056	-
	Ceramic from pots	kg	0.001	0.011	-
	Iron from traps	kg	0.047	-	0.081
	Polyethylene from ropes	kg	0.054	0.048	0.049
Other materials and fuel	Bait from traps	kg	0.706	-	1.082
	Salt from traps	kg	0.009	-	0.000
	Ice from traps	kg	0.014	-	0.022
	Diesel	litres	0.818	0.406	0.907
	Paint (antifouling type)	litres	0.001	0.001	0.002
	Engine oil	litres	0.008	0.008	0.009
	Hydraulic fluid	litres	0.001	0.001	0.000
	Zinc	kg	0.001	0.002	0.001

OUTPUTS					
Products	Octopus	kg	1.000	1.000	1.000
	Other species	kg	0.043	0.000	0.032
Outputs to the technosphere - Fishing gears to waste treatment	Polyethylene from pots and traps	kg	0.012	0.004	0.019
	Concrete from pots	kg	0.006	0.013	-
	Iron from traps	kg	0.031	-	0.056
	Polyethylene from ropes	kg	0.055	0.054	0.049
Emissions to the environment - Fishing gears lost	Polyethylene from pots and traps	kg	0.012	0.014	0.008
	Concrete from pots	kg	0.021	0.042	-
	Ceramic from pots	kg	0.000	0.004	-
	Iron from traps	kg	0.016	-	0.025
Emissions to the ocean	Zinc	kg	0.001	0.002	0.001
	Paint (antifouling type)	litres	0.000	0.000	0.001
Emissions to the atmosphere	Carbon dioxide	kg	2.182	1.083	2.421
	Methane	g	0.125	0.062	0.139
	Nitrogen oxides	kg	0.027	0.013	0.030
	Carbon monoxide	kg	0.014	0.007	0.015
	NMVOC	kg	0.005	0.003	0.006
	TSP	kg	0.003	0.002	0.004
	Particulates < 10 um	kg	0.003	0.002	0.004
	Ammonia	g	0.005	0.002	0.005
	Sulfur oxides	kg	0.007	0.003	0.008

3. Results and discussion

The environmental impacts in the octopus' fishery for the selected impact categories are shown in *Table 2* with breakdown of results for the main items in the LCI. Fuel contribution to GW was very high (82%) and it is where the highest potential exists to lower down the carbon footprint. The overall fuel use intensity resulted in 0.89 L per kg of octopus and when average data is quantified only for vessels with traps (1.21 L/kg), the fuel use is two times higher compared to vessels with pots (0.50 L/kg). Gears were the most important item related to eutrophication, for the FE the main contribution comes from gears' materials production (51%) and iron from traps represented half of this contribution. On the other hand, for ME the main contribution comes from materials waste, especially from landfilling waste management. The main contribution for FET and MET is zinc. Zinc use was the main contributor to ecotoxicity categories, but no reference was found in other fishery LCA studies, even though it is a common requirement to avoid degradation of vessels related with rust abrasion.

Regarding fishery-specific impacts, cephalopods fisheries are excluded from total allowable catch from Common Fisheries Policy, and there is no formal stock assessment for this species (ICES 2020). In Portugal, the fishery is subject of legislation and management measures consisting of regulations defining a minimum landing weight (750g), as well as the number and type of gears used (maximum of 3000 non-baited pots per vessel of any size; traps limits vary according to the vessel length: 750 traps per vessel under 9 m in length, 1000 traps between 9 and 12 m, and 1250 traps over 12 m; with restrictions on mesh size and traps' dimensions) together with spatial-temporal constraints (Sonderblohm 2015). A by-catch of 4.3% was obtained only for traps, whereas discards were mainly related to undersized individuals. In contrast, pots were entirely selective for octopus. The seafloor disturbance is negligible, and results obtained for MTL and PPR showed that this fishery relies on lower requirements from the marine ecosystem when compared to fisheries that catch species from higher trophic levels (e.g. demersal fish).

The bait used in traps is significant (0.7 kg of bait per FU) and raises further environmental costs related with higher fuel consumption due to daily operations to rebait traps. The use of traps resulted in more than a duplication of impacts for all categories compared to pots, except for FET and MET. Vessels using only traps have higher fuel consumption comparing to vessels using only pots, and therefore carbon footprint of octopus caught with pots is half of the value. However, for 1 kg of octopus more pots were lost than traps, resulting in a higher impact related with plastics pollution to the environment (12 g of plastics per kg of octopus). The carbon footprint obtained was 3.1 kg CO_2 eq per kg of octopus, which is in the level of fisheries of small pelagic fish, like herring and sardine (3.9 kg CO_2 eq/kg) (Gephart et al., 2021). It is less than half compared to octopus caught with trawling (7.7 kg CO2 eq for 1 kg octopus) (Vázquez-Rowe et al., 2012). Furthermore, trawling fishery represent high seafloor disturbances (1,950 m^2 per kg of octopus landed) and higher discards (19.5% of the total catch) (Vázquez-Rowe et al., 2012). Pots and traps are highly selective fishing gears, causing negligible disturbance to the seafloor.

Table 2. Characterization values for FU of global warming (GW), stratospheric ozone depletion (SOD), freshwater (FE) and marine eutrophication (ME), freshwater (FET) and marine ecotoxicity (MET), mineral (MRS) and fossil resource scarcity (FRS) for octopus' fishery with pots and traps ("Others" comprises the rest of the items, including ice, paint, engine oil, hydraulic fluid and zinc).

Impact category	**Unit**	**Overall (Pots & Traps)**						**Pots – Total**	**Traps - Total**
		Total	**Gears production**	**Gears waste**	**Bait**	**Fuel**	**Others**		
GW	kg CO_2 eq	3.09	0.25	0.01	0.26	2.55	0.02	1.49	3.55
SOD	mg CFC11 eq	0.40	0.04	-0.40	0.07	0.67	0.02	0.03	0.53
FE	g P eq	0.12	0.06	0.00	0.01	0.02	0.03	0.07	0.17
ME	mg N eq	40.48	5.31	28.73	0.45	2.38	3.60	21.51	56.14
FET	kg 1,4-DCB	0.22	0.01	0.02	0.00	0.00	0.19	0.42	0.27
MET	kg 1,4-DCB	0.31	0.01	0.03	0.00	0.01	0.27	0.60	0.37
MRS	g Cu eq	4.63	3.19	-0.15	0.09	0.53	0.98	2.11	7.18
FRS	kg oil eq	1.07	0.14	-0.03	0.09	0.85	0.01	0.53	1.22

4. Conclusions

The common octopus' fishery with pots and traps in the Algarve uses few resources apart from fuel, which is the dominant contributor to GW. Zinc together with gears' materials production and waste were the main contributors to eutrophication and toxicity impacts, respectively. The common octopus' stock is not assessed, which enhances uncertainty about the state of the fishing resource on the long term, but management measures exist and could be enforced. Primary production required is not very high, but octopus are considered as carnivores or predators. Nonetheless, a drawback exists with the number of gears lost in the environment and potential rubbish continuously released to marine ecosystems. A problem that could be improved with more surveillance, higher commitment from fishermen to support management measures, and further knowledge about environmental impacts from fishing operations. Even though pots and traps are usually considered as a unique fishing metier by authorities and are often assessed together, they have different environmental impacts, i.e. pots have lower fuel consumption and generate octopus with lower carbon footprint.

The common octopus caught with pots and traps presented a low carbon footprint when compared to other type of seafood products, especially to common octopus caught with trawl. It represents a typical case where the fishing gear is more important than the species when assessing environmental impacts from seafood products.

5. Acknowledgments

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ReFish-to-Food: towards the use of resources from the seafood processing industry as a new source of proteins

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Introduction

Food security could be affected by some factors such as limited access to agricultural land and water, and global warming consequences. Considering the current consumption patterns, it will be difficult to comply with further food demand and security since it is expected to reach 9.8 billion inhabitants in 2050, which leads to almost doubling the global protein requirements (Godfray et al., 2010). Likewise, as a consequence of the COVID-19 pandemic, the agri-food sector must try to reduce the risk of food collapse in major future shocks by means of innovation, ensuring a sustainable food supply. In addition, diets perception is changing towards a balance between nutritional requirements and environmental aspects, considering a circular economy approach. Consumers awareness is increasing and they are moving towards a food supply focused on zero waste in the food production chain.

Proteins are one of the essential nutrients considered in diets and it is imperative to ensure their supply (FAO, 2018). The search of new sustainable protein sources will be one of the key challenges in the next decades, following the Sustainable Development Goals (SDGs) (SDG 12 and 13).

Nowadays, among the different protein sources considered (insects, microalgae, laboratory meat, etc), microbial biomass or Single Cell Protein (SCP) is a promising alternative. This type of protein is produced from heterotrophic and autotrophic organisms and it is considered as a promising substitute for ingredients animals- and plants-based.

In this framework, the project ReFish-to-Food emerges with the challenge of join technological innovation, environmental assessment and food security. For that, a new technology based on the anaerobic digestion and dark fermentation processes will be developed to obtain the SCP using as raw material sub-products from the seafood processing industry. The environmental aspect will be considered assessing the environmental impact of this new process by means of the Life Cycle Assessment (ISO, 2006) methodology. Finally, the substitution of conventional protein sources by SCP and the design of sustainable and nutritional diets will be also addressed.

Methodology

The methodology proposed in the ReFish-to-Food project is composed by 7 work packages focused on: i) seafood effluents characterization and bioC (via anaerobic digestion) and bioH2 (via dark fermentation) obtention as protein precursors (WP2, WP3 and WP4), ii) SCP obtention (WP5) and iii) the environmental assessment of the SCP production via this integrated system and the design of new sustainable diets based on the introduction of this protein (WP6 and WP7) (Figure 1).

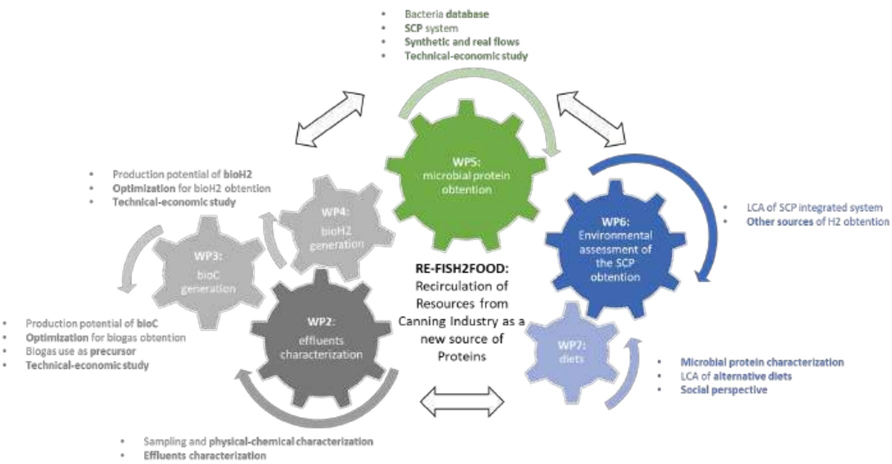

Figure 1. Work packages and main tasks.

Expected results

It is expected that results obtained in the ReFish-to-Food project could improve different aspects:

1. **Technical aspects:** characterizing almost five suitable sub-products from different seafood industries, identifying their physic-chemical characterization and their bioC and bioH2 production potential.
2. **Environmental aspects:** assessing the environmental profile of the SCP production using LCA, focusing on energy consumption, greenhouse gases emissions and land use. Improving the comprehension of negative/positive impacts of different protein sources.
3. **Socio-economic aspects:** making available to the companies a new and more sustainable protein resource to integrate into their current products. Creating new jobs associated to a new business model and consumers dissemination.
4. **Strategic aspect:** demonstrating synergies between a seafood processing industry, which generates sub-products, and a protein marketer company.

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Life cycle assessment of canned tuna products - A comparison of traditional and industrial process.

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INTRODUCTION

The European Atlantic cost of Spain consolidates its position as the most important canning industry in the EU and the second largest producer in the world with a national production of canned fish and seafood of 359.081 tonnes with a value of 1.754.585 million euros during 2020, representing one of the top 5 figures in the world in terms of canned fish and seafood exports. Canned tuna is the main product produced and exported by the processing industry in Spain, where it accounts for 69% of Spanish canned products and more than 67% of EU tuna production (ANFACO-CECOPESCA, 2021). However, there is a big difference in terms of process and industry automation between the 5 large canning companies (located in Galicia, northwestern Spain) and the numerous small and medium-sized canning industries that represent the whole of this important food industry infrastructure.

There are numerous studies that evaluate the processing of fishery and aquaculture products from a life cycle assessment (LCA) perspective, but there are not many that focus on the processing of canned tuna, and there is no reference to any direct comparison between the automated industrial processing of canned tuna versus a traditional and more artisanal processing.

The main objective of this study is to assess the general perception that artisanal processes are more environmentally sustainable and tend to use techniques that have a lower environmental impact than more industrial and mechanized process.

METHODS

In order to evaluate and identify the most important environmental impacts of the processing of canned tuna, the data coming from the production of 2 canning factories during the year 2019, which represents a regular year of work, were used. The company that processes tuna in a traditional and artisanal way is located in Cantabria (northern Spain) and the automated/industrial can processing company manufactures the product in Galicia. The canned tuna is made from two different species: Skipjack/SK (*Katsuwonus pelamis*) for Galician case and bonito tuna/BT (*Thunnus alalunga*) in the Cantabrian, in two different canning formats and with differences in terms of packaging material and quantity of total final product produced (Table 1).

Table 1. Main characteristics of the two tuna processing cases (RO-80/85F.A. & Dingle) under study.

	Industrial processing	Traditional processing
Tuna species	*Katsuwonus pelamis*	*Thunnus alalunga*
Can format	RO-80/85F.A.	Dingle RR-125
Can material	Tinplate	Aluminium
Net weight per can (g)	80	105
Annual can production (units)	80.762.497	15.090
Total raw tuna (tons)	10.500	3,1
Total by-products + losses (%)	60	62
Total output factory production (%)	37	51

The can format used in each case represents the main product of each company. The tuna raw material, as well as the production and transport of other ingredients and packaging materials, were included in the system boundaries. The study has taken into account the specific stage of processing (gate-to-gate approach) and includes from the input of raw materials, fuels and the transport of these materials to the factory and the manufacturing of the products. The upstream stage of extractive fishing and the downstream stages of distribution and consumption of the product have not been taken into account in this study.

Functional unit and inventory analysis

The environmental analysis and assumptions were based following the LCA methodology (ISO 14040) specification. The mass of packaged product ready for dispatch is a functional unit (FU) used by several authors (Ruiz-Salmón et al., 2021); the FU chosen to compare the different processing methods properly, is based on 1 kg of end-product (contains the drained weight of tuna, the sunflower oil and the associated packaging considered for 1kg of end-product), similar to the FU used for a canned mussel tripack (Iribaren et al., 2010) and for an *octavillo* canned anchovy (Laso et al., 2017). In order to perform the comparison between the two inventories in a correct way, the cases under study have been defined in Table 2 and Figure 1.

Table 2. Inventory for 1 kg of final product according to the type of tuna processing.

INPUTS	Industrial Ro-80	Traditional Dingley
Materials (kg)		
Tuna	$5{,}0\cdot10^{-1}$	$5{,}8\cdot10^{-1}$
Tap water	4,7	4,1
Brine solution	$7{,}6\cdot10^{-3}$	$4{,}0\cdot10^{-1}$
Sunflower oil	$2{,}6\cdot10^{-1}$	$2{,}2\cdot10^{-1}$
Diesel	$4{,}2\cdot10^{-2}$	$8{,}8\cdot10^{-2}$
Aluminium	-	$9{,}9\cdot10^{-2}$
Tinplate	$2{,}2\cdot10^{-1}$	-
Folding	$6{,}7\cdot10^{-3}$	$6{,}1\cdot10^{-2}$
Cardboard box	$1{,}8\cdot10^{-2}$	$5{,}0\cdot10^{-2}$
Energy (kWh)		
Electricity	$1{,}2\cdot10^{-1}$	$2{,}2\cdot10^{-3}$
Transport (kgkm)		
Materials by lorry	$1{,}2\cdot10^{+2}$	$3{,}3\cdot10^{+2}$
OUTPUTS		
End-product (kg)	**1**	**1**

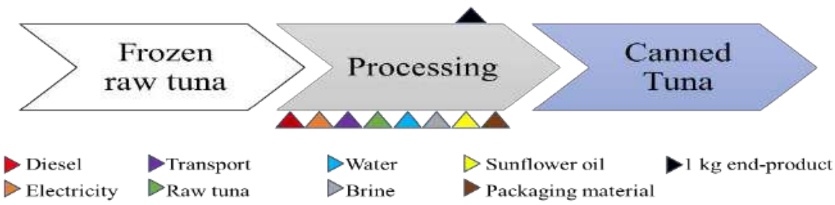


Figure 1. Simplification of the system in a black box diagram used for inventory data analysis.

The SK is cooked whole without defrosting and the tuna pieces are refrigerated prior cleaning to facilitate it; BT is gutted and the head and tail are cut off before cooking. The cleaning processes after cooking are carried out manually for both species, and only the tuna loins and minced tuna pass to the packaging stage. The average processing yield of raw and frozen SK would be 40%, the remaining 60% being losses and discards for category 3 by-products not intended for human consumption (ABPs). In the case of BT, by-products and losses from evisceration, preparation and processing was slightly higher, being 62% of the raw tuna input.

In terms of water use per 1kg of end product, more water is consumed in industrial processing than in artisanal processing, where the industrial processing consumes 9,4 m^3 of water per tonne of tuna processed, while artisanal processing consumes 8,8 m^3. These results are in line with the data provided by IHOBE (1999), which indicated an average volume of water consumed of 9-11 m^3/tonne of processed tuna, where sterilization and cleaning operations can amount more than 50% of the total water consumption.

Energy consumption is higher in the case of industrial processing due to the high level of automation of the whole process. Diesel consumption is associated with the use of boilers for the tuna cooking process, the sterilization of cans and the transport of raw materials. Lower diesel consumption is observed in the industrial process, possibly due to a better optimization of the cooking and sterilization phase. During sterilization, the heat treatment is carried out with steam and involves the highest temperatures of the whole production process (over 115ºC), carried out in overpressure retorts.

In terms of packaging, the RO-80 compared to the dingle format means an 89% reduction of folding and 63% reduction in the cardboard box, given that the RO-80 can is sold in tripack and packed in cardboard boxes that contain up to 40 tripacks (120 cans). The Dingle is individually folded and packed in boxes of up to 24 cans. All packaging material is received by lorries from national and international distributors, more decentralized in the case of the suppliers for Dingle.

To assess the environmental burdens associated with both canning processing, six of the most common impact categories in the LCAs of processed fish and seafood products were analyzed using the CML V3.07 baseline method (Ruiz-Salmón et al, 2021): Abiotic Depletion (ADP) and Abiotic Depletion from Fossil Fuels (ADP-FF), Global Warming Potential (GWP), Photochemical Ozone Creation Potential (POCP), Acidification Potential (AP), Eutrophication Potential (EP), and the impacts directly related to the aquatic environment: Freshwater Water Aquatic Ecotoxicity (FWAE) and Marine Aquatic Ecotoxicity Potential (MAEP).

The software SimaPro 9.0 was used for the computational implementation of the life cycle inventories.

RESULTS AND DISCUSSION

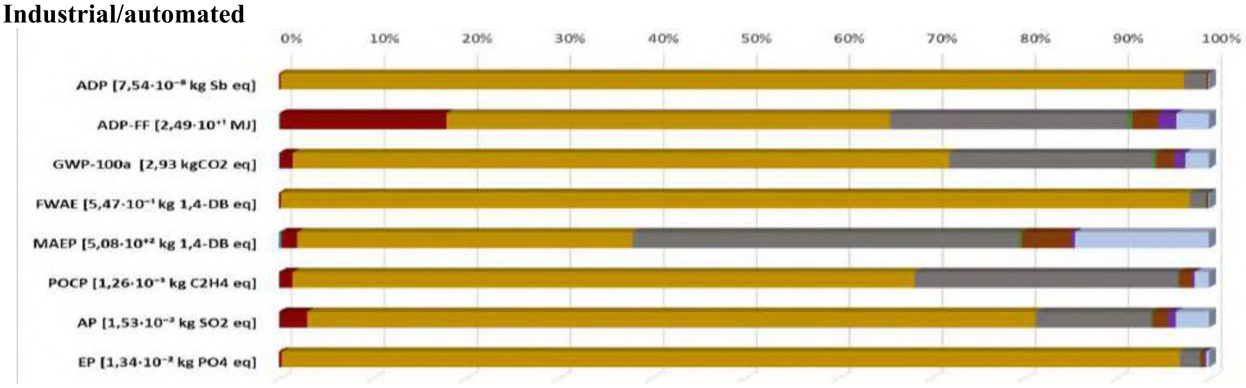
In general, the assessment of the environmental burdens reveals in all cases that the processing of traditional canned tuna provides a higher contribution to the different impacts studied. The results showed that sunflower oil for the covering of canned tuna and packaging materials were the main drawbacks in the environmental profile of canned tuna processing. Thus, sunflower oil governed all impact categories, with the exception of MAEP, which was governed by the can materials, aluminium in traditional process and tinplate in industrial process. The combined contribution of the sunflower oil and the can material accounts for an average of 90-93% of impacts in all impact categories, with a minimum of 72,6% in the ADP-FF and a maximum of 99,3% in ADP in the industrial case, and with a minimum of 76,0% and a maximum of 99,4% in the artisanal case for the same categories.

The GWP is a good processing indicator and widely used for environmental assessment of cannery industry, with a result of 2,9 kg CO_2eq for industrial processing and 8,5 kg CO_2eq for artisanal processing. The comparison of diesel for heat production as a major contributor to the GHG in the GWP (mainly related to the thermal processes of cooking and sterilization), accounting less than 2% of the burden in industrial process and 8% for the traditional, indicates a lower impact on industrial production than the traditional per kg of end-product, probably due to economies of scale.

The results showed that automation on the processing chain in bigger installations resulting in a high annual production rate of canned tuna (with a production 5000 times higher than the artisanal can), seems good to reduce the emissions per kg of processed tuna.

The higher environmental burdens found in traditional tuna canning processes, are influenced in part by the fact that the canning sector has a large family tradition structure and with low or non-optimized processing plants, where minor improvements that can be implemented can achieve a significant reduction in the carbon footprint, as was demonstrated in the project LIFE INDUFOOD (http://www.indufood.org/es/) were use of induction systems reduced the CO_2 emission values close to 20%.

Industrial/automated



Traditional/artisanal

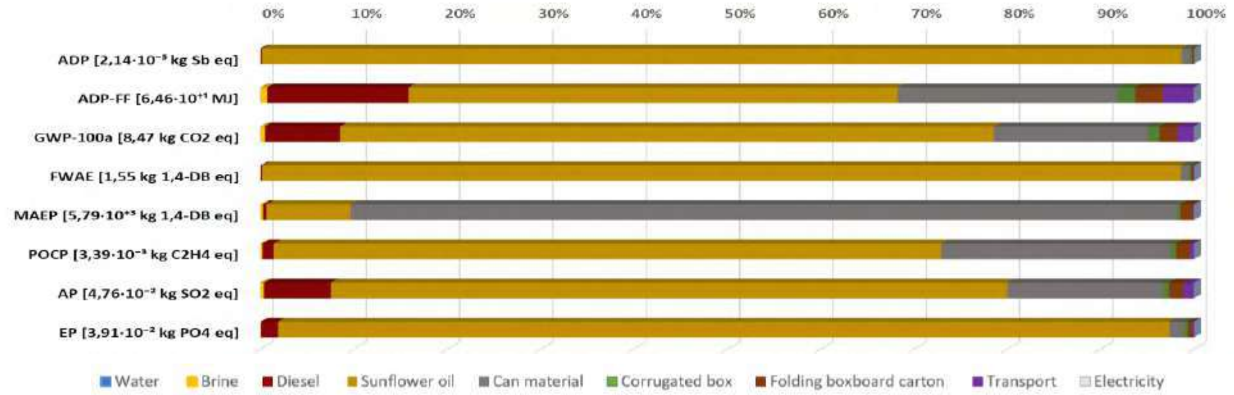


Figure 2. Comparison of the relative contributions for the canned tuna by industrial and traditional processing for 1kg of end-product.

Previous works, such as Hospido et al. (2006) had showed that the processing phase causes the highest contribution of all environmental impact categories (85-95% of the total), whereas Cortés et al. (2021) demonstrated that the multi-product strategy applied to the canning sector is environmentally viable, since the environmental impacts are divided between main products and possible co-products (for instance fishmeal). This could be a strategy for artisanal companies to reduce the carbon footprint of the products, but also, further studies should be done to considered the whole value chain (from the fishing step until de consumer) to validate the results obtained in this study.
Regarding packaging possibilities, previous authors, such as Avadí et al. (2015) suggested to improve the environmental profile of packaging step, using big packaging formats instead typical tripack or no metal packaging. However, the use of plastic materials in the can could significantly compromise the sterilization operations of the product, which are conducted under high temperatures and long processing times. Therefore, to apply this point the quality of the plastic formats should be improved in terms to bear proper sterilization parameters.

CONCLUSSIONS

This study compares from a canned tuna processing stage approach, that artisanal processing contributes in general to a higher environmental burden in all assessed impacts compared than industrial processing. Results showed that the covering liquids of canned tuna (sunflower oil), and the materials of the packaging were the main drawbacks in the environmental profile of canned tuna, independent of the type of processing. The sunflower oil governed all impact categories, with the exception of marine aquatic ecotoxicity governed by can materials in both tuna processing types. The global warming potential comparison reveals lower energy consumption in industrial production than traditional canning process, probably due to economies of scale and a better optimization of the production process, but further studies considering the entire value chain (from sea to fork) should be done to confirm these results.

ACKNOWLEDGEMENTS

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Assessing the environmental impacts of organic vegetable farms using system LCA

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Keywords: *Organic farming; System LCA; Vegetable production; Plastic use; Biodiversity*

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1. Introduction and methods

French organic vegetable farms are diverse with different practices and agronomic approaches. Using the terms proposed by Therond et al. (2017), we can range them from simple *input-based* systems with few vegetables to complex *biodiversity-based* systems, with many vegetables. Beyond this conceptual dichotomy, Pépin et al. (2021) described four farmer types: microfarmers (high crop diversity and a low level of inputs), medium-sized market gardeners (high crop diversity and variable level of inputs), producers specialised in cultivation under shelter (low crop diversity and a high level of inputs), and large market gardeners specialised in open-field cultivation (low crop diversity and moderate input use). The heterogeneity of input use and farming practices, which can be interpreted as sign of bifurcation between "agroecological" and "conventionalised" organic farming (Pépin et al., 2021), may influence environmental impacts, but these have yet to be quantified. Organic farming claims to be environmentally sound, and conventionalisation of organic practices is seen as a threat the identity of organic farming (Darnhofer et al., 2010). Quantifying the environmental impacts of different types of farms will inform the debate on the conventionalisation of organic farming.

Organic vegetable farms, particularly diversified farms, are complex (Aubry et al., 2011), making life cycle assessment (LCA) of such systems challenging. Most often, there is no clear crop rotation, several vegetables can be intercropped, and inputs or operations are not always dedicated to one crop but can benefit many crops in space (e.g. tillage of a field made at the same time for all upcoming vegetables), time (e.g. manure releases nutrients during several years) or both space and time (Goglio et al., 2018). These issues exist in LCAs of other production systems, but they are more pronounced and complex for organic vegetable farms because of the high number of different vegetables that are often grown on a small area (Morel and Leger, 2016). In this perspective, we opted for a system LCA considering the farming system as a whole that produces different products. We assessed the impacts at farm gate, using two functional units (FU) - kg of vegetable, ha of farmland - considering a "farming system approach" where all the inputs and operations are estimated for the whole farm, and the output is the total annual production of vegetables.

We analysed the impacts on cumulative energy demand (CED), climate change (CC), biodiversity and use of plastic on three contrasting farms. Biodiversity is rarely considered in LCA studies (Knudsen et al., 2019) although it is a key environmental issue, particularly in organic farming which claims to enhance biodiversity (European Commission, 2007) and relies more on natural regulations. We adapted the expert system SALCA-Biodiversity (Jeanneret et al., 2014) to vegetable systems to compare the practices and habitats of the farms. SALCA-BD assesses potential impacts of land-use types (including semi-natural habitats) and management practices on terrestrial biodiversity of 11 indicator-species groups. Field-scale impact scores were aggregated at the farm scale. The contribution of each land-use type equalled the land-use type's intrinsic score weighted by the proportion of the farm area it occupied. Thus, a large or small contribution could be due to a high or low intrinsic score, respectively, or to the occupation of a large or small proportion of the farm, respectively, or both.

Plastic pollution is an emerging concern worldwide. The use of plastic in agriculture and the accumulation of microplastic in agricultural soil is a threat to long-term soil quality (Steinmetz et al., 2016). Vegetable crops, including in organic farming, are a major user of plastic, particularly as mulch and tunnels. However, there is no ready-made indicator in current LCA methods to assess plastic and microplastic pollution, which remains a challenging issue. We developed an indicator of plastic use calculated by summing the mass of plastic used per year on the farm.

2. Results and discussion

2.1. Climate change and cumulative energy demand

Environmental impacts of the three farms differed among impact categories and FUs (**Fig. 1**). Per ha of land occupied, OP had the lowest CC impact (1.3 t CO_2 eq./ha) and CED, due to its low input use. Conversely, SP had the highest CC impact (13.3 t CO_2 eq./ha) and CED per ha due to its high input use, which allowed the production of two to three crops per year. MF had an intermediate CC impact (7.5 t CO_2 eq./ha) and CED. This farm had one crop per year in the open field, and two per year in its tunnel. The CC impact of SP per ha was 10.6 times as high as that of OP. Major contributors to CC impact and CED included the use of diesel (MF) and electric (SP) pumps for irrigation, the tunnel structure (MF and SP), the use of plastic water pipes and mulch (SP), and seedling production in heated greenhouses (SP); these inputs were not used by OP. Impacts of tunnels were due mainly to their galvanized steel structure, which was assumed to last 20 years, and plastic covers, which were assumed to last 4-8 years, depending on the farm. Using the same tunnel longer would reduce impacts.

Per kg of vegetables, MF and SP had a similar CC impact (215 and 198 g CO2 eq./kg, respectively), while that of MF was 1.6 times as high as that of OP (134 g CO2 eq./kg). This difference was much smaller than for the CC impact per ha because OP had a lower yield than MF and SP. The higher productivity of SP gave it a similar or slightly lower CC impact per kg despite using more inputs per ha; however, for CED, SP had higher impact than MF. SP used more direct (diesel and electricity) and indirect (plastic and seedlings) energy than MF and OP. Higher productivity per ha did not fully compensate higher CC and CED impacts.

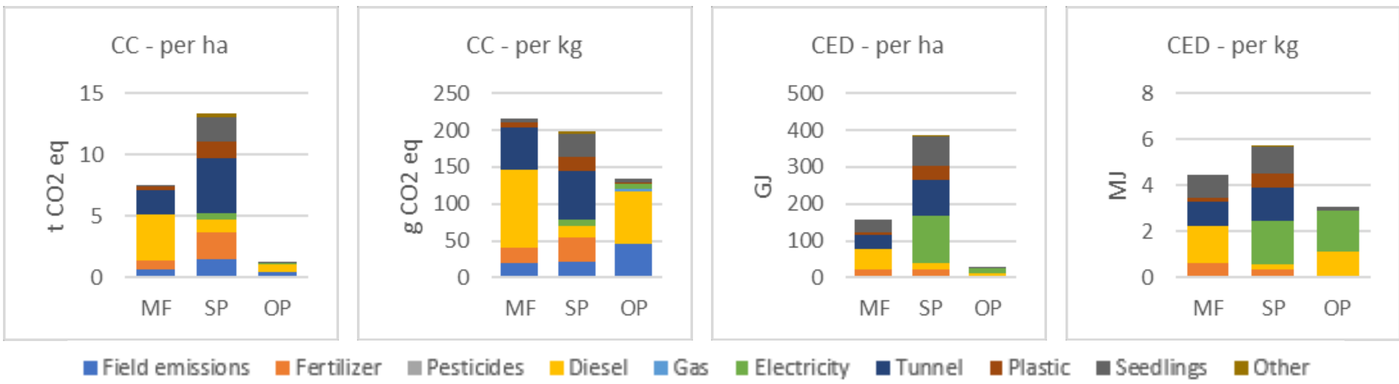

Fig. 1. Impacts per ha of farmland during one year, per kg of vegetables; and contributions of inputs and field emissions for the microfarm (MF), sheltered production farm (SP), and open-field production farm (OP).

2.2.Biodiversity

Assessing biodiversity on the cultivated land alone or on the entire farm gave contrasting results, which highlighted the importance of a farm's semi-natural habitats for biodiversity (Chiron et al., 2010; Jeanneret et al., 2021; Rischen et al., 2021). On SP, the cultivated land yielded a somewhat lower biodiversity score (**Fig. 2**), which was offset by its high share of ruderal area (i.e. spaces between tunnels left to ruderal organisms). On OP, fields were generally surrounded by a ruderal strip or hedge. As its fields were large, its share of semi-natural habitat was lower than that of SP, resulting in a lower biodiversity score at the whole-farm scale. On MF, the cultivated land yielded a biodiversity score similar to those of the other systems. Out of a maximum score of 45 in SALCA-BD for semi-natural habitats such as hedges, biodiversity-friendly managed grasslands and pastures can reach a score of 25 (Lüscher et al., 2017), which was the case for the SP grassland. These scores were far higher than those of the vegetable fields studied here (3-8).

Consequently, for all farms, semi-natural habitats contributed more to the biodiversity score than cultivated land. This result is in line with ecological studies that conclude that semi-natural habitats are important for spiders (e.g. Šálek et al., 2018), carabid beetles (e.g. Knapp and Řezáč, 2015), butterflies (e.g. Dover et al., 2000), birds (e.g. Billeter et al., 2007), and vascular plants (e.g. Billeter et al., 2007). The benefits of small farms for biodiversity are also acknowledged by Ricciardi et al. (2021), since these farms tend to have smaller fields, which have a higher perimeter:area ratio than larger fields. Smaller farms are also more likely to create heterogeneous landscapes.

SALCA-BD considers impacts on biodiversity of land-use type, farmer practices, and elements of farm spatial organisation. Other biodiversity assessment methods (Chaudhary and Brooks, 2018; Knudsen et al., 2017; Koellner and Scholz, 2008; Mueller et al., 2014) quantify impacts on biodiversity based on land-use classes and the distinction between organic and conventional farming. These methods are not adapted for assessing organic farms that have the same land use (arable land) but different farming practices.

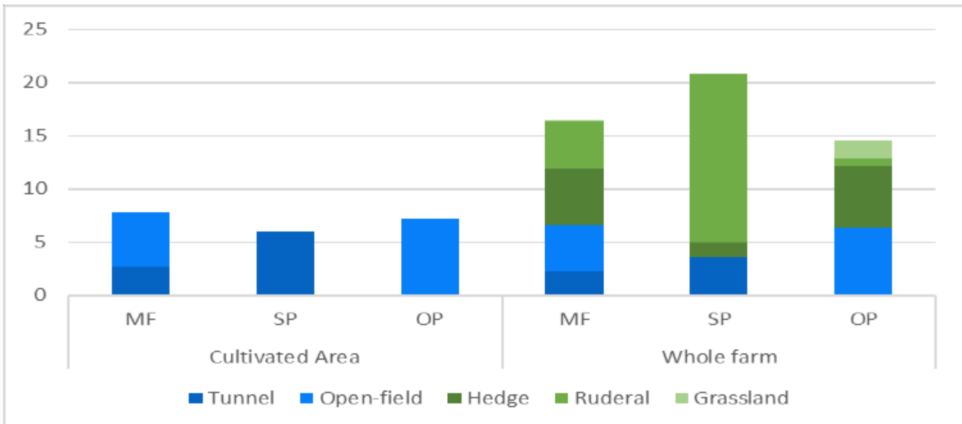

Fig. 2. On-farm biodiversity scores (higher = better for biodiversity) and contributions of land-use types for the three farms (microfarm (MF), sheltered production (SP), and open-field production (OP)) for cultivated land (blue bars) and semi-natural habitats (green bars).

2.3.Plastic use

OP used very little plastic (2 kg/ha; 0.2 kg/t of vegetables) (**Fig. 3**). SP used the most plastic (1129 kg/ha; 16.8 kg/t of vegetables), particularly to cover its tunnels. MF (299 kg/ha; 8.5 kg/t of vegetables) also covered its tunnels, but used less plastic, for two reasons: 1) only some of the cultivated land was under shelter, whereas all was under shelter on SP, and 2) the plastic lifetime was 8 years for MF and 4 for SP. The smaller tunnel area of MF allowed the farmer to repair plastic when damaged. SP also used more plastic for mulching than MF and OP. On SP, all crops were mulched with single-use plastic, whereas on MF, straw mulch, manual weed control, and reusable plastic mulch were combined.

Plastic use is not an LCA indicator, and to our knowledge it has not been included before in an environmental assessment of vegetable production. In our study, it revealed major differences among systems. Plastic use in agriculture is a growing concern (United Nations Environment Programme, 2021). Plastic mulch is a major source of microplastics (Bläsing and Amelung, 2018; Campanale et al., 2022) as it is thin and hard to remove from the soil (Qi et al., 2020). Microplastics may have detrimental effects on plant growth (Liu et al., 2021), soil properties (Zhang et al., 2020), and the fitness of soil bacteria and earthworms (Jiang et al., 2020), and can be found in fruit and vegetables at worrying concentrations (Oliveri Conti et al., 2020). An alternative to single-use plastic mulch is biodegradable plastic mulch, which is a common substitution approach (Hill and MacRae, 1995). Its benefits remain uncertain, as some studies conclude that it has no noxious effects on soil organisms (Sforzini et al., 2016), while others state that single-use and biodegradable plastic mulch have the same effects on earthworms (Ding et al., 2021; Kumar et al., 2020).

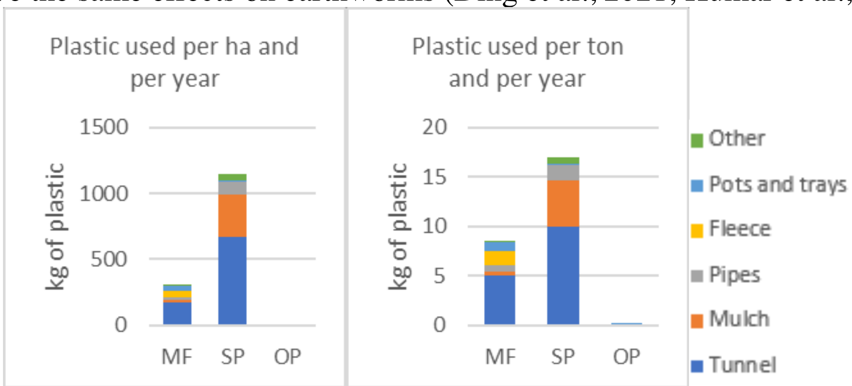

Fig. 3. On-farm plastic use per ha of farmland, per t of vegetables, and contributions of plastic uses for the three farms: microfarm (MF), sheltered production (SP), and open-field production (OP).

3. Conclusion

Farming-system LCA allowed the environmental assessment of farms with different practices and agronomic approaches, including complex systems with a wide variety of crops grown on small areas. It followed the rationale of agroecology, in which inputs are farm-oriented rather than crop-oriented. Considering the different impacts and FUs, a clear ranking of the farms did not emerge. Per ha, differences in the CC impact and CED among the systems were large. SP had the highest impacts, whereas OP had the lowest impacts, which correlated with the intensity of input use. Per kg, differences in the CC impact and CED among the systems were much smaller. OP had a lower CC impact and CED per kg. OP used much less plastic but had a lower biodiversity score and total yield than MF and SP (75% and 90% lower, respectively), which required more land to produce the same quantity of vegetables. Despite its high total yield, SP did not perform well for CC impact, CED, or plastic use per kg. The impact on on-farm biodiversity, which highlighted the importance of semi-natural habitats, contrasted with the other impacts. The quantification of plastic use echoes growing concerns about (micro-)plastic pollution in agricultural soils and landscapes.

Microfarming is often promoted as a solution to produce food with lower environmental impacts, but in this case study this benefit is not obvious. However, microfarms may be a good compromise by having higher yields than large open-field farms and lower impacts per ha than sheltered production farms.

Although we selected farms that were typical of three farming systems, their potential farm-specific effects cannot be ignored. Farming-system LCA required a relatively moderate amount of data, and allowed to compare contrasting farming systems and identify hotspots within them.

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Water-related energy consumption and associated greenhouse gas footprint of the vegetable supply chain in Australia

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1. Introduction:

Water-related energy can be defined as energy use that changes with the extent of water use (Kenway et al., 2019). While water-related energy and associated greenhouse gas (GHG) emissions in agricultural production due to irrigation are well recognized, less is known about the extent of water-related energy and GHG emission for the downstream components of food systems, in processes such as fresh produce processing, storage, and preparation (Islam et al., 2021). Understanding the nature and scale of energy use influenced by the water use over the full life cycle is important for eco-efficiency programs for the vegetable food system. With the current interest in achieving net-zero GHG emissions, information about where to direct eco-efficiency efforts is needed to avoid duplication and cost savings. Therefore, the objective of this work is to assess the water-related energy of the food system, and how such energy use influences the GHG emission.

2. Methodology:

The goal of the LCA study was to quantify the water use, energy use, and GHG emission of vegetables over their life cycle, and then identify specifically the water-related energy component. As a representation of the Australian food system, this research modeled fresh vegetable production in Queensland (QLD). The home consumption was modeled in Southeast Queensland (SEQ) consisting of Brisbane City, Gold Coast, Moreton Bay Region, Logan City, Sunshine Coast, Ipswich, Redland City, Toowoomba, Noosa, Scenic Rim, Somerset, and Lockyer Valley. In total, 30 types of fresh vegetables were evaluated for a field to plate system boundary. Processes included were growing, storage, processing, packaging, retail, home transport, home preparation, home consumption (waste generation), and waste transport and management. Inputs to all these processes were accounted for (fertilizers, pesticides, fuels, plastics, disinfectants, electricity, water, etc.). The functional unit (FU) was 1 kg of fresh vegetable produced in QLD and consumed by an average SEQ household. The life cycle environmental impacts were estimated using SimaPro software 9.1.1.1 (PRé Sustainability, 2020), based on the Australian Life Cycle Assessment Society (ALCAS) Best Practice Guide for Life Cycle Impact Assessment (LCIA) in Australia V 2.04 (Renouf et al., 2018). Impact categories included were Climate change (kg CO_{2eq}), Resource depletion –fossil fuels (MJ) as an indication of primary energy demand, and Consumptive water use (L_{eq}), which derived by multiplying water use with water stress factors.

3. Results and discussion:

Life cycle water-related energy as shown in Figure 1 includes energy used for irrigation, washing during the process and in the household, and cooking. Life cycle water-related energy use ranges from around 15% to 40% for different studied vegetables, in comparison with the supply chain fuel use (diesel use for transport and tractor) (~10% to 30%), agrochemicals (~5% to 15%), and packaging materials (~1% to 30%) (Figure 1). Similarly, life cycle GHG emissions from water-related energy use ranged from around 12% to 35% for different studied vegetables, in comparison with the agrochemicals (~5% to 35%), supply chain fuel use (diesel use for transport and tractor) (~2% to 26%), and packaging materials (~1% to 15%). This indicates the importance of directing the eco-efficiency programs towards energy saving through water management along with other ongoing focuses, such as fertilizer application, transport, and packaging efficiency improvement.

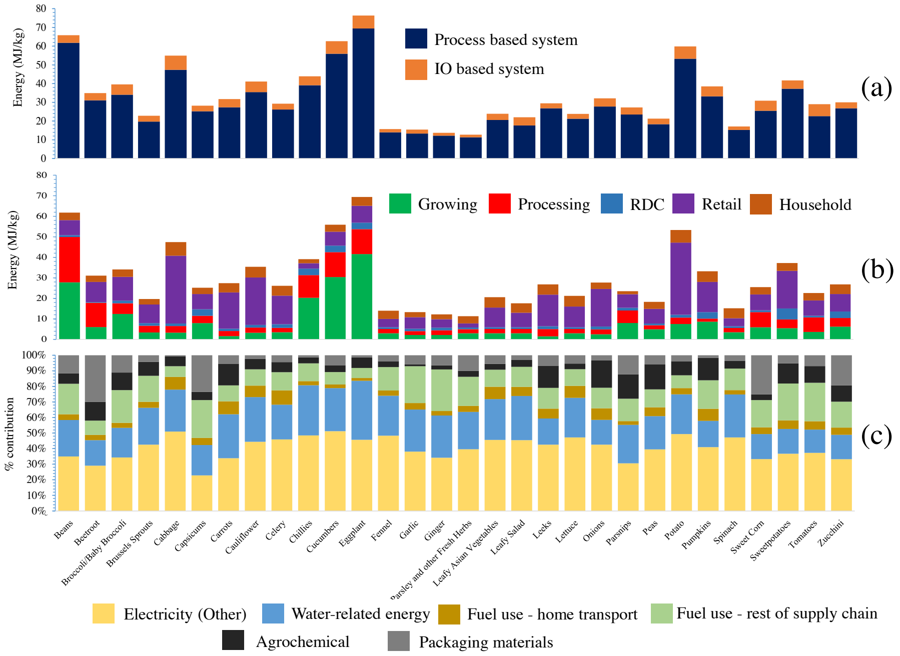

Figure 1: Life cycle (field to plate) energy used for vegetables produced in QLD and consumed in SEQ (MJ/kg), disaggregated by (a) supply process versus wider economy aspects, (b) life cycle stages, and (c) resources inputs.

4. Conclusion:

This study investigated water, energy, and GHG emissions of city vegetable food systems considering field to plate system boundary. It considered 30 fresh produce vegetables grown in QLD and consumed in SEQ. The life cycle water-related energy use of the studied vegetable system ranged from around 15% to 40% for different studied vegetables, compared to the GHG emissions from water-related energy use of 12% to 35%. This indicates the importance of increasing the efficiency measures for water-saving, which will also reduce the energy and GHG footprint. Through scenario analysis, it was observed that water use efficiency increase (5-30%) in the studied vegetable system can reduce the life cycle water-related energy use by ~2-21%, and associated GHG emissions by ~2-20%. Therefore, a holistic assessment of the impact of water use efficiency along with other measures, such as low-carbon electricity mix, process optimization through waste reduction, and energy efficiency can be explored for a climate-friendly and sustainable vegetable food system for cities.

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Conventional Agriculture, Greenhouses, and Hydroponics: An LCA of Lettuce

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Abstract

The life cycle nutrient, energy, land and water impacts of US conventional, greenhouse, and hydroponic lettuce production are compared in a cradle-to-gate analysis. The inventory includes the pesticide and fertilizer use, and the energy and water requirements for lettuce cultivation. Even with cross-continental transportation, energy requirements and greenhouse gas emissions for conventional open field cultivation are substantially lower than those for standard greenhouse and hydroponic cultivation. Conversely, water consumption and pesticide and fertilizer use are higher for conventional open field production than for greenhouse or hydroponic cultivation. Land use for conventional and greenhouse cultivation may be similar, whereas hydroponics is more space efficient than conventional agriculture.

Introduction

There has been considerable recent interest in the potential for local sustainable agriculture through hydroponics techniques (Chen et al., 2020; Delaide et al., 2016; Suhl et al., 2016; Korner et al., 2021; Kulak et al., 2013; Barbosa et al., 2015; Bartzas et al., 2015; Chen et al., 2020; Romero-Gamez et al., 2014; Stoessel et al., 2012; Romeo et al., 2018; Martin and Molin, 2019; Van Ginkel et al., 2017; Dorr et al., 2021). Previous work has indicated that conventional agriculture may have lower environmental impacts than local agriculture using greenhouses or hydroponics, and Weber et al. (2008) have shown that transportation has a small impact on the environmental impact of food over several categories. Goldstein et al. (2016) also find that reducing food miles does not lead to more efficient supply-chains or reduced environmental impacts; the potential for symbiosis between farm and urban environment may be overstated; and that urban agriculture (UA) does not provide reductions in land use and carbon sequestration. McDougall et al. (2019) document high inputs for local UA. Nevertheless, besides new technological fixes, other actions such as increasing seasonal and local consumption, reducing animal product consumption, and better management of food waste can have positive and significant environmental impacts (Saxe, 2014; Tilman and Clark, 2014; Heller and Keoleian, 2015; Eshel et al., 2014). This underscores that the choice of environmental metrics for comparing UA to conventional agriculture influences the results. Rothwell et al. (2016) say that the "examination of a wider range of regionally specific environmental impacts should be considered with any environmental claims on local food". Stoessel et al. (2012) recommend paying attention to impacts other than carbon footprint to prevent 'problem shifting'. Here, we examine the lifecycle environmental impacts of lettuce production, addressing land use, water, energy, nutrients, and pesticide use for greenhouse, hydroponics, and conventional farming. This extends previous work by providing more complete data on pesticide use and the relative environmental impacts of different remote versus local agricultural practices.

Material and Methods

The objective of this study is to compare the environmental impacts of different agricultural methods of growing lettuce and highlight hotspots for improvement. Therefore, we develop a life cycle inventory including energy, water, nutrients, pesticides, carbon dioxide (CO_2), nitrous oxide (N_2O), nitrogen oxides, ammonia (NH_3), and particulates. We assess the impacts using ReCipe impact assessment methods (Huijbregts et al, 2017).

The system boundary is a cradle-to-gate analysis, with the aim of providing a comprehensive approach to calculate the environmental and human health impacts of agriculture. For the cultivation of 1 kg of the conventional, greenhouse, and hydroponic vegetables, we include production and utilization of electricity, pesticides, nutrient and provision of water, energy use in the operation of production and harvesting for conventional farm production, greenhouse production, and hydroponics production. We include post-harvest transportation at a continental and regional scale to market. Excluded from the system boundary are the post-transportation retail sale of the vegetables, residential or commercial preservation, preparation, consumption, and end-of-life. In this case study, regional or local lettuce production is assumed to be in the state of Georgia and long distance is lettuce cultivated in California and Arizona.

For the LCI, we use national United States Department of Agriculture (USDA) data of pesticide and fertilizer use, and energy and water requirements for conventional vegetable cultivation. We use data from Stoessel et al (2012), and Ecoinvent 3.7 for greenhouse lettuce cultivation. And, finally, we use vertical farming in modified hydroponic shipping container as a case study for the hydroponics cultivation. Yield, energy, and water consumption data for the hydroponics lettuce are from a commercial hydroponics farming company's website and reports (Freight Farms 2019, and Freight Farms 2020). For fertilizer use in hydroponic farming, we use lettuce fertilizer use rates from Brechner et. al (1996), Romeo et. al. (2018), Martin and Molin (2019), and Chen et. al (2020). For the LCIA, the impact categories considered are energy use, climate change, land use, freshwater use, particulate matter formation, acidification, ecotoxocity, eutrophication, and ozone formation.

Results and Discussion

Figures 1, 2, and 3 show the results of the LCI analysis. Figures 1 and 3 show that even with cross-continental transportation, energy requirements and greenhouse gas emissions for conventional open field cultivation (2.5 MJ/kg, 0.9 kg CO_2e/kg) are substantially lower than those for the greenhouse (47.6 MJ/kg, 4.8 kg CO_2e/kg) and hydroponic cultivation (142 MJ/kg, 8.5 kg CO_2e/kg). Conversely, figures 1 and 2 show that water consumption and pesticide and fertilizer use are higher for conventional open-field production (165±15 L/kg, Pesticides 0.6 g/kg, Nitrogen 5.5 g/kg, Potassium 1.7 g/kg, and Phosphorus 3.8 g/kg) than for greenhouse (16 L/kg, Pesticides 0.06 g/kg, Nitrogen 1.6 g/kg, Phosphorus 0.5 g/kg, Potassium 2.4 g/kg) or hydroponic cultivation (Water 1.8 L/kg, Pesticides 0 g/kg, Nitrogen 1.6 g/kg, Phosphorus 1.9 g/kg, Potassium 2.2 g/kg). Land use for conventional and greenhouse cultivation may be similar, whereas hydroponics is more space-efficient (0.008 m2/kg) than conventional agriculture (0.22 m2/kg).

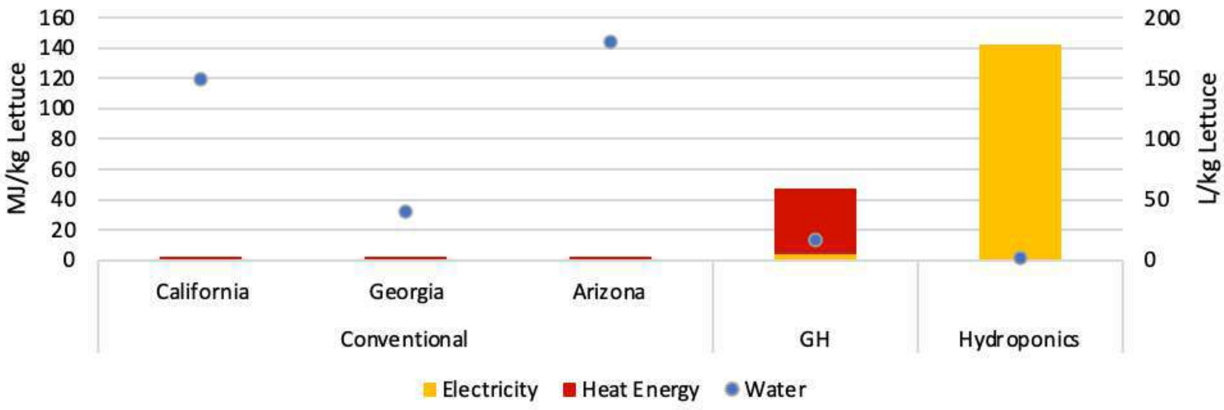

Figure 1. Comparison of energy use and water use per kg of lettuce for each method

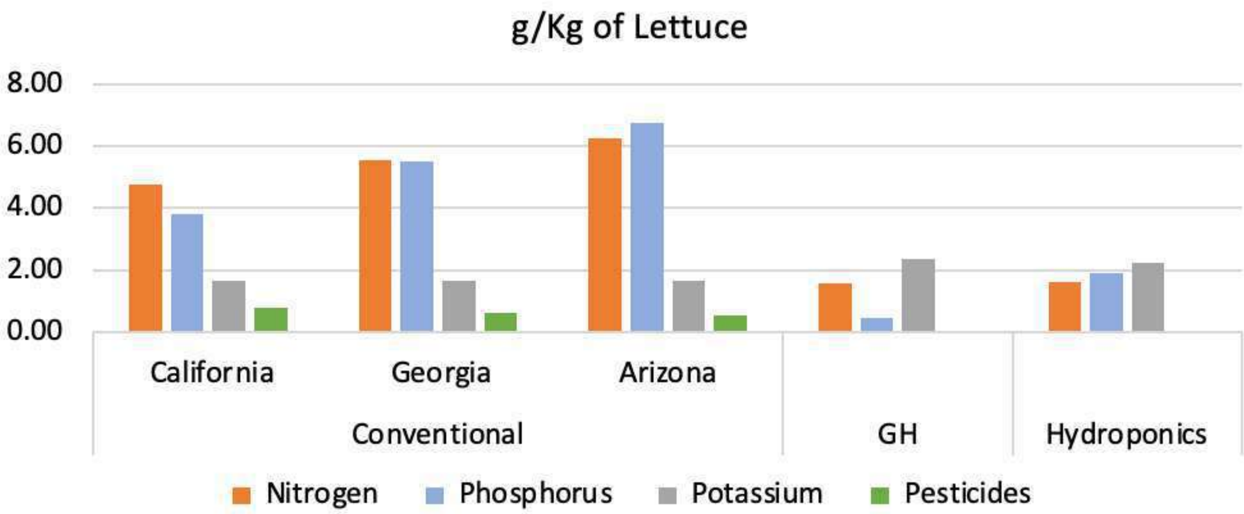

Figure 2. Comparison of nutrients and pesticides intake by each of the methods

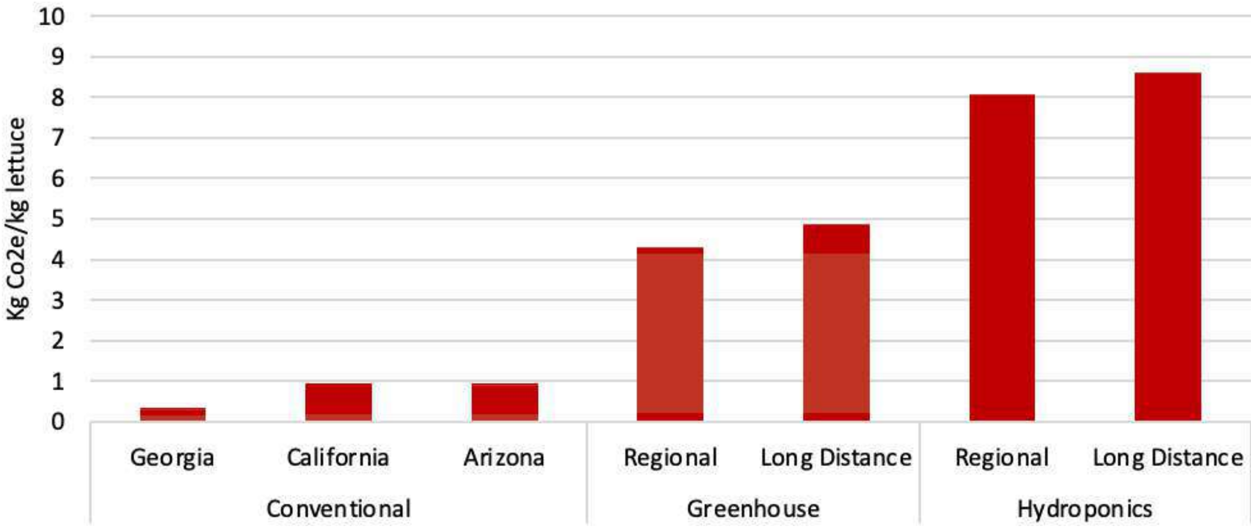

Figure 3. Comparison of CO_2e emissions per kg of lettuce by each method

Using ReCipe for impact assessment, Figure 4 shows that fine particulate matter is the dominant contributor to the human health impacts and that the impact is greater for conventional farming than for greenhouse or hydroponic cultivation. Greenhouse and hydroponic cultivation have similar human health impacts. Figure 5 shows that conventional cultivation has greater impacts on species due to land use, terrestrial acidification, freshwater eutrophication, and ecotoxicity, yet overall, conventional farming has a lower impact on species compared to greenhouse and hydroponic cultivation, due to their higher energy use and resultant greenhouse gas emissions. Global warming impact on terrestrial ecosystems is the main impact of greenhouse farming and hydroponics on species which can be tied back to their high use of energy.

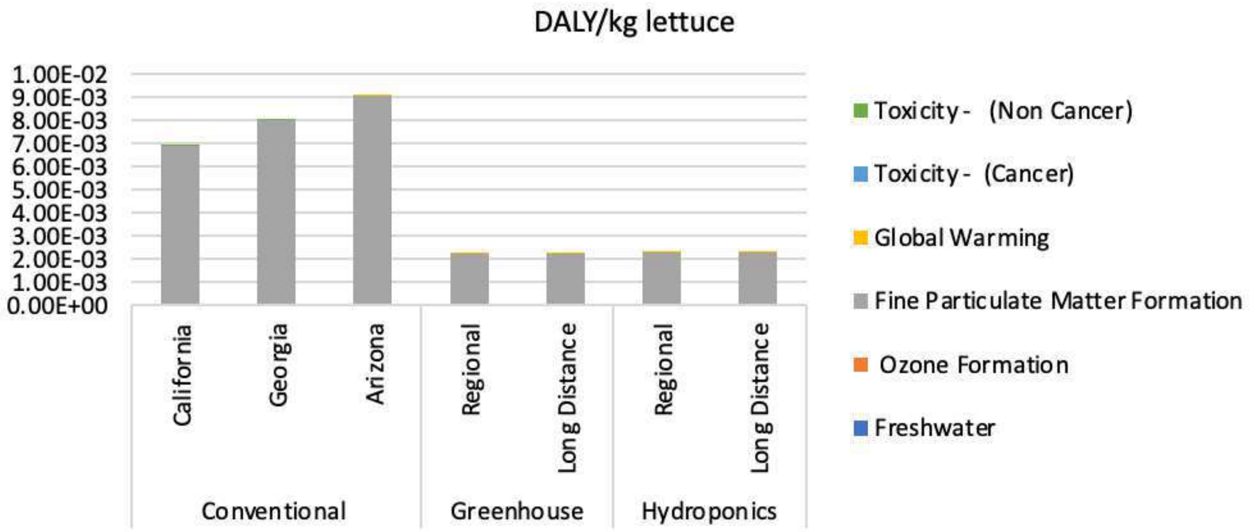

Figure 4. Comparison of the life cycle impacts on human health for each method

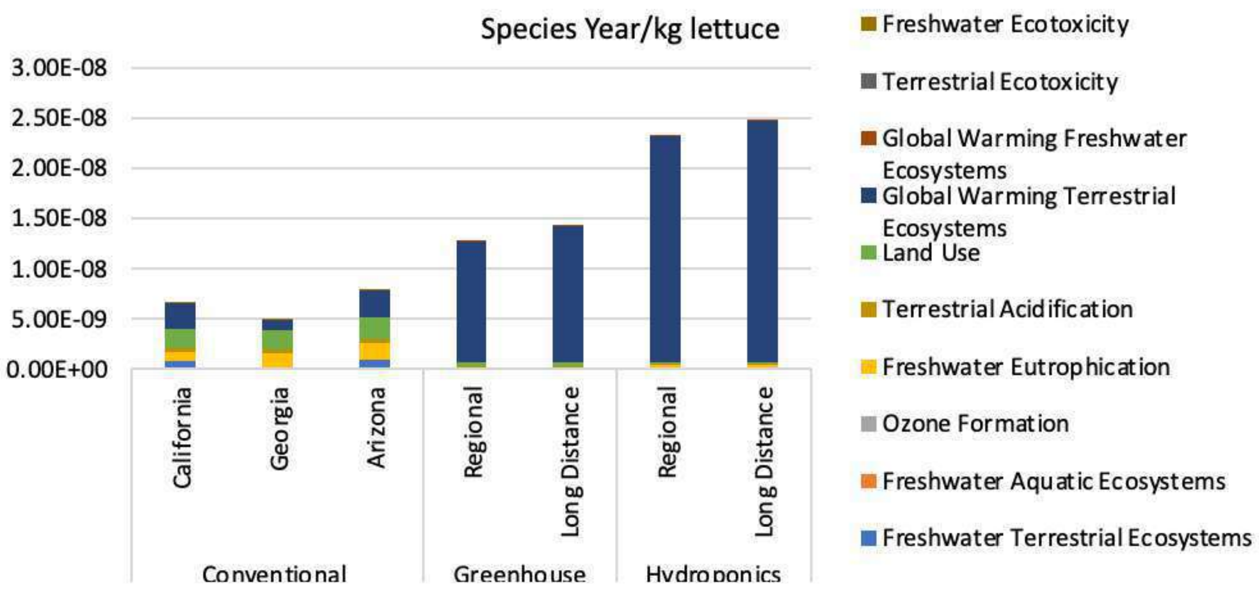

Figure 5. Comparison of the life cycle impacts on species for each method

Conclusion and Discussion

Open-field production and distribution of lettuce in the United States uses far less energy than standard hydroponic production, even with trans-continental transportation. Hydroponic farming and greenhouse farming have the potential to be more efficient of land and water. Lettuce and other vegetables generally have much lower environmental impacts than meat and dairy products (Weber et al., 2008). However for the greenhouse and hydroponics methods assessed here, the climate impacts of vegetables may approach those of meat, eggs and dairy products (Eshel et al., 2014). Lower human health and environmental impacts of lettuce cultivation may be achieved by reducing electricity, transportation, and water use, as well as by the choice and management of pesticides and fertilizers. There may be potential for much greater energy efficiency in hydroponics and greenhouse farming.

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Evaluating the Environmental Impacts of Growing Avocados in New Zealand

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Objective

The avocado sector in New Zealand is growing rapidly, driven particularly by demand in overseas markets. To facilitate continuous improvement in the environmental profile of the New Zealand avocado supply chain, an environmental Life Cycle Assessment (LCA) of conventional avocado production was undertaken, focusing on four impact categories – climate change, eutrophication, water use, and ecotoxicity (freshwater and terrestrial).

Methodology

The study took a 'cradle-to-orchard gate' approach (excluding the nursery stage). Using disproportionate stratified sampling for subgroups (based on region, size, and performance), data were collected for 53 orchards in New Zealand's three main avocado growing regions: the Bay of Plenty, the Mid North and the Far North[1]. This sample represents 19% of the New Zealand avocado sector. The sample was divided into 'Tier 1' and 'Tier 2' orchards using a scoring system developed to reflect the overall quality of the collected data for each orchard. Input data included fertiliser, water, electricity, agrichemical, and fuel use. Each orchard was modelled for 1kg of Hass avocados, guided by the relevant ISO standards ISO (2006a), ISO (2006b), and the associated guidelines (EC-JRC-EIS, 2010a; and EC-JRC-IES, 2010b), as well as the International Environmental Product Development (EPD) System's Product Category Rules (PCRs) for fruits and nuts (EPD International, 2019). Climate change and eutrophication impacts were calculated using the CML 2001 method. Water use impacts were calculated using the Water Use in Life Cycle Assessment (WULCA's) AWARE method (using the aggregated characterisation factor for New Zealand). USEtox 2.12 was used for freshwater ecotoxicity and both recommended and interim characterisation factors were used as advised (USEtox, 2022)[2]. Since USEtox only assesses freshwater ecotoxicity, ReCiPe 2016 (V1.1) (H) was used for terrestrial ecotoxicity impacts as this method includes emission flows for most of the pesticides used on avocado orchards. Ranges, averages, and production-based weighted averages in each region, for the Tier 1 and 2 orchards separately, were calculated for each impact category. The weighted average impact values for both tiers were weighted again against total production of the sampled orchards in each region to provide regional weighted average values for each impact category.

LCA Inventory Analysis and Modelling

The main agrichemicals used in avocado growing in New Zealand are fungicides (mostly copper-based), insecticides (including miticides), mineral oil, herbicides (mainly glyphosate and glufosinate), and a plant growth regulator. All conventional avocado production in New Zealand also involves the use of synthetic (mineral) fertilisers (straight, blended, and complex), organic and

[1] Of these, four recently established supra-massive orchards were excluded from the baseline model, since their low productivity resulted in unusually high impact values when using a mass-based functional unit.
[2] USEtox provides a distinction between 'recommended' and 'interim' characterisation factors, based mainly on the applicability to respective substances or the availability/quality/reliability of input data. However, USEtox (2022) recommends that ideally, both should be included

natural fertilisers like kelp, and in small quantities, compost. Most of the products are straight/simple fertilisers, but a few blended and complex fertiliser products are also used frequently. Based on informal consultations with industry members, all agrichemical and fertiliser products were modelled for transport from Germany (except a few like lime and urea, and gypsum which was imported from South Australia). Application impacts of insecticides, herbicides, fungicides, and mineral oil were modelled as 100% of their respective Active Ingredients (AIs) being emitted to agricultural soil. Fertilisers were modelled for emissions of direct and indirect N_2O, NO_x, NO_3^- (leaching), NH_3, P_2O_5, P, and CO_2). Emission factors for all of the listed emissions (except CO_2) were obtained from EPD International (2019). The MfE (2020) guide was used for CO_2 emissions from urea and lime. The New Zealand electricity grid mix was used to model electricity use on orchard. Electricity use data on orchard was obtained from the growers and was mainly used by pumps for extracting groundwater. In addition, water use data was classified by source (groundwater, town supply, etc.), and electricity use was modelled for water purification when town water supply was used. Fuel use predominantly comprised diesel and petrol, and was mainly attributed to activities like mowing, spraying pesticides and fertilisers, pruning, chipping, mulching, harvesting, shelter belt trimming, and diesel-powered bore pumps on irrigated orchards. Overall fuel use was modelled as not all growers had data readily available for fuel use disaggregated by activity. Data related to the manufacturing of production equipment, building, and capital goods were not included in this analysis.

Results and Discussion

For each impact category, the Life Cycle Impact Assessment (LCIA) values for Tier 1 and 2 orchards and the regional averages are presented in Figure 1[3].

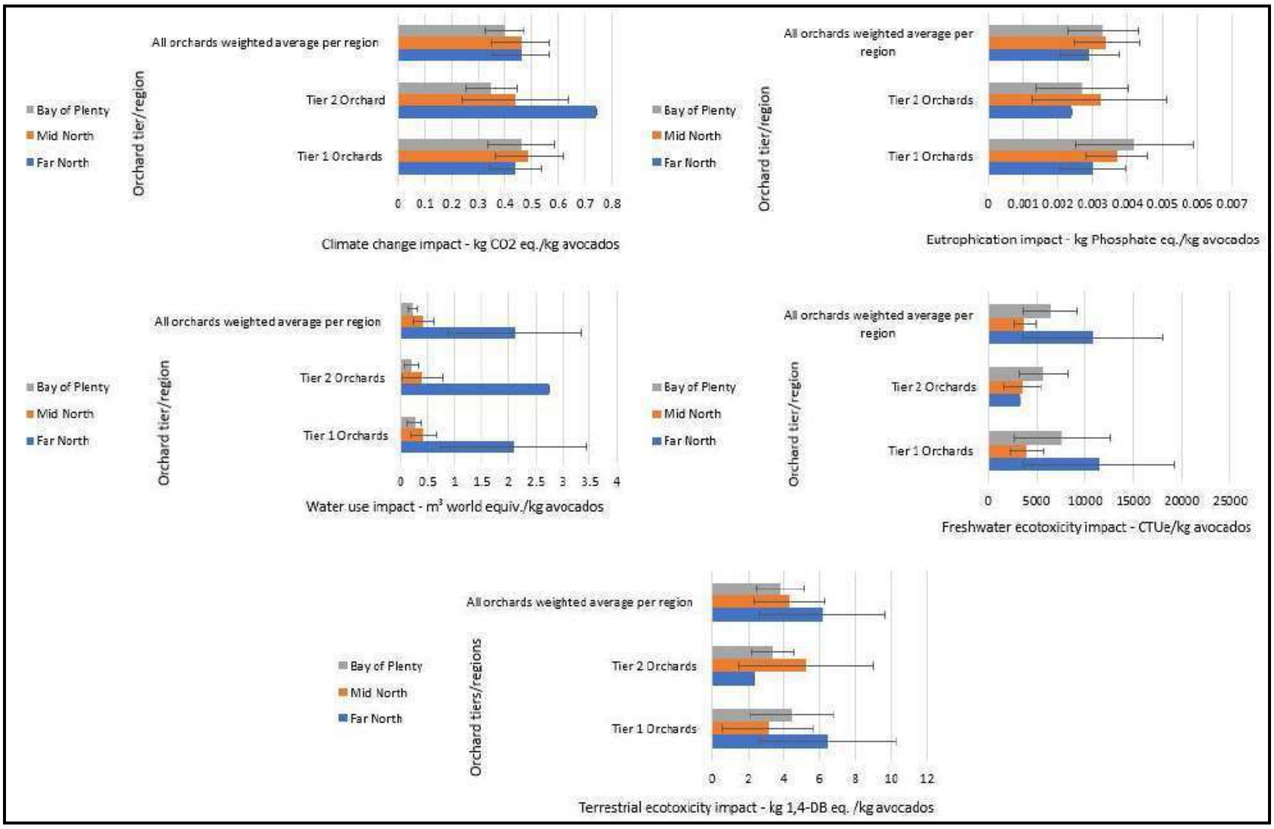

Figure 1 Environmental impact scores of sampled orchards, in all five impact categories. The error bars represent the 95% confidence interval of the impact values of the orchards in each region.

[3] There was only one Tier 2 orchard in the Far North sample. Thus, there is only one score for this orchard for all impact categories, and therefore, no weighted average or confidence interval.

The regional impact scores for climate change are similar, apart from the Tier 2 orchard in the Far North, which had a higher score. The main contributing sub-stages/inputs to the climate change impact category in all three regions are fuel and fertilisers. All fertiliser-related impacts are due to emissions of CO_2 and N_2O to air. These impacts are related to both 'non-application' activities (production/formulation, and transport), and application on the orchard. Of these, the regional non-application activities account for >62% of the impacts on average.

The Mid North has the largest eutrophication impact, followed by the Bay of Plenty and the Far North. Fertiliser and soil conditioner use contribute the most to the eutrophication impact category in all three regions. The majority of the impacts (80% on average) are from fertiliser application due to the emission of nitrates, phosphates, and phosphorous.

The water use impacts in the Far North are much higher than those the Mid North and Bay of Plenty, and the Bay of Plenty has the lowest impact. The water use on orchards is the main contributor to the overall water use impact score for the Mid North and the Far North. This is on account of the water sourced from town supply or drawn from aquifers by bore pumps for irrigation (and to a smaller extent, spraying) in these two regions. In contrast, the water requirement for many of the orchards in the Bay of Plenty are met with rainfall and harvested rainwater. Thus, the water used on orchards in the Bay of Plenty is not a major contributor to this impact category. A conservative approach was taken to model water use impacts – water 'consumed' was considered to be equal to water 'withdrawn' for use in irrigation.

The Far North had the highest scores for both the average freshwater and terrestrial ecotoxicity scores. Agrichemical use dominates the freshwater ecotoxicity impact (on average, 47% of total freshwater ecotoxicity impact in each region), particularly when copper-based fungicides are used on the orchard. In the absence of fungicide inputs, the production and transport of fertilisers contributes more to this impact category. Terrestrial ecotoxicity impacts are mainly due to emissions of heavy metals (particularly copper) to air during the manufacturing of agrichemicals and fertilisers.

Overall, fertiliser and fuel inputs are the hotspots for all impact categories except water use, where irrigation-related water use on orchard is the hotspot. For ecotoxicity, agrichemical use is an additional hotspot. Regional impact score analyses shows that for water use, the Far North score is 5 and 9 times the value of the Mid North and Bay of Plenty respectively, and the Far North is therefore a regional hotspot for this impact category. However, there is variability in both inputs and impact category results between orchards in all three regions. For example, the values of the orchards with the highest climate change impacts are 252%, 238%, and 387% greater than the orchards with the smallest impacts in the Far North, the Mid North and the Bay of Plenty, respectively. In contrast, the Tier 1 and Tier 2 results for each region (per impact category) are relatively similar to each other, which suggests that the data estimated by the Tier 2 growers in each region are fairly accurate.

Some methodological challenges, and associated recommendations, were identified in this study:

~ For this study, the nursery stage was excluded. However, the nursery stage can be environmentally demanding, depending on the specific conditions required to grow saplings of different species – for example, there may be requirements for growth substrates or plastics to protect certain plant species in the sapling stage (Cerutti et al., 2014). If the temporal aspect of the avocado life cycle is considered, and the impacts of the nursery stage allocated across its life cycle of approximately 50 years, these impacts are likely to be insignificant compared to the core agricultural production stage. However, until such an assessment is done, the exact contribution of the nursery stage to overall impacts remains unknown.

~ This study focuses only on the productive stage of the orchard and excludes the initial years between orchard establishment and commercial production as well as the low-yield years of senescent trees). For future studies, it is recommended to include this initial stage, and then allocate the impacts across the perennial fruit tree life cycle – but report them separately from the productive stage.

- ~ It was assumed that 100% agrichemical emissions go to agricultural soil. However, ReCiPe 2016 does not account for emissions to agricultural land because agricultural soil is modelled as part of the technosphere; therefore, the terrestrial ecotoxicity impacts on agricultural soil are not assessed. For freshwater ecotoxicity, the actual fractions of emissions emitted to air and water are overlooked, and corresponding impacts are not assessed. The Danish collaborative research project called Operational Life Cycle Assessment of Pesticides (OLCA-Pest) recently recommended methods to incorporate default emission fractions to different environmental components within LCI databases (Nemecek et al., 2022). Use of these default factors along with a consensus-backed impact assessment method like USEtox, could provide a more realistic assessment of actual pesticide-related impacts at the orchard stage.
- ~ The main challenge with using the CML 2001 (2016 version) characterisation model for eutrophication is its spatial and temporal environmental relevance, due to nearly total absence of fate modelling. However, until more updated methods are available that are globally valid and yet have site-specific characterisation factors based on all limiting nutrients of local relevance, it is recommended to use this approach to model eutrophication impacts for New Zealand.
- ~ For this study, the annual, national level, aggregated and undifferentiated (average of agricultural and non-agricultural factors) characterization factor was used was assessing water use impacts via the AWARE method. It is recommended that future studies build on this and calculate impact values with more resolution, by using the sub-national, agricultural characterisation factors for monthly time intervals.

Conclusion

This study quantified the life cycle-based environmental impacts associated with avocado cultivation in the three main avocado growing regions of New Zealand – the Far North, Mid North, and Bay of Plenty. Impacts were assessed in five categories – climate change, eutrophication, water use, and ecotoxicity (freshwater and terrestrial), and environmental hotspots were identified for each impact category. Fertiliser and fuel use were the main contributors to all impact categories, except water use, in which irrigation-related on-orchard water use was the main contributor. One interesting learning that emerged from the study was the significant difference in water use impacts between the Far North and the other two regions. The regional average (weighted by production) climate change impact was 0.46 kg CO_2 per kg avocados for both the Far North and Mid North, and 0.4 kg CO2 eq./kg avocados for the Bay of Plenty. These values are at the lower end of the range calculated in other avocado studies which range from 0.5 to 2.24 kg CO_2 eq./kg avocados (Bartl et al., 2012; Stoessel et al., 2012; Astier et al., 2014; Frankowska et al., 2019; Esteve-Llorens et al., 2022). However, these results are not directly comparable with each other because of the different system boundaries and/or orchard life cycle stages addressed in each study.

The lack of site-specificity with respect to modelling of the eutrophication, water use, and ecotoxicity impacts were noted in this study. However, aiming for site-specificity when modelling these impacts for a large sample size is very challenging, therefore it might be appropriate to continue using simpler indicators when the goal of the study is to develop national level benchmarks, and not for comparing the environmental performance of individual orchards. Another point of interest is the high variability in both the input and environmental impact scores across orchards in all three regions, across all the four impact categories. The results of this study are being used to develop a more extensive model that includes packhouse and coolstore activities, and distribution to domestic and overseas markets. This could potentially lead to the development of a sector-based environmental monitoring system and/or certification scheme. It will be important to consider the reasons for the variability between orchards when establishing such a system so that it can be tailored to support individual orchards to improve their environmental profiles (Poore & Nemecek, 2018).

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The impact of farm-inherent variability in environmental assessment of dairy products

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The European Commission's Product Environmental Footprint (PEF) initiative, in its work towards developing a harmonized methodology to calculate and help to communicate the environmental footprint of agri-food products, must deal with inherent variability of the agricultural sector. This study aims to assess the environmental impact of the dairy value chain in Catalonia, north-eastern Spain, from cradle to distribution, and to test the suitability of the PEF and dairy-specific PEF Category Rules (PEFCRs) guidelines to our production systems.

The environmental impact of cow milk (characterized, normalized, weighed values) was assessed at three dairy farms located in Catalonia. For the study to be PEF compliant all the impact categories listed in the dairy specific PEFCR guidelines were assessed according to the EF 3.0 Method (adapted) V1.00 (Fazio et al., 2018), through LCA Software (PRéConsultants, 2020). Only some characterized results are shown in this study, selected according to model robustness and relevance for the sector. The functional unit was 1 tonne of fat protein converted milk (FPCM). The scope of the study was cradle to industry gate including packaging and distribution. A questionnaire was designed to collect primary data from each stage. Data collection was an iterative process, completed with interviews and farm visits. Datasets used for secondary data were retrieved from Ecoinvent 3.6 database (Wernet et al., 2016) and Agribalyse (Asselin-Balençon et al., 2020), and adapted to local conditions when possible. Regarding feed, when ingredients were grown in the same farms, its impact was calculated using primary data. Impact from commercial feed was assessed using secondary datasets for each of the ingredients of the compound. Emissions were calculated following Tier II from IPCC (2019) and European Environmental Agency (EMEP/EEA, 2019). Data from dairy processing plant (confidential) were collected, and impact was assessed including packaging and distribution (thus, transport to market and supermarket centrals). To account for the environmental footprint from the raw milk, impact from the 3 farms was weighed according to their productivity.

Regarding system multifunctionality, emissions from manure storage, transport and application were allocated to the field crops from the farm where it was valorised as fertilizer. The rest of the manure was considered as a residual product (by-product) and therefore burden was allocated to raw milk produced at farm (European Commission, 2018). For the farm impact allocation to the different co-products, upstream burdens were shared between raw milk and live animals at the farm gate based on the biophysical allocation method (IDF, 2015) as indicated by PEFCR for dairy products (European Commission, 2018). The results from this method were then compared with the allocation method proposed by Nemecek and Thoma (2020), which proposed an alternative allocation approach for farms with high (>3%) BMR (ratio between live weight of sold animals and FPCM) values. At the dairy processing industry, impact of the upstream burden was done by mass allocation between the different co-products (cream and liquid milk in this case) depending on their dry matter content following the PEFCR for dairy products (European Commission, 2018).

Farm inventory data were collected to calculate the environmental impact of producing raw milk at farm gate for three different farms representative of the studied system:

- Farm 1: family dairy farm. Animal heads: 33 calves, 30 heifer, 73 mature females. Breed Holstein Friesian, Commercial milk rate of 12.7 tonne a year per productive animal. Own crops, 34 hectares (fodder 521 tonne per year and farm) and compound feed (unweaned calf: 22.5 tonne per year and farm; dry cows: 3.6 tonne per year and farm; lactating cows: 278 tonne per year and farm)
- Farm 2: dairy experimental farm. Animal heads: 56 calves, 57 heifers, 119 mature females. Breed Holstein Friesian, Commercial milk rate of 11.5 tonne a year per productive animal. Own crops, 70 hectares (fodder 1539 tonne per year and farm) and compound feed (unweaned calf: 109 tonne per year and farm; dry cows: 101 tonne per year and farm; lactating cows: 529 tonne per year and farm)
- Farm 3: family dairy farm. Animal heads: 18 calves, 18 heifers, 59 mature females. Cross breed Holstein Friesian-Belgium Blue. Commercial milk rate 6.2 tonne a year per productive animal. Own crops, 41 hectares (fodder 573 tonne per year and farm), compound feed (unweaned calf, dry cows, lactating cows: 72, 24, 180 tonne per year and farm respectively).

Table 1 shows the results from a selection of impact categories for each farm (raw milk) as well as the impact including processing, packaging, and distribution (FPCM). Impact at industry gate, including the milk processing impact, as well as the packaging of the milk and its distribution to market and supermarket centrals, was assessed. Carbon footprint (CC) resulted in 1,460 kg CO_2 eq tonne^{-1} FPCM (Table 1). This was in the range of the European benchmark value which is 1,530 kg CO_2 eq tonne^{-1} including processing and distribution (European Commission, 2018). Regarding the main drivers of the impact for the studied milk production system, it was the raw milk production the process with greater contribution to most indicators (over 60% contribution to the potential impact of all the indicators). Therefore, it is at the farm stage where more efforts should be placed if the aim is to improve the sustainability of the final product.

CC from the dairy farms ranged between 1,450 and 2,270 kg CO_2 eq tonne^{-1} of raw milk at farm gate (Table 1). Considering farm specific fat and protein values (between 3.69 and 3.8% for fat content and 3.09 and 3.3% for protein content) CC from milk resulted between 1,480 and 2,410 kg CO_2 eq tonne^{-1} FPCM at dairy farm gate. Main contribution came from feed which explained 40-60% of the total impact to CC (in particular, own crops contributed between 23 and 33% to CC). This was followed by contribution of enteric fermentation emissions which explained around 30-40% of the total impact to CC. This was in line with data found in literature (FAO, 2016).

Overall, despite the high variability inherent in agricultural activities, results were lower (acidification) or in the range (CC and eutrophication) of the European benchmark values given by the PEFCR for dairy products (Table 1). Impact to acidification being lower than the benchmark is explained by the use of regionalized factors in the foreground data (e.g.: ammonia flow regionalized CF for Spain is 0.076) which are considerably lower than in other European countries (site-unspecific CF of 3.02) due to the location of the emission source and its local atmospheric conditions, soil pH, and sensitivity of the ecosystems (Seppälä et al., 2006; Posch et al., 2008).-However, this was not the case for the water use impact category (CA), which scored considerably higher in the assessed farms compared to the European reference value. The potential impact to water use impact category came from different sources at each farm. At farm 1 the contribution to this indicator came mainly from irrigation of some of the ingredients of the fodder (in particular, maize) grown at the farm, followed by the water used at the farm (mainly animal drinking, followed by cleaning). In farm 2, main contribution came from the water used at the farm (mainly animal drinking, followed by cleaning and cooling), as well as from the water needed for producing the ingredients of the commercial feed compounds (in particular, maize grain). In farm 3 main contribution came from the water needed for producing the ingredients of the commercial feed compounds (in particular, maize flour) followed by the water used at the farm (mainly animal drinking, followed by cleaning). A more efficient use of water, together with more research in slurry treatment for its use as irrigation and cleaning water (without compromising safety and health) could help reduce impact. Moreover, to calculate the impact for this indicator, water was characterised according to the availability at a national level following the PEF guidelines. The characterization factor (CF) of Spain for a year (77.7 m^3 eq) is one of the highest from Europe (e.g.: equivalent CF for Greece, 68.4 m^3 eq; CF for Europe without Switzerland, 42.9 m^3 eq). Due to large differences among watersheds inside Spain, using regionalized CFs when higher spatial resolution is available could reduce uncertainty in the results. However, in this case farms were less than 10 km apart, and watershed-scale CFs varied from 80.6 to 3.6 m^3 eq among them. Therefore, water impact results should be considered precautionary due to the need of further research and development of improved models/factors.

Concerning variability across the studied farms, climate change impact varied up to 820 kg CO_2 eq per tonne of FPCM across farms, which is 50% of the benchmark value (1.530 kg CO_2 eq per tonne FPCM). It would be meaningful to distinguish between different farms of origin of the raw milk entering the industry instead of using averages where impact from higher footprint milk gets diluted in the final results.

The PEFCR for dairy products has been developed with the focus (i.e. foreground) on the industry stage. This makes sense in most cases as, from an ecolabelling perspective, we are buying milk knowing the processing plant, but not the exact farm it comes from. The milk arriving to an industrial processing plant to process the liquid milk for a specific label could come from dozens or even hundreds of different farms. When applying the PEF guidelines to perform an LCA from liquid milk at the industry gate, one challenge would be how to account for the high impact that this variability at the farm level can have on the results. The most accurate way would be to perform a weighted measure. Selecting, surveying, and assessing a representative sample, could be time and effort consuming as farms can be very different from each other. Furthermore, potential lack of data registry at family and small-scale farms can complicate this task. Another solution would be to have a representative picture (local databases) of the different farm types (i.e.: according to those management choices and parameters that have greater potential to contribute to environmental impact) on the region, initiative that should be promoted. In addition, we would propose labels that show the range in which the impact vary, rather than absolute values, to account for the primary sector high variability in agrifood products. This would better represent the impact and it could help to motivate industry to take responsibility for those providers on the lower bound.

Allocation of environmental impact remains challenging when applying PEF guidelines. When allocating the burden from milk losses at industry stage, impact of milk that is disposed with wastewater is accounted for. However, milk losses used for a different purpose (e.g.: producing biogas or animal feed) than the product under study should be considered as a co-product (European Commission, 2018). This does not distinguish whether there is an economic value for this milk losses. This approach seems inconsistent with the allocation approach for other by-products at the farm stage, e.g.: if manure does not have an economic value it is treated as a residual product (i.e., burden allocated to raw milk). Moreover, economic allocation is often questioned by its temporary and geographic variability. We would recommend revising this approach for consistency across different stages of the production life cycle, as well as across different sectors. In particular if a by-product of one system can become an input for another system (e.g.: manure from livestock used as fertilizer in crops) to avoid double counting impact at a territorial level. A price independent approach such as circular footprint formula could be explored.

Regarding allocation of environmental milk-meat burden at dairy farms, approach from Nemececk and Thoma (2020) resulted more appropriate (milk allocation factor 67.17% versus 42.79% following PEFCR for dairy products), in particular in farms with multi-purpose breeds (Farm 3).

Table 1. Characterised results of the environmental impact assessment for a selection of categories by tonne of raw milk at farm gate and by tonne of FPCM produced at industry including processing, packaging, and distribution. BMR: ratio between live weight of sold animals and FPCM. Comparisons are only feasible between the farms and between the two last columns.

	Units	*Farm 1*	*Farm 2*	*Farm 3*	*Including Processing + Distribution*	*Characterised benchmark values*
BMR	%	2.13	3.35	9.47		N/A
Climate change	kg CO_2 eq	1.45E+03	1.46E+03	2.27E+03	1.46E+03	1.53E+03
Acidification	mol H+ eq	5.32E+00	8.13E+00	7.85E+00	6.50E+00	1.25E+01
Eutrophication, freshwater	kg P eq	1.70E-01	1.74E-01	2.75E-01	1.98E-01	1.04E-01
Eutrophication, marine	kg N eq	4.27E+00	7.88E+00	8.61E+00	5.77E+00	3.75E+00
Eutrophication, terrestrial	mol N eq	3.32E+01	5.50E+01	6.38E+01	4.21E+01	5.34E+01
Water use	m^3 depriv.	3.15E+03	2.82E+03	2.92E+03	2.64E+03	3.11E+02

In conclusion, farm stage was determinant in milk environmental footprint at industry gate. Feed was the major contributor to the impact for most impact categories. Results showed to be lower or in the range of the European benchmark, except for water footprint. This was mainly due to the location of the farms, where according to the methodology the use of water is penalized. We would recommend a revision of the guidelines to address the challenges encountered when utilising the PEF methodology in real-world applications to assess environmental impact of agri-food products: how to capture the agriculture-inherent variability in final product results. PEFCR for dairy products has the focus on the industry. To improve their PEFCR profile and achieve a competitive advantage, the milk industry should (for environmental reasons) and will (for economic reasons) purchase raw milk from farms with a better environmental performance which needs to take responsibility for the origin of the raw milk. Given the large contribution of the dairy farm stage to milk environmental footprint at industry gate, raw milk impact should not be accounted at industry using averaged secondary data. As primary representative data can be challenging to obtain, we propose to promote work towards having a representative picture of farms at regional level (thus, regional databases). In relation to eco-labelling, we propose talking in term of ranges instead absolute values, what should be addressed when translating environmental impact into ABC-type scores.

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Chemical and mechanical weeding strategies in maize crops

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Nowadays, the use of pesticides to remove weeds from the crops is a controversial technique. In that context, regulations are becoming more consistent with environmental issues. The European Commission, through its action plan European Green Deal (European Commission, 2019) and in the frame of Farm to Fork strategy (European Commission, 2020) has as an objective the reduction of pesticides dependence in agriculture, setting two key targets for pesticides by 2030 aiming to reduce by 50%: the use and risk of chemical pesticides as well as the use of more hazardous pesticides.

In this study, the main objective was to conduct an LCA following the defined methodology in the ISO reference framework (ISO-14040, 2006) to analyse the contribution of different weeding strategies to each environmental impact category for maize production, including the use of pesticides. It is for that purpose that scenarios were defined considering three different strategies: chemical weeding, mechanical weeding, and a mix of both.

Primary data had its origin in experimental fields in Girona, Catalunya. Emissions related to the use of fertilizers were estimated considering the emission factors proposed in PEFCR guideline (European Commission, 2017) but for phosphorus losses due to surface water erosion, Per, which were estimated considering local conditions using Prasuhn methodology (Prasuhn, 2006). To estimate pesticides application emissions, PestLCI consensus model (Nemecek et al., 2022) was followed, which gives air, water and soil emission factors according to the type of crop, growth stage and the machinery used to apply pesticides.

The followed production process was equal for all the scenarios but for weeding process. Nine scenarios were assessed: i) control (no weeding process included); ii) chemical weeding, high load; iii) chemical weeding, low load; iv) simplified mechanical weeding (1-2 weedings); v) intensive mechanical weeding (required number of weedings); vi) chemical pre-emergence (total) plus mechanical weeding; vii) mechanical plus chemical post-emergence (total) weeding; viii) precision chemical pre-emergence plus mechanical weeding; ix) mechanical plus precision chemical post-emergence weeding. These four last scenarios corresponded with two strategies, ones which applied pesticides in the total crop area but in different crop stages, and the others, which apply the pesticides just in crop rows, reducing approximately by up to 60% the pesticide amount applied. The weeding machinery used was a row-crop cultivator, finger hoes, a precision tine harrow, and a boom sprayer.

Regarding the use of pesticides, the following types and amounts were applied to the scenarios analysed.

Table 1. Amount of herbicides active matter applied in scenarios analysed. Mechanical weeding specification.

	kg/ha								
Herbicides, active matter	i	ii	iii	iv	v	vi	vii	viii	ix
Terbutilazine	-	0,66	-	-	-	0,66	-	0,26	-
Mesotrione	-	0,13	-	-	-	0,13	-	0,05	-
S-metolachlor	-	1,09	-	-	-	1,09	-	0,44	-
Nicosulfuron	-	-	0,06	-	-	-	0,06	-	0,02
Mesotrione	-	-	0,09	-	-	-	0,09	-	0,03
Dicamba	-	-	0,19	-	-	-	0,19	-	0,06
Mechanical weeding	no	no	no	yes	yes	yes	yes	yes	yes

Secondary data were retrieved from Ecoinvent 3.6 database (Wernet et al., 2016) and Agribalyse (Asselin-Balençon et al., 2020), adapting the processes to local conditions whenever possible.

The functional unit was 1 tonne of maize. The environmental impact assessment was done following the Environmental Footprint, EF, 3.0 method from European Commission initiative (European Commission, 2013) (European Commission, 2017) using Simapro 9.1.1.7 (PRéConsultants, 2020).

Table 2 shows the contribution of each scenario for each impact category. Bars indicate the contribution in one impact category of each scenario from highest to lowest. As seen from the results, the last three scenarios (vii, viii, ix) have a lower environmental impact in all impact categories analysed, affected by crop yield, which is considerably higher compared with the other scenarios. As crops have been developed in same conditions, the yield differences could be allocated to the weeding technique.

Table 2. Results per tonne of maize grain expressed in equivalent units for the 16 impact categories (yellow marks highest contribution).

Management	Convencional									
Maize	Scenario	i	ii	iii	iv	v	vi	vii	viii	ix
	Yield (tons/ha) / Unit	14.84	16.39	16.11	15.53	15.25	15.85	17.54	17.15	17.53
Climate change	kg CO_2 eq	2.75E+02	2.52E+02	2.56E+02	2.65E+02	2.72E+02	2.61E+02	2.37E+02	2.40E+02	2.37E+02
Ozone depletion	kg CFC11 eq	2.18E-05	2.10E-05	2.06E-05	2.13E-05	2.19E-05	2.18E-05	1.93E-05	1.96E-05	1.92E-05
Ionising radiation	kBq U-235 eq	1.14E+01	1.05E+01	1.06E+01	1.10E+01	1.13E+01	1.09E+01	9.90E+00	1.00E+01	9.88E+00
Photochemical ozone formation	kg NMVOC eq	1.80E+00	1.66E+00	1.68E+00	1.75E+00	1.79E+00	1.71E+00	1.56E+00	1.58E+00	1.56E+00
Particulate matter	disease inc.	9.05E-05	8.22E-05	8.34E-05	8.65E-05	8.82E-05	8.50E-05	7.67E-05	7.84E-05	7.68E-05
Human toxicity, non-cancer	CTUh	7.32E-06	7.26E-06	6.84E-06	7.09E-06	7.26E-06	7.51E-06	6.35E-06	6.62E-06	6.34E-06
Human toxicity, cancer	CTUh	1.80E-07	1.66E-07	1.71E-07	1.74E-07	1.78E-07	1.72E-07	1.59E-07	1.58E-07	1.57E-07
Acidification	mol H+ eq	1.77E+00	1.65E+00	1.65E+00	1.72E+00	1.76E+00	1.71E+00	1.53E+00	1.56E+00	1.53E+00
Eutrophication, freshwater	kg P eq	3.14E-02	2.92E-02	3.04E-02	3.04E-02	3.12E-02	3.02E-02	2.83E-02	2.77E-02	2.76E-02
Eutrophication, marine	kg N eq	2.81E+00	2.55E+00	2.60E+00	2.69E+00	2.75E+00	2.64E+00	2.39E+00	2.44E+00	2.39E+00
Eutrophication, terrestrial	mol N eq	2.10E+01	1.91E+01	1.94E+01	2.02E+01	2.06E+01	1.98E+01	1.79E+01	1.83E+01	1.79E+01
Ecotoxicity, freshwater	CTUe	1.71E+04	2.04E+04	1.65E+04	1.64E+04	1.67E+04	2.11E+04	1.52E+04	1.67E+04	1.48E+04
Land use	Pt	3.36E+04	3.05E+04	3.10E+04	3.21E+04	3.28E+04	3.15E+04	2.85E+04	2.91E+04	2.85E+04
Water use	m^3 depriv.	1.89E+04	1.71E+04	1.74E+04	1.81E+04	1.84E+04	1.77E+04	1.60E+04	1.64E+04	1.60E+04
Resource use, fossils	MJ	1.91E+03	1.77E+03	1.79E+03	1.86E+03	1.91E+03	1.83E+03	1.67E+03	1.68E+03	1.67E+03
Resource use, minerals and metals	kg Sb eq	4.82E-03	4.48E-03	4.54E-03	4.73E-03	4.88E-03	4.64E-03	4.27E-03	4.28E-03	4.27E-03

As it can be seen in **table 2**, scenarios vii, viii and ix have the highest yield, consequently a lower impact per tonne of product is assigned; scenario i (control), is the one with the lowest yield, most affected by the weeds leaved in crop; chemical scenarios (ii and iii), have relatively higher yields; yield differences between scenarios vi and v come from the number of mechanical weedings, as the machinery damaged the crop, but both of them have a lower yield than chemical scenarios. Pre-emergence pesticides (scenario vi) had less efficiency in controlling weeds than post-emergence (scenario vii), what affected yields.

Regarding freshwater ecotoxicity results, mainly affected by the use of pesticides, it can be detected that a greater impact is assigned in scenarios ii and vi, coinciding in the type and amount of herbicides used (**table 1**). Comparing the last three scenarios (vii, viii and ix), which is probably the clearest way to compare a weeding behaviour for their similar yield, it can be detected that the type of **post-emergence pesticides has a lower effect to freshwater ecotoxicity** than pre-emergence pesticides.

In addition, Monte Carlo uncertainty analysis was conducted. This analysis allows to know the probability that the results are significantly different or not. It is considered significantly different when 95% of runs a specific scenario produces higher or lower environmental impact than other.

The Monte Carlo analysis was conducted taking as reference the lower potential environmental impact scenario (with 1000 fixed number of runs and a 95% confidence interval). Results suggest that there is no better or worse scenario as the differences between scenarios are **not significant enough** in **all the environmental categories**.

However, significant differences were found in some categories. Specifically, for freshwater ecotoxicity between all scenarios but for iv and vii (in scenario iv a low intensity mechanical weeding is applied, thus a similar result in this category makes sense as no pesticides are applied; in scenario vii the pesticides applied are the same type than reference scenario), for water use between all scenarios but for vii and viii, for mineral and metal resources depletion between scenarios i, iv and v, and for acidification and terrestrial eutrophication between scenario i.

Yield differences between scenarios vi and viii (scenarios with a pretty similar management) could be attributed to the amount of pesticide used, as in scenario viii the strategy followed was to apply pesticides just in crop rows (the use of hoeing machine enable to conduct this kind of management). Although in scenario vi a hoeing machine was also used, the strategy was to test the yield behaviour when additionally applying pesticides in all the crop, and the result was a 1.3 tonne decrease, reaffirming that pre-emergence pesticides in maize crops (same as chemical weeding high LOAD scenario, ii) tends to affect the crop yield to a greater extent in comparison with post-emergence pesticides (in which there are no significant differences between the yield of scenarios xii and ix).

Considering other categories with significant differences in Monte Carlo analysis, results showed that water use, category mainly affected by irrigation, is influenced by crop yield, The amount of irrigation was the same in all scenarios and the difference between maximum and minimum yield was 2.7 tonnes (standard deviation of 0.99 tonnes). Acidification and terrestrial eutrophication follow the same line than water use, differing in the origin of affecting inputs, being in that case the emissions related to the use of fertilisers and the production process itself, and also due to diesel consumption for acidification. Finally, for minerals and metals resource depletion, the differences come not just from crop yield but also the agricultural machinery needed for agricultural operations, which changes between scenarios according to the mechanical weeding intensity and the amount of pesticides used.

In conclusion, although the environmental impact differences between scenarios are not significant enough to define clearly a better or worse scenario for all the environmental impact categories, some insights are given. It must be considered how weeding techniques affect the crop yield.

Mixed weeding scenarios had the highest yields except for scenario vi, affected by the use of a large amount of pre-emergence pesticides, so impact per tonne can be reduced with a mixed weeding. Also, it has been proven that environmental impact changes in relation to the use of different types of pesticides, mainly related to toxicity impact categories.

In addition, other points should be considered. There are other processes such as the diesel consumption due to other agricultural operations but weeding process that contribute even more to the environmental impact, including toxicity. As an example, diesel consumption due to other agricultural operations contributes around 55 to 60% to ozone depletion. Emissions from fertilizer application or irrigation infrastructure are also inputs that considerably contribute to environmental impact.

Summarizing, mechanical and mixed weeding (excluding scenario vi) allow to reduce impact to toxicity categories, being that reduction strongly dependent on the active matter used in chemical weeding, in line with study done in 1999 (Gaillard & Irla, 1999). However, mechanical weeding affects other environmental categories as climate change, or acidification to a greater extent (Ahlgren, 2004). A mixed weeding with herbicide band application maintain a high yield while allows to reduce the amount of herbicide applied (Loddo et al., 2020). Herbicide impact can be reduced considering the type of active matter and the amount applied while still optimizing weed control.

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Soil organic carbon accounting in agricultural life cycle assessments

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Soil organic carbon in the agriculture sector has often been looked to as a long-term climate change mitigation strategy. It is associated with better soil health and often included in critical climate change mitigation documents (Drever et al., 2021). However, the true impact of soil organic carbon and sequestration has potentially been overemphasized (Powlson et al., 2011; Amundson & Biardeau, 2018; Popkin, 2021). Evidence reveals that carbon sequestration in the form of soil organic carbon (SOC) storage is not an effective method for long-term climate change mitigation (Powlson et al., 2011; Amundson & Biardeau, 2018). Moreover, carbon that is sequestered by soil is finite and can be released back into the atmosphere (Amundson & Biardeau, 2018). Therefore, the significance of carbon sequestration to mitigating climate change impacts in the long term has dwindled and remains contentious. Hence, understanding the true impact of SOC and sequestration has never been more crucial.

To understand the true impact of SOC in agriculture, there needs to be a holistic assessment of greenhouse gas (GHG) emissions resulting from crop production. This includes assessing factors such as soil type, precipitation, and land management practices. Life cycle assessment (LCA) is often chosen as a method to model those holistic emissions, i.e., emissions throughout the crop's life cycle. However, modeling soil organic carbon fluxes in LCA is often left out due to lack of clear procedure (Joensuu et al., 2021; Goglio et al., 2015). A previous study by Goglio et al. (2015), analyzes soil carbon (C) accounting methods in LCA and recommends that a universal method should be applied to future LCA studies in assessing SOC fluxes. The study also reviews how land management practices (LMP) are considered in the various methods (Goglio et al., 2015). Since the study's publication, new soil C accounting methods have emerged. Moreover, studies show that model initialization method and timeframe have significant impacts in SOC estimations (Joensuu et al., 2021). Consequently, an in-depth and up-to-date exploration of SOC modeling approaches is necessary to provide consensus within future LCA studies. This is particularly true of LCA studies that model organic field cropping systems. Organic field crop systems are underrepresented in LCA and their heterogenous land management practices (LMPs) make assessing and comparing SOC fluxes complicated across studies.

Whether or not soil carbon sequestration can be relied on as a climate change mitigation solution, there are multiple co-benefits of sequestration that highlight its importance in agricultural systems. The benefits of healthy soil C stocks include "advancing food and nutritional security, increasing renewability and quality of water…strengthening elemental recycling (Lal et al., 2015, p. 79), species conservation (Flores-Rios et al., 2020), and increased biodiversity (De Beenhouwer et al., 2016; Lal et al., 2015; Miles et al., 2009), among others. These co-benefits illustrate the importance of studying SOC regardless of its use as a mitigation solution.

As previously mentioned, SOC fluxes are often left out of LCAs because there is no clearly defined procedure for modeling (Joensuu et al., 2021; Goglio et al., 2015). A paper by Goglio et al. (2015) outlines several common modeling techniques but conclude that a common methodology to assess soil C fluxes in LCA be developed. Further, Sevenster and colleagues (2020) echo the importance of modeling SOC changes, advocating that ongoing development of SOC methodology and modelling is vital. An assessment of the current SOC methodologies is needed. Hence, the purpose of this review is twofold: (1) further the learning surrounding how land management practices are approached in regard to modeling carbon fluxes, and (2) learn about challenges and specifications that exist for soil C accounting in LCA that can be applied to the organic agricultural sector. This will aid in understanding how LMPs are assessed with each method and what can be learned from these approaches in order to better model SOC in organic agriculture.

To understand the approaches to modeling C flux, a literature review search was conducted to capture current soil organic carbon modeling techniques used in life cycle assessment studies. The Scopus database was used to perform this systematic literature review search. The following keywords were included: "LCA" OR "life AND cycle AND assessment" OR "life AND cycle AND analysis" OR "carbon footprint*" OR "environmental footprint*" AND "corn*" OR "pea*" OR "oat*" OR "lentil*" OR "potato*" OR "wheat" OR "hay" OR "grain*" OR "cereal*" OR "oilseed*" OR "barley" OR "rye" OR "soy" OR "soybean*" OR "maize" OR "maise" OR "pulse*". Terms such as "soil organic carbon" or "carbon flux" or "soil carbon flux" were left out of this search because preliminary searches revealed those terms are exclusive to LCA studies which looked at SOC, but do not include SOC in the title or keywords. Thus, this all-encompassing search included papers with SOC in the title and keywords, and those without which still assessed SOC. Further, search results were narrowed by including the publishing dates of 2010-present (2022). This ensured the timeliest papers were chosen and the most modern modeling techniques were showcased. An additional geography filter was included: selecting papers with a similar climate and soil types as the US and Canada.

The final number of papers that were included in the full analysis was 125. This list of papers was used to understand and categorize current modeling approaches of soil organic carbon in life cycle assessment studies. From this list, papers were analyzed in-depth for the land management practices that were simulated with each modeling approach. Furthermore, the modeling approaches were looked at for their usefulness and accuracy in the organic agriculture sector.

In total, 20 different SOC accounting approaches were identified in the literature review. The most common method, calculation, is a combination of calculation-based approaches such as minimum residue return rate, estimations based on previous studies' calculations, and plugging in emissions factors. Field-level sampling was the chosen method for ten studies. Finally, the method using external, downloadable software packages to assess SOC are common, but there are a multitude of these models which makes choosing an appropriate one difficult. The immense number of these software mean that LCA results are not as readily comparable due to potential differences in software parameters. Some studies have compared several modeling methods (e.g., Obnamia et al., 2019; Peter et al., 2016) or even combined methods (e.g., Riggers et al., 2019), but there is no comparison which encompasses the holistic breadth of models. Hence, the necessity for best practices in choosing an SOC modeling approach is great.

There is not an organic-specific modeling approach to the authors' knowledge. However, the flexibility of the models' ability to simulate a variety of LMP makes incorporating organic practices easier. CropSyst and EPIC have the ability to simulate both organic and inorganic fertilizer. DNDC and ICBM have an organic soil option. For the above reasons, CropSyst, EPIC, DNDC, and ICBM can be considered for use with organic systems. However, data availability and geography still have a more important role in choosing a soil C accounting method due to the ability to simulate LMP in a certain region.

Due to the controversy surrounding the reliability and effectiveness of soil organic carbon as a climate change mitigation solution, a literature review was undertaken to assess current SOC modeling approaches in life cycle assessment, how land management practices are approached with each model, and which model or models can be applied to organic systems. Results show that from 125 analyzed studies, over 20 different modeling approaches exist, meaning a procedure to choose an appropriate SOC modeling approach is necessary. A set of best practices for choosing a modeling method will guide LCA researchers and achieve a higher consistency and comparability between LCA studies. Furthermore, the literature review assessed which LMP were simulated with each model and revealed that most models have the same essential LMP modeling capability. Applying these models to organic, however, may be more difficult. Since no model is informed solely by organic data, LCA practitioners should rely more heavily on geography and available data, rather than on underlying organic data within the models.

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Using the carbon footprint and biodiversity metric as key indicators for zero emissions and biodiversity protection in vineyards: a case study from Cyprus

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Introduction

The Carbon footprint (CF), expressed as CO_2-eq per kg of product or per ha of cultivated land is the most popular indicator to assess the environmental performance of products (Martinez et al. 2019). The CF is linked to C farming, which refers to the management of carbon pools, flows and Greenhouse gas (GHG) fluxes at farm level, with the purpose of mitigating climate change. Besides the CF, reconciling agricultural production and biodiversity conservation remains a challenge globally even though historically agriculture and biodiversity have always had a mutualistic relationship. Biodiversity continues to support agriculture through several services (e.g., genetic resources, soil fertility, pest, and disease resistance) while in the EU 50% of all species and 63 habitat types rely on agricultural habitats and/or agricultural activities. Therefore, determining the CF and impact of agricultural activities on biodiversity are essential for sustainable agriculture.

Viticulture and winemaking are important for the EU economy and as in most Mediterranean countries, they are essential for the economy and rural development in Cyprus (Litskas et al. 2020). Most of the vineyards on the island are located in High Nature Value farmland (HNVf) areas, i.e., agricultural areas important for the conservation of species and habitats of EU importance (Zomeni et al. 2018). Climate change and vineyard abandonment are considered as long term threats for viticulture on the island (Chrysargyris et al. 2018).

The aim of this work was to determine the C balance in vineyards, under different management practices, after applying LCA. In addition, a biodiversity metric was developed and validated, to assess the impact of viticultural management practices on biodiversity.

Methodology

GHG emissions

For achieving the aims of this work, we have used the CFT (Cool Farm Tool-www.coolfarmtool.org), modified for grapes. Its development was based on 1) the Ledo et al. (2018) perennial GHG model and 2) the Cool Farm Tool (CFT; Hillier et al. 2011; www.coolfarmtool.org). All the information about the tool, the equations and modelling approach are provided in detail in these sources and will not be repeated here. Briefly, the CFT is used worldwide for estimating the GHG impacts of agricultural production and is largely based on IPCC Tier 1 quantification methods (Hillier et al., 2011; Whittaker et al., 2013). Its most recent version supports carbon farming projects development worldwide and incorporates the latest IPCC work. It also incorporates the philosophy of the ROTH-C model (https://www.rothamsted.ac.uk/rothamsted-carbon-model-rothc), for assessing the C balance in the soil. The tool follows the LCA principles from cradle to winery door. The CFT was tested after monitoring management practices in a vineyard cultivated with the indigenous grape cultivar "Xynisteri" (Table 1). The management practices applied are representative for vines cultivation in the PDO area of Limassol, Cyprus and semi-arid non irrigated vines.

The soil in the vineyard was clay with 4% organic carbon and pH 7.5. Annual rainfall was 600 mm. Pruning was practiced once (0.1-1 kg w.w. per vine) and the material was burned. In the field margins, natural vegetation was present at the density of 100 shrubs per ha (e.g., *Quercus infectoria, Olea europea, Pistacia terebinthus).* The vineyard life is typically 30 years and the planting density 2500 vines ha^{-1}. These and the data presented in Table 1 were used for modelling to estimate the GHG emissions (baseline scenario). The next step was to explore a scenario to mitigate GHG emissions focusing on reducing synthetic fertilizer use, energy consumption and avoiding burning of the plant residues (e.g. pruning).

Table 1. Management practices for Xynisteri grapes.

Input/practice	**Value**	**Comments**
Pesticides application	2 times/season	Insecticides a cypermethrin; Acetamiprid 20%; applied according to label for grapes (500l spraying machine) Sulfur 100-150 kg/ha
Fertilizer (21-0-0)	60 kg N/ha	286 kg product incorporated once (mid-February)
Tillage	3 times per year	Rotary cultivator at the depth of 40 cm
Energy use	150 L diesel/year/ha	Machinery for the field practices (pesticides application; tillage; field visits)
Pruning management	0.7 kg/vine/year	Burned
Transportation	3,800 kg grapes ha^{-1} for 20 km	With a light goods vehicle (diesel)
Yield per vine	1.52 kg	Average for the last 3 years

<u>Biodiversity metric</u>

To develop the biodiversity metric, a questionnaire survey was used to identify the main management practices applied in each of 36 vineyards, 12 in each of three regions. The vineyards were located in the Commandaria Protected Designation of Origin region and the Krasochoria Protected Geographic Indication region. The Commandaria region is famous for the production of the sweet desert homonymous wine for more than three millennia, and is very interesting ecologically as it covers two distinct sub-regions, one within an agricultural landscape with calcareous soils, and one within a forested landscape with volcanic soils. Vineyards in Commandaria have a production cap at 6000 kg /ha to maintain product quality. The Krasochoria region is similar to Commandaria-agricultural without a production cap. Pairwise comparisons between the three regions enabled the assessment of the effect of a production cap on biodiversity in an agricultural landscape (Commandaria-agricultural vs Krasochoria), and the effect of landscape type on biodiversity (Commandaria-agricultural vs Commandaria-forest).

Monitoring of flora and fauna was carried out in each vineyard from May to July of 2020 and 2021. A multi-taxon approach monitoring was carried out focusing on five taxonomic groups (wild bees, butterflies, reptiles, birds, and plants). Monitoring was performed once per month, from April to July, for wild bees, butterflies, reptiles and plants and from April to June for birds. The monitoring period has been chosen to cover the main flight period of the target groups as well as the period with the most intensive agricultural activity (pesticide application, tillage). Sampling for pollinators (butterflies and wild bees), reptiles and plants was carried out both in the center and the margin of the vineyards, following a transect of 100 m, while for birds, data were recorded at the vineyard level.

A scoring system ranging from 0 (lowest) to 100 (highest – positive effect) was developed to assign a score on the effect of nine management practices on biodiversity for four taxonomic groups (plants, pollinators, reptiles, and birds). Scores were assigned based on expert opinion informed by personal experiences as well as literature data.

Results and discussion

GHG emissions

For the management practices presented in Table 1, the CF was 0.034 kg CO_2 eq kg^{-1}. Therefore, for the life cycle of the vineyard the emissions were 3923 kg CO_2 eq ha^{-1}. Per ha and for the life cycle of the vineyard (30 years), C storage in the plant biomass (biogenic emissions) was estimated at 14718 kg CO_2 eq ha^{-1} and the respective stored in the soil and margins natural vegetation was 10653 kg CO_2 eq ha^{-1} (land use related emissions) (Figure 1). On the other hand, emissions related to inputs (e.g., fuel, fertilizer, pesticides) were equal to 29294 kg CO_2 eq ha^{-1} (fossil fuel related emissions). The respective values per ton of grapes were 129, 93 and 257 kg CO_2-eq. Energy use for cultivation, spraying and transportation, soil emissions due to fertilizer application and fertilizer production were the hotspots for GHG emissions in the vineyard system studied.

Carbon storage in the vineyard could be achieved by 1) reducing fertilizer use by 30%, 2) reducing tillage frequency (from 3 to 2 times) to reduce fuel consumption by 10%, 3) maintaining natural vegetation in the field margins and 4) stop burning the pruning material and leaving it into the vineyard (soil incorporation) for the life cycle of the vineyard. In this case (Figure 1), biogenic emissions would be 18619 kg CO_2 eq ha^{-1}, and the fossil fuel related emissions 25481 kg CO_2 eq ha^{-1}. The respective values per ton of grapes were 129, 93 and 257 kg CO_2-eq. Since natural vegetation was assumed not to be preserved, the land use related emissions were the same as the baseline case (10653 kg CO_2 eq ha^{-1}). Therefore, it seems feasible that C credits schemes could be achieved, where farmers could cooperate with other entities to store C.

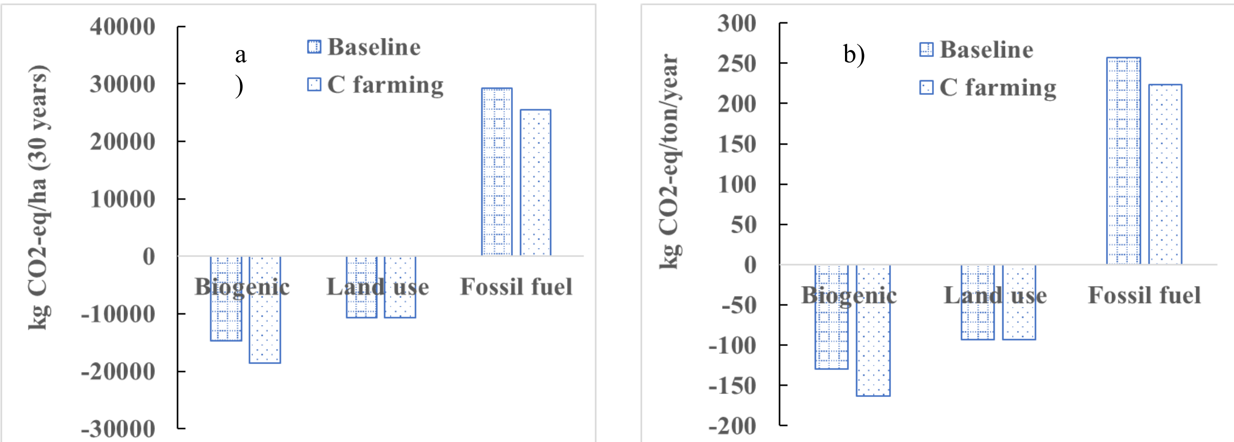

Figure 1. GHG emissions for the baseline and the C farming case a) total per ha and 30 years vineyard life and b) per ton of grapes and year.

Biodiversity assessment/metric:

The vegetation inventories identified 329 species of vascular plants, 30 genera of wild bees, 35 species of butterflies, eight species of reptiles and 41 species of birds. The diversity of plants, pollinators and reptiles was higher in the margins than the center of the fields. Preliminary results show that there was a trend of higher species richness in the region located Krasochoria for plants and pollinators, whereas there was a trend of lower bird diversity in Commandaria-forest. Reptile richness was higher in the Commandaria-forest.

The excel Tool incorporates three main groups of management practices, namely soil tillage, fertilizer application (synthetic / organic), and pesticide use (insecticides, fungicides and herbicides). In addition, the Tool incorporates three main vineyard characteristics with potential impact on species abundance and diversity: a) The proportion of (semi-)natural vegetation in the vineyard plot, b) The number of cultivated trees per decare (da) in the vineyard area, and c) The length of stonewalls in the vineyard area per ha. A score of 50 means a neutral effect, whereas a higher score a positive effect and a lower score a negative effect. Application of the Tool in the 36 sampling vineyards resulted in total biodiversity scores ranging from 35 to 80, with a mean score at 56. Current work focuses on further validation and adjustment of the Tool.

Conclusions

The results of the GHG emissions study support the design of eco-schemes relevant to C farming. The practices typically applied in Cypriot viticulture could be relatively easily transformed towards Zero emissions grape production. For this, reduced tillage and preserving natural vegetation is the key. In general, practices that reduce the carbon footprint, such as reduced tillage and natural vegetation, provide biodiversity benefits, and therefore optimizing CF-biodiversity relevant practices provides double benefits. The work is a good starting point towards sustainable, zero emissions viticulture, also highlighting the maintenance of natural vegetation and not only the reduction of inputs for cultivation.

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Accompanying agro-ecological transitions through eco-design: For a better consideration of nitrate emissions in viticultural LCA.

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ABSTRACT:
In the frame of the AVATEC research project, models for calculating nitrate emissions were compared to determine those that combine the best consideration of soil management and fertilisation practices, accuracy, and availability of entry data for use in LCAs evaluations for eco-design of viticulture, especially with the Vit'LCA tool for LCA calculation for viticulture.
Three steps were followed: i) selection of nitrate emission calculation models from the scientific literature, ii) detailed study and test of the pre-selected models, and iii) validation using a set of data from the PEPSVI experimental system and from a commercial Vineyard to check data availability for practitioners. A selection grid with 23 parameters allowed a synthesis.
Three models were compared Azote Viti, INDIGO® and SQCB. SQCB was little sensitive to climate and soil management and fertilisation practices. Azote viti was sensitive to fertilisation but highly overestimated nitrate emissions compared to measurements and INDIGO® was more sensitive to plot than to modalities but with values closer to plot measurements. INDIGO® got the highest global score in the selection grid but the difficulty of accessing certain parameters remains, and more uncertainties. The model selection grid allowed to compare the models on a set of different criteria. INDIGO® got the higher score even if still needing refinements, like inclusion of previous years fertilisation. Consistency between field data and model results was not obtained. Sensitivity analysis and increase of the datasets, and a new version of INDIGO® calculator would consolidate the results of this study

INTRODUCTION: The adoption of sustainable practices in agriculture is necessary. The AVATEC research project (FEDER, 2018-2022) on the agro-ecological evolution of wine-growing areas is in line with this logic by accompanying Protected denominations of origin (PDOs) vineyards for the choices of best practices through ecodesign. A focus was done in the project on soil management and fertilisation practices. In order to accurately assess these practices impacts, it is necessary to improve the consideration of nitrate emissions in the vineyard LCA inventory. The streamlined LCI and LCA calculator dedicated to viticulture assessment and ecodesign called Vit'LCA (Renouf, Renaud-Gentié et al. 2018) was used in the AVATEC project. Vit'LCA must be updated concerning nitrate emissions by vineyard.
Different models for calculating nitrate emissions found in literature can be considered for viticulture LCA, like SALCA-NO_3 (Nemecek-and-Kagi 2007), Denmark calculator of leached nitrate (Audsley, Alber et al. 1997), or SQCB-NO_3 (Koch P. 2015). However, when it comes to account for detailed practices and environmental conditions for eco-design, all the models don't offer the same advantages.
In this study, three models for calculating nitrate emissions were compared and applied to determine those that combine the best consideration of soil management and fertilisation practices, accuracy,

and availability of entry data for use in LCAs evaluations for eco-design of viticulture.

METHODOLOGY: Three steps were followed: i) selection of nitrate emission calculation models from the scientific literature, ii) detailed study and test of the pre-selected models, and iii) validation using a dataset of nitrate leaching measurements. Then all was synthetised in a selection grid.

For the choice of the models, the methodological reports and documentations of the models and scientific papers were used.
For testing the models and check data availability for practitioners, we constituted a dataset from one plot from a commercial Vineyard, in Anjou region, planted with Cabernet Franc for rosé wine production, and characterised during three vintages: 2018, 2019 and 2020 with different rainfall levels. Soil management practices were identical during the three years with 40% of the surface with grass mowed and herbicide use on 60%. Mineral fertiliser was applied on the plot: 19.8kg N/ha in 2018 and 2020.
For model test and validation with leaching measurements, we selected four contrasted situations from the PEPSVI dataset (Thiollet-Scholtus, Muller et al. 2020) under a vineyard from the PEPSVI experimental station in Alsace (UEAV, INRAE, 2018. Viticulture Facility), France, as follows:
-The 2014 vintage of the organic system (BIO 2014) planted with Pinot Blanc: experimentation of pathways of technical operations (PTOs) with replacement of herbicides by mulching; the four PEPSVI experimental plot were planted in 2014, so BIO 2014 will be considered in this study as a young vineyard, with young vine characteristics;
-The 2017 vintage of the system designed with a vine resistant variety to downy mildew and powdery mildew (RES 2017), the soil is managed by herbicides and tillage;
-The 2020 vintage of the integrated production system (PI 2020) planted with Pinot Blanc: reference system representative of the experimental station's practices, soil management is like RES 2017;
-The 2020 vintage of the system designed with the same vine resistant variety as RES 2017 (RES 2020), with grass under the vine row.
Mineral fertiliser was applied for BIO 2014 (140.57 kg N/ha) and RES 2020 (30 kg N/ha).
For both PEPSVI and Anjou datasets, practices data were collected by interviewing the manager of each plot.

We listed 23 parameters that could be considered by these different nitrogen emission models, and a selection grid was established in consultation with the research team and based on the initial bibliographical study of the models (Brentrup, Küsters et al. 2000; Thiollet 2003; Faist Emmenegger, Reinhard et al. 2009.; Bellon-Maurel, Peters et al. 2015) to determine the models corresponding to the needs of the project. The scoring of the criteria used for the score is as follows:

- Total number of entry parameters (n): 1 for high (n between 20 and 50), 2 for medium (n between 8 and 20 and 3 for low (n less than 8).
- Data accessibility: 3 for very high, 2 for high, 1 for medium, -1 for low and -2 for very low.
- Consideration of viticultural practices: 4 for very good, 3 for good, 2 for medium and 1 for low.
- Site dependency taking account entry parameters (n): 3 for high (n more than 14), 2 for medium (n between 7 and 14) and 1 for low (n less than 7).
- Time dependency through time-related entry parameters: 4 for very high, 3 for high, 2 for medium and 1 for low.
- Ease integrating formula in MS Excel: 1 for very difficult, 2 for difficult, 3 for not very difficult and 4 for easy.
- Model field validation: 3 for closer, 2 for close enough and 1 for less close.

The total score for each model was obtained by summing the product of the criterion weight with the corresponding score.

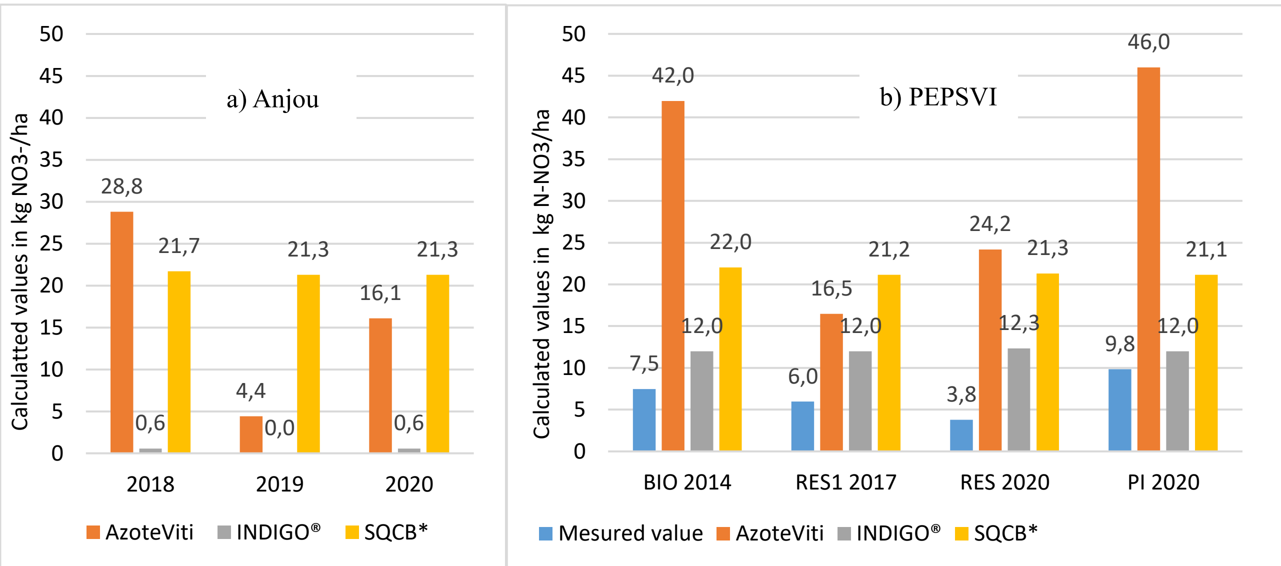
RESULTS AND DISCUSSION:

Preselection of the models:

Three models were pre-selected for an advanced comparison because of their applicability to viticulture and their consideration of viticultural practices (residue management, weed control, etc.), and the constraint of having data easy to obtain: INDIGO® (Thiollet 2003), AzoteViti (Bellon-Maurel, Peters et al. 2015) and SQCB-NO_3 (Faist-Emmenegger, Reinhard et al. 2009). INDIGO® and AzoteViti were used through Excel calculators existing (AzoteViti) or adapted by us (INDIGO®) and SQCB through calculation formulas. Two other models were set aside (Brentrup, Küsters et al. 2000; Richner, Oberholzer et al. 2014) as they were not directly suitable for viticulture or the formulas for calculation were not available, moreover, SalcaNO3 is more suitable for the relative comparison of different crop variants, than for the calculation of absolute nitrate leaching amounts (Nemecek and Schnetzer 2011; Richner, Oberholzer et al. 2014).

Test and Comparison of the results of models

The figures 1a and b below is a comparison of the models used to calculate leached nitrates. It shows that SQCB model values are nearly constant between 21 and 22 kg No3/ha in all tested situations, it is thus not useful to distinguish a modality or a vintage from the others. INDIGO® shows few variations between vintages or modalities for a same plot however it differentiates a plot from the other. AzoteViti is the most sensitive to variations of fertilisation than the other models and gives higher values on the PEPSVI plot than on the Anjou one. It will be interesting to consolidate these results with data from other plots, and by a sensitivity analysis of the models to the entry parameters variation to better identify the reaction of each model to practices and weather.



Figures 1a) and 1b): AzoteViti, INDIGO® and SQCB models comparison for N leached a) on the Anjou plot, France. b) with measured values on the PEPSVI plot, in Alsace, France.

SQCB*: SQCB in Vit'LCA with fixed assumption on soil depth = 2m and soil N org content = 35 kg N/ha.

Validation of the models with plot measurements:

The figure 1b includes leached nitrates plot measurements for the PEPSVI plots. It shows that the 3 models results are all higher than the measured values. The lowest models' results are for INDIGO® model. And INDIGO® model results are the closest to the measured values. Whereas AzoteViti model results are different for BIO 2014 and PI 2020 plots (42,0 and 46,0 respectively) and for RES 2017

and RES 2020 (16,5 and 24,2 respectively).
The models gave results sometimes very far from field measurements partly because they don't consider the variations of N stock due to previous years practices, and possibly due to the variability of the results of field measurements by lysimeters under the vineyards.
The low number of data is a limit to the results of this study, but plots instrumented for nitrate leaching measurements are rare in viticulture, it would thus be interesting to increase the number of data with future years of measurements on the PEPSVI plot to consolidate our results and conclusions.

Comparison of the models according to the selection grid:
The Table 1 which summarises the comparison of the models by scoring from the assessment according to the 23 parameters.
The Anjou dataset was used to check data availability for filling the models from a classical LCI done in a winegrower's interview. SQCB was the easiest to fill as it demands the lowest number of entry parameters (17) of which 13 very accessible and 3 difficult to access, giving a total score of accessibility of 34, INDIGO® demands 35 parameters of which 22 easy to access and 12 difficult to access giving a total score of accessibility of 32, due to the high number of easily accessible parameters ; and AzoteViti demands 27 parameters of entry of which 11 easy to find and 14 difficult to access, it gets the lowest accessibility score 5. Whereas SQCB considers 3 parameters of viticultural practices, and INDIGO® 15, they didn't prove to be sensitive to them in the calculation results. This has to be further investigated by sensitivity analysis.

Table 1: Nitrate emission models results in the selection grid.

Criteria	Criteria weight*	Model score		
		AzoteViti	INDIGO®	SQCB
Total number of entry parameters	2	1	1	2
Data accessibility	4	5	32	34
Consideration of viticultural practices	3	1	15	3
Site dependency	3	3	3	2
Time dependency	2	4	6	2
Ease Integrating formulas in MS Excel	4	1	2	3
Model field validation	4	1	3	2
Total score		50	216	179

***Criteria weight**: Very important 4, important 3, quite important 2 and less important 1.

The INDIGO® model got the overall highest score (table 1). However, the difficulty of accessing certain parameters and the model readjustment to the vine during this study make the INDIGO® the most subject to uncertainties among the models tested. Moreover, some assumptions like 30cm for the soil horizon depth for nitrogen mineralization or the calculation of vine's nitrogen requirement need further refinement. A new version of this model should be available soon and will permit to consolidate these results.

CONCLUSION: The model selection grid established during the study was a good means to compare the models on a set of different criteria. It should be completed by a sensitivity analysis of the models to their entry parameters. It pointed out the INDIGO® model as the best-suited to the needs of the study however needing further refinement. The study also showed the difficulty of a consistence between field data and model results. Field validation put in evidence the importance of previous years fertilization practices that are not accounted in all the models. Further investigations need to be done in the future with an extended dataset to consolidate these results and with the coming new INDIGO® calculator that still must be adapted to vineyards. Last, the question of how many previous fertilization years should be considered in the chosen model should be addressed. The calculator should then be integrated into the Vit'LCA tool for LCA calculation for viticulture.

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Developing a point system for farms to reduce greenhouse gas emissions by 10%

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Keywords: GHG emissions of farms; GWP reduction goals; point system climate protection

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Introduction

Agriculture is a major contributor to global warming, and efforts must be made to reduce this impact. One of the most important agricultural producer and distributor associations in Switzerland, IP-SUISSE, has recently launched a "point system climate protection" which makes it mandatory for all member farms (around 10,000) to implement greenhouse gas (GHG) reduction measures for which they get a certain number of "climate points". The goal is to reduce the overall global warming potential of the association by 10% compared to 2016. The underlying calculation system and the greenhouse gas saving potential of measures were developed by Agroscope together with IP-SUISSE. In this contribution, we describe the different components of the point system and their calculation.

Design of the point system

Four components are necessary for a workable point system (figure 1): 1) The baseline, i.e. the total GHG emissions of all member farms in the base year (2016). 10% of this figure is the overall reduction goal of the association IP-SUISSE. 2) An information on the GHG emissions of each member farm to determine their individual goal on how many climate points they need to achieve. 3) A catalogue of GHG emission reduction measures with a defined GHG saving potential (translated into climate points) that every farmer can choose from in order to achieve their individual goals. 4) A working online tool where farmers can submit their data and that allows the association to monitor the success of the program. The system needs to be flexible so it can adapt the overall reduction goal if the association grows over the years. Agroscope delivered the components 1) to 3). Component 3), the catalogue of measures, is described in another contribution to this conference (Stüssi et al.). Component 4), the online tool, is currently being developed. Here, we focus on components 1) and 2).

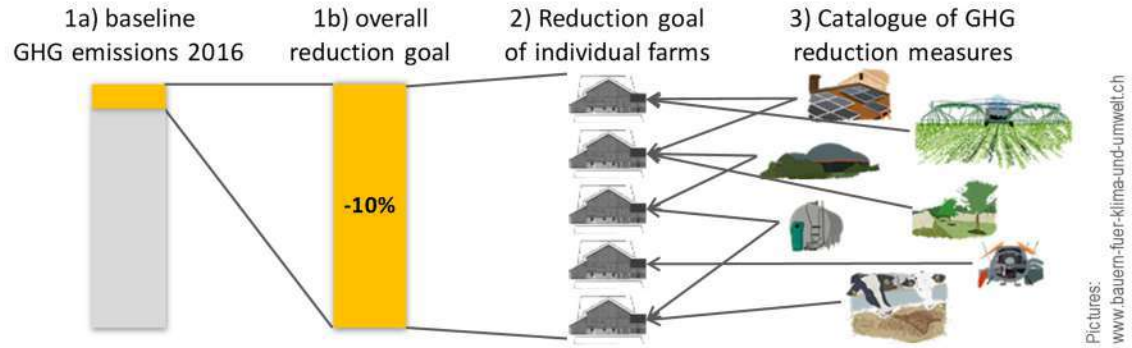


Figure 1: Components of the point system climate protection

Underlying methodology

For components 1) and 2) it was necessary to estimate GHG emissions with few general metrics that are available for all farms. We used data from 33 pilot farms to calculate their GHG emissions in detail using the SALCA method (Swiss Agricultural Life Cycle Assessment), which calculates direct and indirect emissions. This requires detailed activity data from the farms on crop cultivation, animal husbandry, machinery and infrastructure use, and purchase of fertilizers, pesticides and other inputs, which we collected from the pilot farms in 2016. Using the results, we tested the correlation of the pilot farms' calculated GHG emissions with a number of general metrics that are available for all Swiss farms – e.g. total agricultural land, arable land, livestock numbers, animal categories, etc. This resulted in a formula with which to estimate GHG emissions of the total of the IP-SUISSE member farms.

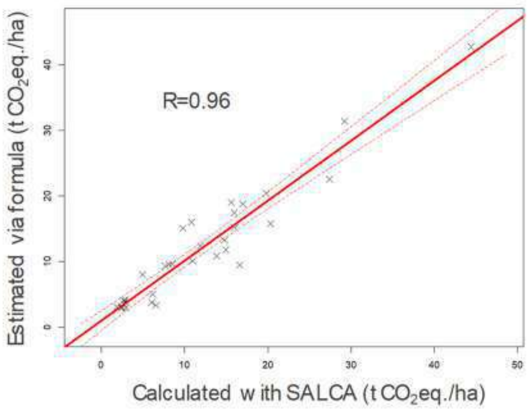
Results and discussion

The GHG emissions per hectare of the pilot farms can be approximated by a function of livestock units (*LU*) and the share of open arable land (*OA*) per hectare agricultural land (*AL*). The livestock units correlate strongly with methane emissions and emissions from purchased feedstuff, while the open arable land area correlates strongly with machinery use and N_2O emissions from fields. Statistical analyses showed that a polynomial regression approach was best suited for our purpose. Eq. 1 shows the preliminary regression formula, which we used it to estimate GHG emissions in t CO_2eq. per hectare agricultural land of all IP-SUISSE farms (GHG_{farm}). Hectares were chosen as a reference for the statistical analysis to ensure that small farms are similarly weighted than larger ones. In the point system itself, all values are given per farm.

Eq. (1): $GHG_{farm} = 10.56 - 2.73 \times \frac{LU}{AL} + 1.48 \times \left(\frac{LU}{AL}\right)^2 - 23.61 \times \frac{OA}{AL} + 17.91 \times \left(\frac{OA}{AL}\right)^2$

Figure 2 shows a high positive correlation between the GHG emissions as calculated with SALCA and estimated using the regression formula.

Figure 2: Correlation between the GHG emissions of pilot farms calculated with SALCA and estimated via the regression



The mean relative error of the estimated and calculated GHG emissions is 24.8%. Over the entirety of the calculated farms, the deviations largely cancel each other out. The regression constitutes a rough estimate and does not serve for advisory purposes to communicate GHG emissions of individual farms. But it is sufficient to estimate the overall GHG emissions of a large network of farms; it leads to very similar results as other sources (FOEN, 2020). We used the regression formula to calculate both the baseline (component 1) and the individual GHG reduction goal for each member farm (component 2). The latter is set higher than 10% of each farm's GHG emissions to compensate for "pioneer efforts", i.e. GHG-reducing measures that were already implemented before 2016 and therefore do not count for IP-SUISSE's reduction goal.

IP-SUISSE member farms from 2021 on have to deliver information on the climate protection measures that they implement on their farms, and if they do not reach their individual goal, they have to implement more measures or ultimately have to leave the association. This would mean a financial loss, as they get payed higher product prices when they produce under the IP-SUISSE label. Apart from that, Swiss agricultural policy also has climate protection goals (greenhouse gas emissions have to be reduced by 40% in 2050 compared to 1990), but it is not yet clear how these will be enforced. Nevertheless, it is to be expected that farms, even if they leave IP-SUISSE will have to implement climate protection measures on the long run.

Conclusion and outlook

Our work provides the necessary background for a point system climate protection, which currently is being put into practice, with 2021 as the first year of compulsory participation. In the coming two years, we will analyze whether all farms can reach their individual reduction goals or whether these have to be adjusted, e.g. according to farm type or their pioneer efforts, and we will monitor the success of the approximately 10,000 farms to see if they can achieve their goal of reducing the overall GHG emissions by 10%.

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Participatory eco-design at production basin scale, case study in viticulture

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Introduction: Viticulture territorial bodies like protected denominations of origin (PDO) are expected to develop their environmental policies and actions. The Cognac PDO, through the DOMECCO project, chose to implement Life Cycle Assessment (LCA) with researchers for environmental burdens and best practices identification in grape production and transformation. As all winegrowing territories in Europe, Cognac is on the way to replace herbicides in the vineyards by alternative soil management strategies. The PDO wishes to involve some of its members for generation and discussion of ideas and solutions and to assess the environmental soundness of these strategies. Participatory design is implemented in agriculture, it permits stakeholders empowerment and knowledge sharing around an common object (Meynard et al. 2012; Belmin et al. 2022) However, to be effective, this innovative design must 'mobilise collective and distributed intelligence' (Belmin et al. 2022). Basing agricultural co-design on LCA results has still been little implemented (Kulak et al. 2016). In viticulture, Rouault et al. (2020) proposed and tested a framework and tools for participatory eco-design of vineyard management at field scale with winegrowers. A serious game, was derived from this work (Renaud-Gentié et al. 2020).
This research aims to explore the feasibility and interest of an LCA based participatory eco-design process for a prospective reflection in a collective organisation covering a wide territory and implying a variety of stakeholders like a PDO. Vineyard soil management will be the case study.

Material and methods: Rouault et al.(2020)'s framework and the serious game Vitigame (Renaud-Gentié et al. 2020) providing tools for participatory eco-design in viticulture were used and adapted to meet the objectives of the research and time constraints of the participants. The eco-design workshop was introduced by knowledge input to participants about LCA and environmental impacts. The participants were dispatched around 3 tables (Fig.1), each facilitated by an LCA and viticulture scientist and an agent of the PDO specialised in viticulture or environment. Eco-design was based on LCA results of a real case of vineyard pathway of technical operations (PTO) representative of the PDO main soil management practices. The eco-design work was focused on soil management, and fertilisation was included as this practice is correlated to soil management choices, with the objective to design a low impact soil management PTO without herbicides. The main fixation bias - i.e. reluctance to propose innovations too different from what they already know (Della Rossa et al. 2022) - identified by the scientists through the experience of previous eco-design workshops with winegrowers was related to the fact that the eco-designed PTO is for contemporaneous implementation, then some participants resist to introduce very innovative solutions that they judge not possible to implement immediately in the vineyard. To limit this fixation bias, the participants had to design a PTO for year 2030.
The 17 participants were elected members of commissions of the PDO with various profiles: winegrowers, vine nursery manager, individual distillers, environmental or technical managers of big distilleries, viticulture extension officers, and agents of the PDO. The LCA results of the eco-designed cases were calculated and presented to them in the same day and they were asked to fill in

a feedback survey at the end the day to feed the reflexive analysis.
The LCA results used for and from the workshop were calculated from cradle to field gate with Recipe 2016(H), thanks to VitLCA calculator (Renouf et al. 2018) which includes LCI calculations. The functional unit was "1ha of vineyard cultivated for 1 year". Primary data came from field survey and secondary data from Ecoinvent 3 and Agribalyse 3.

Figure 1: One of the three tables where participants were dispatched with facilitators and a view of the Vitigame eco-design serious game used here for eco-design of vineyard soil management and fertilisation**.**

Results: <u>Hotspots of the initial case:</u> LCA results were shown to the participants after explanation of the meaning and phenomenons concerning each impact category, for a selection of categories (see Fig.2). We presented the contributions to the impacts of the part of the PTO on which the workshop was focused i.e. soil management and fertilisation (SM & F) relatively to the full PTO's (tot PTO). The main hotspots are fertilisers manufacturing and emissions, pesticides manufacturing and emissions and fuel combustion emissions from machine use, and SM& F represent from 8 to 93% of the impacts depending on the impact category.

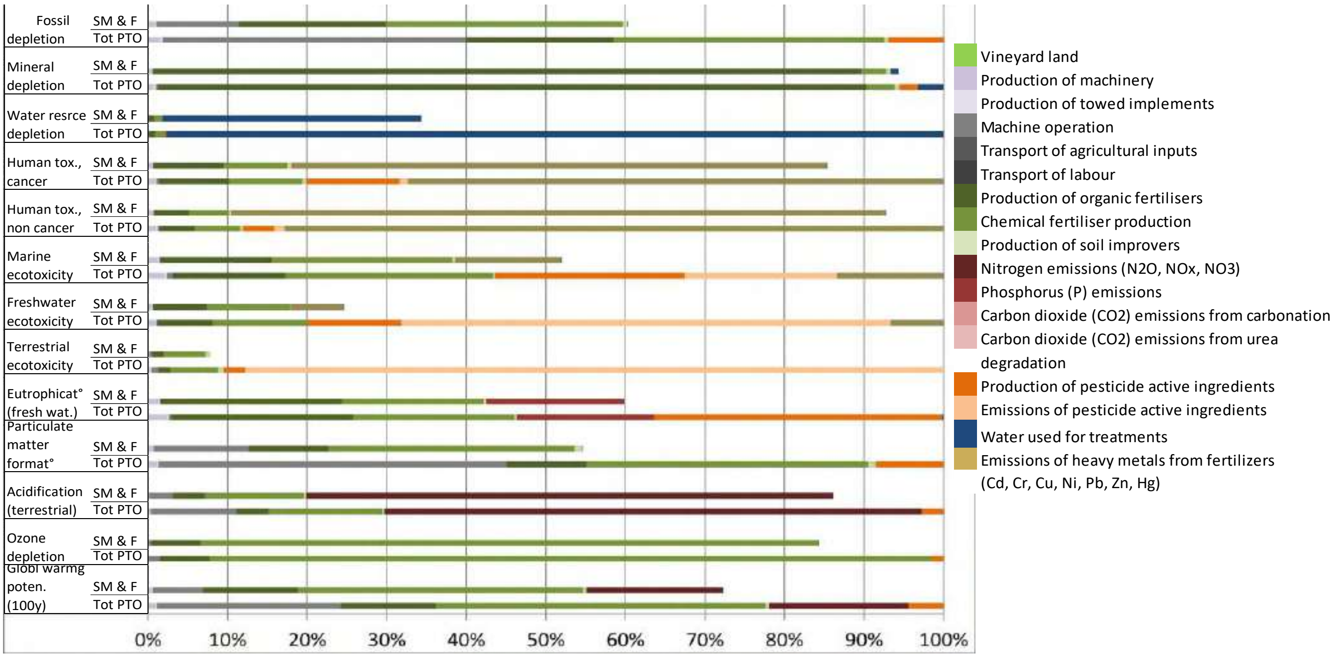

Figure 2: LCA Contribution chart shown to the participants for the reference case, Recipe Midpoint (H) FU: 1ha of vineyard cultivated for one year. SM&F = annual soil management and fertilisation pathway; Tot PTO = total annual pathway of technical operations for the vineyard.

Interactions between the participants and eco-design choices: The workshop lasted 1h30. After a time to learn about the case and understand the causes of its impacts calculated by LCA, the dynamics of exchange and of eco-design were different in the three tables according to the profiles and personalities of participants and facilitators. The participatory design generated rich discussions and point of views confrontations around the tables. The ecodesign levers mobilised by the participants in response to identified sources of impact concerned fossil energy replacement, fertilisers, use of grass cover and green manure, grass mowing by sheep or robots, and tools combination on the tractor.
At table 1, the decision was made not to worry about the yield of the vineyard and the participants decided to grass all the floor with green manure, permanent grass in the alleys and non-competitive plants (still to be found by research) under the vine row; however, the competition from grass imposed to add organic fertilisation to limit yield decrease. Choice of green manure was made after careful consideration. An autonomous diesel robot, lighter than a tractor, was taken for mowing under the row. Solutions adopted to save diesel for the other operations, were "Vario" technology, eco-driving and reduction of the number of passes by tools combination on the tractor. The group imagined tools and grass varieties that do not yet exist, particularly for soil maintenance under the vine row. For table 2, we noticed fixation, a participant imposed to the group the necessity of a high technical feasibility of the strategies based on nowadays available solutions. However, they proposed a well optimised PTO in terms of machinery use and searched for the best solutions for weed management under the vine row. Different important questions were discussed: i) The yield: should we fertilise and maintain it or leave it decrease to reduce the impacts of fertilisation? leading to the following question to be explored in further studies for their PDO: "is it better for the environment to produce more on a smaller area or less and with fewer inputs especially fertilisers, on a larger area? ii) Energy: solutions were looked for to replace fossil fuels with used cooking oil from restaurants, Hydrogen, leading to the following question to be explored in further studies for their PDO: "which sources of energy for viticulture machines will be available and should we encourage for the future on our territory?", iii) incompatibility between "green practices" like green manure and sheep grazing or mowing robots and protection of hedgehogs. At table 3, another element of fixation was observed, one of the participants imposed to maintain production at the maximum yield authorised today in the Cognac PDO. A long period of discussion on yield, on the opportunity of the use of wooden chips mulching and the most appropriate green manure management preceded the construction of the PTO. The decrease of impacts was targeted by replacing fossil fuels 100% per electricity, synthetic fertilizers by organic ones, herbicide use by sowing green manure and roll it later to create a mulch on half of the surface and tillage on the other half, and by tool combinations on the machine (sowing+blade+discs), however the competition from grass imposed to add fertilisation to maintain the targeted yield.

Eco-design results:
The replacement of synthetic and organo-mineral fertilisers by organic ones permitted important decreases of impacts (Fig. 3) due to their manufacturing for all the tables like mineral depletion (-94%), fossil depletion (-35 to -59%), Ozone depletion (-48% to -90%), or due to their emissions of N or heavy metals as human toxicities and ecotoxicities. Impacts decreases were more limited in table 2 by the quantity of organic fertiliser used (3 times more than in table 1 for example) and the introduction of sheep grazing generating water use and emissions of CH_4 and N compounds, Table 1, with a low organic fertilisation, generated the best results. The replacement or decrease of Fossil energy use were the main drivers for diminution of Contribution to climate change, particulate matter formation, Fossil resources depletion and Acidification. The table 3, with 100% electric machinery got the best results overall but even more on these categories.

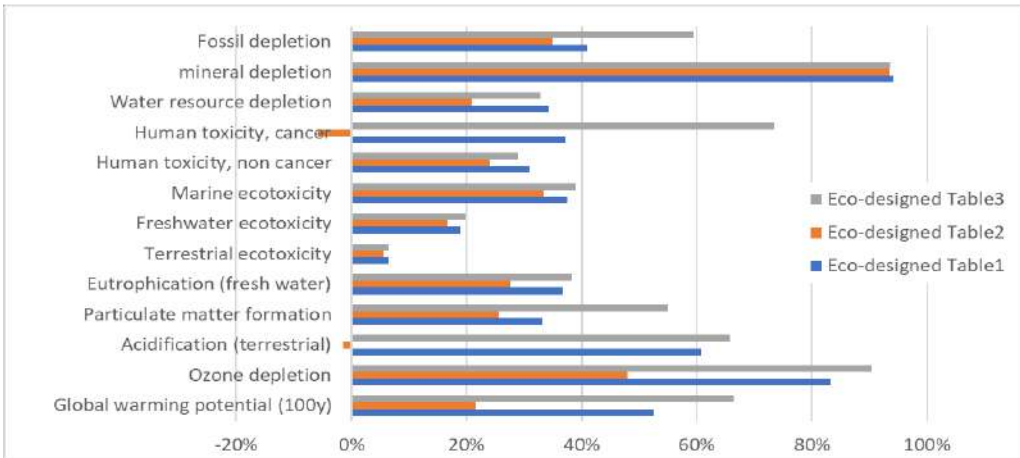

Figure 3: Percentage of decrease in environmental impacts, obtained by the 3 groups (called tables 1 to 3) of stakeholders, related to a reference case (identical case for all groups), FU: 1ha vineyard cultivated for 1year.

<u>Feedbacks from participants:</u> A participant suggested to add the Gustafson index for water pollution by pesticides as a complementary indicator to LCA. Some facilitators pointed out the complexity of results chart for the participants. Most participants (85%) felt that the session had enabled them to gain a better knowledge and understanding of the contributions of practices to environmental impacts, and that the LCA method was useful in helping to clarify technical choices in Cognac AOC from an environmental point of view. All the participants felt that the session had provided useful elements for reflection on AOC Cognac, and 62% of the participants felt that the discussions helped them to reflect on soil maintenance practices. Several mentioned that it would be interesting to repeat this experience with a complete technical itinerary. Suggestions for improvement were given (more information on the type of soil, more time to put together the technical itinerary, more people in the field at each table, etc.).

Discussion and conclusions: This process, as a step in the definition of environmental policy of the PDO, was successful to involve stakeholders, to make them understand and manipulate LCA results and eco-design and catalysed discussions and prospective thinking at PDO scale. It could '*mobilise collective and distributed intelligence*' as advised by Belmin et al (2022), the diversity of profiles of the participants brought richness to the debates; it might, also have increased the power of fixation of certain participants with a better technical knowledge and could impose their views. Concerning LCA, fertilisation was the main hotspot of the viticulture reference case for the workshop, making it a priority for eco-design, followed by diesel combustion. The participants, helped by the facilitators and the initial presentation, well identified the ecodesign objectives and levers, even if the charts were sometimes difficult to read. They mobilised different solutions according to the groups giving average improvement rates (38%, 22% and 51% respectively for the three tables) comparable to previous experiences made by Rouault et al. (2020) with 33% in average. However, as they also could experience, some LCA results are not in line with general thinking like the case of sheep grazing in the vineyard which increased the impacts. The workshop raised new strategic questions for the territory like environmental soundness of intensive versus extensive evolution of the production, the replacement of fossil fuels on the territory, the need of experiments on green manures and grass species little competitive to the vines, the role of fertilisers in the environmental performance of the territory. A future step of the study will be to estimate effect of the eco-designed PTOs on yield and potential alcoholic degree and thus on impacts per kg of grapes and par Hl of pure alcohol. Finally, communicating LCA results to stakeholders for eco-design and more widely for decision remains a challenge as pointed out by Guérin-Schneider et al. (2018), which should be addressed and tested in such context in the future. More generically, this experience showed that participatory eco-design can successfully be used at PDO scale in a prospective reflection process.

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Prospective life cycle assessment of viticulture under climate change scenarios

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Abstract

Purpose The viticulture sector is facing climate change, which has already caused loss of production due to more frequent extreme events, with potential increased impacts in the future. Therefore, winegrowers need to envision adaptation levers to cope with the effects of expected climate change on future grape production. Nonetheless, the influence of projected climate change and the implementation of adaptation options on the environmental performance of viticulture has not been evaluated. This study aims to perform a prospective life cycle assessment (LCA) of grape production in two contrasted French vineyards, one located in the Loire Valley, and another in Languedoc-Roussillon, according to two *Shared Socioeconomic Pathways* (SSPs) associated with low and high greenhouse gas (GHG) emissions.

Methods We performed a prospective LCA at two levels of analysis. First, we evaluated the effect of climate-induced yield change on the environmental impacts of future viticulture according to the time series of grape yield, temperature, and precipitation. Second, in addition to climate-induced yield change, we included the projected impacts of extreme weather events, namely hail, heatwaves, droughts, spring frost, and phytopathology on grape production and the adoption of adaptation options according to the forecasted probability and potential yield loss rate caused by extreme events.

Results and discussion When accounting for only the climate-induced yield change, the LCA scores indicate divergent conclusions for the analyzed vineyards. The carbon footprint of the vineyard located in Languedoc-Roussillon is forecasted to increase by 29% under the high GHG emissions scenario (SSP5-8.5), while the carbon footprint of the vineyard situated in Loire Valley is expected to decline by roughly 10%. Nevertheless, when accounting for the impacts of extreme events and the adoption of adaptation levers, the potential environmental impacts of grape production under future scenarios are forecasted to rise considerably for the vineyards of the case study. By the end of the century, according to the SSP5-8.5 scenario, the carbon footprint for the vineyard of Loire Valley would rise threefold compared to the present footprint, whereas it would increase fourfold for the vineyard of Languedoc-Roussillon.

Conclusions Overall, our study demonstrates the feasibility of conducting a prospective LCA by applying the principle of parsimony, i.e., using relatively simple models with available data, on two contrasted French vineyards. The findings indicate the relevance of considering the impact of both climate change and extreme events on the LCA results of viticulture under prospective scenarios.

Keywords: *Climate change, Life Cycle Assessment, Environmental impacts, Viticulture, Prospective LCA*

Introduction

The viticulture sector is facing climate change, which has already provoked the earliness of harvest dates, an increase of pests and disease in wetter regions, frequent water stress in Mediterranean vineyards, changes in grape composition, higher alcohol content, lower acidity, and more dramatically, loss of production due to more frequent extreme events (Marín et al., 2021; Santos et al., 2020).

Nevertheless, future estimates of grape yield in Europe show divergent patterns. While augmented drought over southern regions will entail reductions in grape yield, increases in the atmospheric concentration of CO_2 may partially offset the dryness impacts, promoting yield increases in central and northern Europe (Fraga et al., 2016; van Leeuwen et al., 2019). Since more frequent extreme events are expected under climate change, particularly heatwaves and drought, there is a growing concern that these events cause a reduction in grape yield and quality under future conditions. To cope with extreme events, some short-term adaptation levers comprise irrigation, modification of vine management practices, and the installation of anti-hail nets, fans, and heaters (Naulleau et al., 2021; Sacchelli et al., 2017). Nonetheless, the influence of forecasted climate change and the adoption of adaptation options on the environmental impacts of viticulture has not been evaluated. This study aims to perform a prospective LCA of grape production in two contrasted French vineyards, one located in the Loire Valley, and another in Languedoc-Roussillon, according to two *Shared Socioeconomic Pathways* (SSPs) giving the range of low and high GHG emissions.

Materials and methods

Baseline scenarios were first defined for the LCA of two French vineyards, one located in the Loire Valley and another in Languedoc-Roussillon. The life cycle inventory was based on traceability and working reports of the analyzed vineyards. Direct emissions resulting from the application of fertilizers and metal-based fungicides were computed with AGEC-LCI (Viveros Santos et al., 2020), and emissions from organic pesticides were modelled with the version adapted to viticulture of PestLCI2.0 (Renaud-Gentié et al., 2015). In a second step, by means of detrending, the sensitivity of grape yield to climate variables was computed based on grape yield datasets from Agreste (2021) and climate data from Agri4Cast Resource Portal (Biavetti et al., 2014). Detrending produced residuals of yield ($\Delta Yield$) (kg ha^{-1}yr^{-1}), average temperature (ΔT_{avg}) (°C yr^{-1}) and total precipitation (Δppt) (mm yr^{-1}). Successively, we performed linear regressions with yield residuals ($\Delta Yield$) as the dependent variable and residuals of average temperature (ΔT_{avg}) and total precipitation (Δppt) as explanatory variables. The slope coefficients of these linear regressions correspond to yield change per unit change in mean temperature (kg ha-1 °C^{-1}) and total precipitation (kg ha^{-1} mm^{-1}). We computed maps of change in average temperature and total precipitation during the growing season of wine grapes by calculating the difference between current and future climate, according to four future periods and two SSPs (SSP1-2.6 and SSP5-8.5) derived by the GCM IPSL-CM6A-LR (Fick and Hijmans, 2017). Successively, according to Eq. (1) the expected change in grape yield $\left(E(YC)_{t,s}\right)$ due to projected climate change for each period (t) and SSP (s) was computed by adding the product of the sensitivity of grape yield β_c to each climate variable (c) (i.e., the slope coefficients of linear regressions, kg ha^{-1} °C^{-1} and kg ha^{-1} mm^{-1} for average temperature and total precipitation, respectively) and the projected change in average temperature and total precipitation ($\Delta C_{c,t,s}$) for period (t) and SSP (s).

$$\mathrm{E}(YC)_{t,s} = \sum_{c} \beta_c \cdot \Delta C_{c,t,s} \tag{1}$$

Third, the framework proposed by Sacchelli et al. (2017) was employed to include the effect of extreme events on future grape yield and the implementation of adaptation levels. According to Eq. (2), the expected yield loss rate ($E(YLR)_{t,s}$) (%) for each period (t) and SSP (s) caused by an extreme event (e) was calculated based on the expected probability of the extreme event – $P(e)_{t,s}$ (%) – and its potential level of damage (d_e). The expected probability $P(e)_{t,s}$ (%) of frost, drought, heatwaves, and phytopathology was estimated based on agroclimatic indicators (Copernicus, 2021), while the corresponding probability of hail was based on projected changes in summer mean temperature (Fick and Hijmans, 2017). Besides, we assumed that winegrowers activate adaptation levers when the

$E(YLR)_{t,s}$ is greater than 1%. The adaptation levers considered were anti-hail nets, wood-burning system, irrigation, and increase of phytosanitary treatments. The modelling of extreme events and their corresponding adaptation levers is described in more detail in Viveros Santos, et al. (2022).

$$E(YLR)_{t,s} = \sum_{e=1}^{m} P(e)_{t,s} \cdot d_e \qquad (2)$$

Results and discussion

The projected increase in temperature was found to negatively affect grape yield in the vineyard from Languedoc-Roussillon, with a value of -233.7 (kg ha^{-1} °C^{-1}). Nevertheless, the sensitivity of grape yield to temperature was estimated at 151.9 (kg ha^{-1} °C^{-1}) for the vineyard in Loire Valley, which indicates that temperature increase in this vineyard is favorable to grape yield. For both vineyards of the case study, precipitation reduction adversely affects grape yield, with values of -1.34 and -3.88 (kg ha^{-1} mm^{-1}) in Languedoc-Roussillon, and in the Loire Valley, respectively.

The grape yield sensitivities reported previously in combination with the projected changes in mean temperature and total precipitation lead to potential increases in the environmental impact of grape production in the vineyard from Languedoc-Roussillon. However, the opposite conclusion was found for the vineyard from the Loire Valley. The SSP1-2.6 scenario projects the lowest increases in the carbon footprint per kg of wine grapes in the vineyard from Languedoc-Roussillon with a maximum increase of around 8.2% for the period 2061-2080 compared to the baseline scenario, whereas the SSP5-8.5 scenario projects higher increases of 12, 18, and 29% starting from the period 2041-2060. On the other hand, under the scenario SSP5-8.5, the carbon footprint per kg of wine grapes for the vineyard from the Loire Valley could potentially decrease by around 10% by the end of the century. Nevertheless, the potential reduction of the carbon footprint of this vineyard is less pronounced according to the scenario SSP1-2.6, which projects a decrease of around 4% for the same period compared to the current scenario (Figure 1). To put these results into perspective, an LCA of organic viticulture in France found that the interannual variability entails up to 52% of variability per impact category due to the modification of management practices following the diverse climatic conditions and disease and pest pressure (Renaud-Gentié et al., 2020).

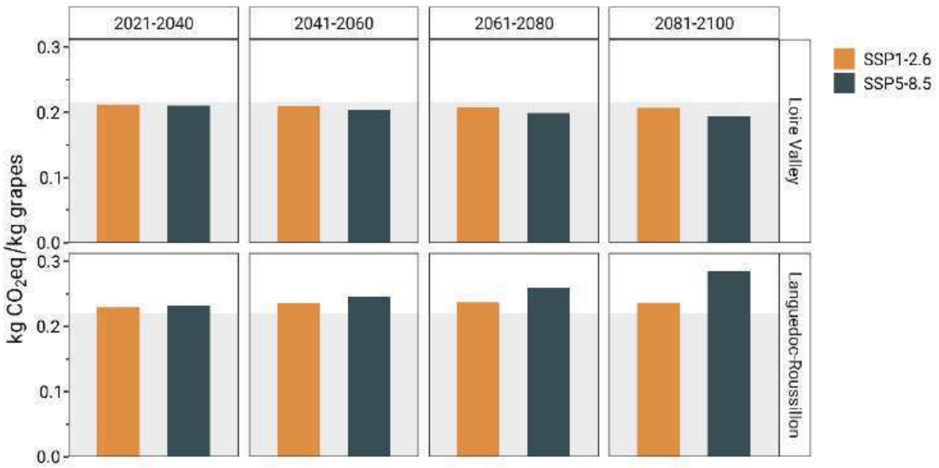

Figure 1. Projected carbon footprint (kg CO_2eq kg grapes^{-1}) associated with grape production in two French vineyards (calculated with IMPACT World+ (Bulle et al., 2019)). The height of the lighter shaded envelope behind the bars represents the impact score of baseline scenarios.

The potential yield loss rates due to extreme events for grape production obtained from previous work (Viveros Santos et al., 2022) were used to account for the influence of extreme events and adaptation levers on the LCA results. As depicted in Figure 2, when including the effect of extreme events, the carbon footprint of both vineyards is forecasted to increase considerably. However, in most cases, the activation of adaptation options leads to lower impact scores (26% on average) compared to a situation in which adaptation levers are not adopted. In those cases, the prevention of yield loss by implementing adaptation levers offsets their corresponding carbon footprint. Previous studies have already shown the crucial effect of grape yield on the environmental profile of grape production in both interannual and interregional dimensions (Renaud-Gentié et al., 2020; Vázquez-Rowe et al., 2012). Regarding the vineyard from the Loire Valley, the highest increase in carbon footprint is expected under the SSP5-8.5 scenario by 2081-2100, for a scenario without adaptation strategies (0.628 kg CO_2eq kg grapes^{-1}), corresponding to an increase of roughly 191% compared to the baseline scenario. However, the lowest increase in carbon footprint for the same vineyard is anticipated under the SSP1-2.6 scenario by the end of the century for a scenario without adaptation levers, with an increase of 44% compared to the baseline scenario. The latter situation is explained by the increase in the carbon footprint by 73% due to the installation of the anti-frost and the anti-hail net systems compared to a scenario without adaptation levers, while the prevention of the associated yield loss is 2.5%. Concerning the vineyard from Languedoc-Roussillon, by the end of the century, the SSP5-8.5 scenario forecasts sharp increases in the carbon footprint of grape production of roughly 326% for a scenario without adaptation levers (0.935 kg CO_2eq kg grapes^{-1}), and of 187% for a scenario with adaptation options (0.630 kg CO_2eq kg grapes^{-1}) compared to the baseline scenario. According to the SSP5-8.5 scenario, for most periods, the carbon footprint of the scenarios adopting adaptation levers is offset by the avoidance of yield loss that adaptation strategies would engender. Nevertheless, the latter conclusion is inverted under the SSP1-2.6 scenario by the end of the century since the expected yield loss rates caused by extreme events are lower than those for other periods, and more specifically those caused by heatwaves. This is explained by the fact that the SSP1-2.6 scenario models low GHG emissions and CO_2 emissions decreasing to net zero after 2050, with fluctuating levels of negative CO_2 emissions afterward (IPCC, 2021). Consequently, less occurrence of extreme events is forecasted under the SSP1-2.6 scenario by the end of the century.

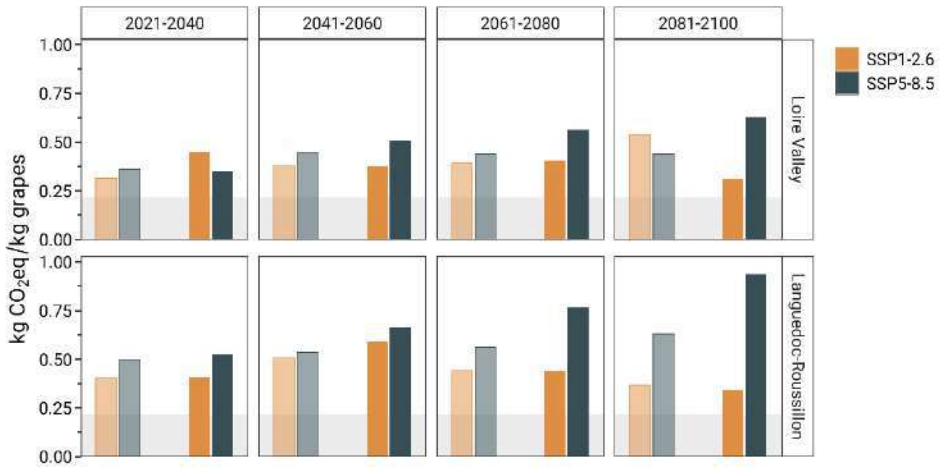

Figure 2. Projected carbon footprint (kg CO_2eq kg grapes^{-1}) associated with grape production in two French vineyards (calculated with IMPACT World+ (Bulle et al., 2019)). The height of the lighter shaded envelope behind the bars represents the impact score of baseline scenarios. The lighter bars indicate the impact score when adaptation levers are activated, while darker bars indicate that adaptation levers are not activated.

Conclusions

The outcomes of this exploratory study indicate that the forecasted changes in mean temperature and total precipitation over the wine grape growing season should influence grape yield in reversed ways in the French vineyards of the case study, which will propagate to the LCA results: while the impact score is projected to increase for the vineyard from Languedoc-Roussillon, it is expected to decrease for the vineyard from the Loire Valley. Nevertheless, when accounting for extreme events and the adoption of adaptation levers, the environmental impacts of both vineyards are projected to increase considerably. Lastly, this study highlights the need to account for climate change when analyzing agricultural systems to enhance the relevance of LCA when applied to prospective analyses.

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02 Oral Session Day 2

LCA-WEF nexus approach to assess meals in Barcelona schools

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Keywords: low carbon meal, food policy, carbon footprint, land use, blue water footprint

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The "Good Food Cities Declaration" is a global initiative that commits to the transition towards sustainable food systems (C40 Cities, 2019). One of the commitments of this declaration is to take action to reduce food waste and ensure sustainable eating patterns for all citizens by 2030. In this regard, Barcelona has committed to several actions within the public-sector meals: increase organic and locally sourced food products, and reduce meat. In addition, after the climate emergency declaration, the municipality of Barcelona has committed to promote healthier diets that are low in carbon in 2021, in schools and all municipal dining rooms. This study evaluates the nutritional and environmental benefits of this transition to low-carbon meals in public schools of Barcelona. To do so, the Life Cycle Assessment (LCA) is used, and a functional unit (FU) that considers the caloric energy and nutritional quality of the meals (Batlle-Bayer et al., 2020) is applied.

In addition, this study argues the importance to combine the LCA methodology with the Water-Energy-Food (WEF) nexus approach, which also has a holistic perspective. The WEF nexus is a concept that evaluates the interactions between three resources - water, energy and food - systems, and it identifies the synergies and trade-offs between them for an optimal integrated management (FAO, 2014). Most WEF nexus studies focus on specific issues at the production level, and little has been done at the consumption level. In this regard, this study selects three common LC-based impacts that can be related to the WEF nexus approach (Blue Water Footprint (BWF), Primary Energy Demand (PED) and Land Use (LU)), as well as, Global Warming Potential (GWP).

Life cycle inventory data of all food ingredients were retrieved from Batlle-Bayer et al. (2019). For LU, data on the average country-specific crop yields from the FAOSTAT were used to estimate the land required to produce all plant-based food products considered in this study. Animal feed consumption was based on the studies considered in Batlle-Bayer et al. (2019). About BWF, country-specific data from Mekonnen and Hoekstra (2010b, 2010a) were used. Data on preparing and serving meals in schools were retrieved from García-Herrero et al. (2019), since primary data were not available. Food losses were based on Garcia-Herrero et al. (2018) and data on food waste in the kitchen and catering service were retrieved from García-Herrero et al. (2019).

The key result of this study is that the transition to a low-carbon meal can potentially reduce between 46 and 60% the environmental impacts. These benefits could even be higher when extra interventions within the school boundaries are applied. This study is an exploratory study and, thus, to improve the current assessment we suggest to involve all key stakeholders within the school food system to obtain primary data on food ingredients and resources (i.e., energy and water) used to prepare and serve the food, as well as the food wasted in the plates in Barcelona schools.

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Sustainable diets optimal design for the massive food services: Economic versus Environmental aspects

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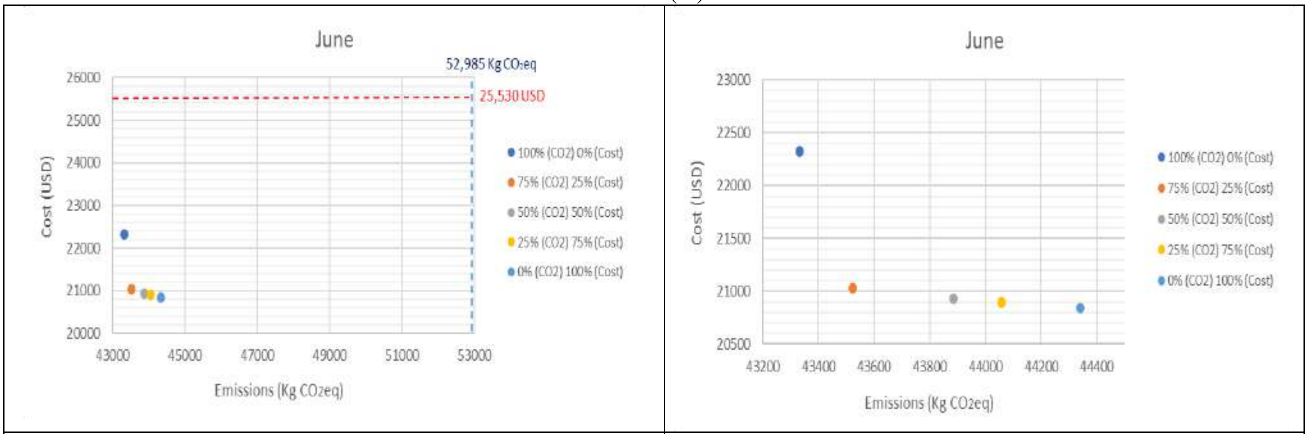
Two important aspects considered by the Sustainable Development Goals are global warming and malnutrition. On the one hand, global warming has had severe negative impacts on the life quality and the efficiency of several productive sectors. On the other hand, malnutrition is a complex issue worldwide, reaching around 60% of the population. In this setting, we conducted a literature review related to diet optimization problems, identifying research challenges and main problems. Consequently, to explore the transformation of the massive food services towards more sustainable consumption patterns, we introduce the sustainable diet design problem for the massive food services. To address this problem, we focus on the trade-off between the equivalent carbon dioxide emitted (CO_2eq) in the process of ingredients production and collection as well as food residues transport and final disposition involved, and the monthly costing. Specifically, we formulate three quadratic mixed-integer programming (QMIP) models: (i) to minimize the CO_2eq from the system subject to nutritional constraints, operational requirements, and cultural acceptability aspects; (ii) to minimize the monthly costing from the system subject to nutritional constraints, operational requirements, and cultural acceptability aspects; and (iii) the ponderation for CO_2eq and monthly costing from the system subject to nutritional constraints, operational requirements, and cultural acceptability aspects.

Chile is one of the wealthiest countries in the Global South and prevalence of overweight (OECD, 2017). In addition, Chile has addressed several international initiatives such as United Nations SDGs and National Determined Contributions, where the reduction of GHGs generation is one of the more important aspects to be considered (Gobierno de Chile, 2020). Consequently, an alternative approach for the generation of public plans and policies that aims to change consumption patterns is relevant. We selected a prestigious public Chilean University located in Santiago, housing all communities on a single campus. Unlike other higher education institutions that have subcontracted food services, this public university is the owner of the University's refectory and is responsible to deliver massive food services for the community, focusing mainly on the scholarship students. In practice, the university's refectory is managed by a specific operational area and provided on average over 3,000 recipes per working day (USACH, 2021). The university refectory offers a daily lunch menu from Monday to Friday, consisting of a starter, main dish, and dessert. The refectory manager plan menus for a planning horizon of one month. The manager also provides us the minimum and the maximum number of calories in addition to the set of nutrients to be considered: 1) proteins, 2) lipids, 3) carbohydrates, 4) saturated fatty acids, 5) fiber, 6) cholesterol, and 7) sodium. Concerning the menus prepared previously, they correspond to the months between June and November 2019. Thus, we use the recipe data to optimize the same planning period considering 44 starter recipes, 76 main dish recipes, and 31 dessert recipes.

Illustration 1 presents the main results for June, where it is possible to appreciate that cheaper menus were obtained with higher CO2eq emissions. In Illustration 1. A, we can observe that all the optimization results provide emissions and cost improvement. At least 16.31% of CO2eq emissions and at least 12.55% of costs can be reduced, considering the emissions and cost for the menu delivered in June 2019.

In Illustration 1. B, we can observe that when both objectives with equal weight were optimized (grey dot) the costs result similar to the lowest total cost obtained, with a difference of only 0.43% (90 USD). Furthermore, the emissions are approximately 1.26% higher than the lowest total emissions (554.77 kg of CO_2eq). It shows us that, despite conflicting objectives, it is possible to achieve a balance to successfully meet both costs and environmental impact reduction.

Illustration 1. Comparison among the different models for the sustainable diet optimal design. The Blue and the red line show the amount of USD and kg CO_2eq for the menu effectively delivered in June 2019. (B) is a zoom of the optimized data of (A)



(A)	(B)

Regarding the nutritional aspect of the optimized diets, the recipes combinations in general respect the established limits. The nutrient that generates "problems" is fiber, but according to the Chilean reality and its consumption deficit, this does not translate into a disadvantage. Illustration 2 presents the comparison for the optimization results against the real values for the menu delivered in June 2019.

Furthermore, the changes in the recipes for the starter are presented in Table 1. Note that the beef soup is presented almost every week in the optimization results, while the chicken soup predominates when emissions are more relevant than costs. In addition, for the real menu delivered, eighteen starter types were prepared, while for the optimizations only 9 o 10 preparations were selected. This indicates that another constraint should be introduced in the model to reduce the starter repetition in the planning horizon.

Regarding the changes in the recipes for the dessert, presented in Table 2, we note that pineapple jelly and semolina with milk are presented all the weeks for the optimized menu. Note that the apple is only delivered when emissions have higher relevance over costs. While the marble jellies, pumpkin-based, and banana desserts are preferred when the cost has relevance over emissions. In addition, for the real menu delivered, eleven dessert types were prepared, while for the optimizations only 7 or 9 preparations were selected.

Finally, concerning the main dish changes, we highlight that only four of the main dishes effectively delivered appear on the optimized menus (beef stew with rice, "carbonada", minestrone, and lentils). Additionally, the main dishes on the optimized menus are the same for each weighted optimization, except for meat in juice with noodles that appears only when emissions weight is 100%, which changes for "ajiaco", a common soup in Latin America.

Illustration 2. Changes in nutrients levels among the optimizations. Blue line: lower level for nutrients. Orange line: upper level for nutrients.

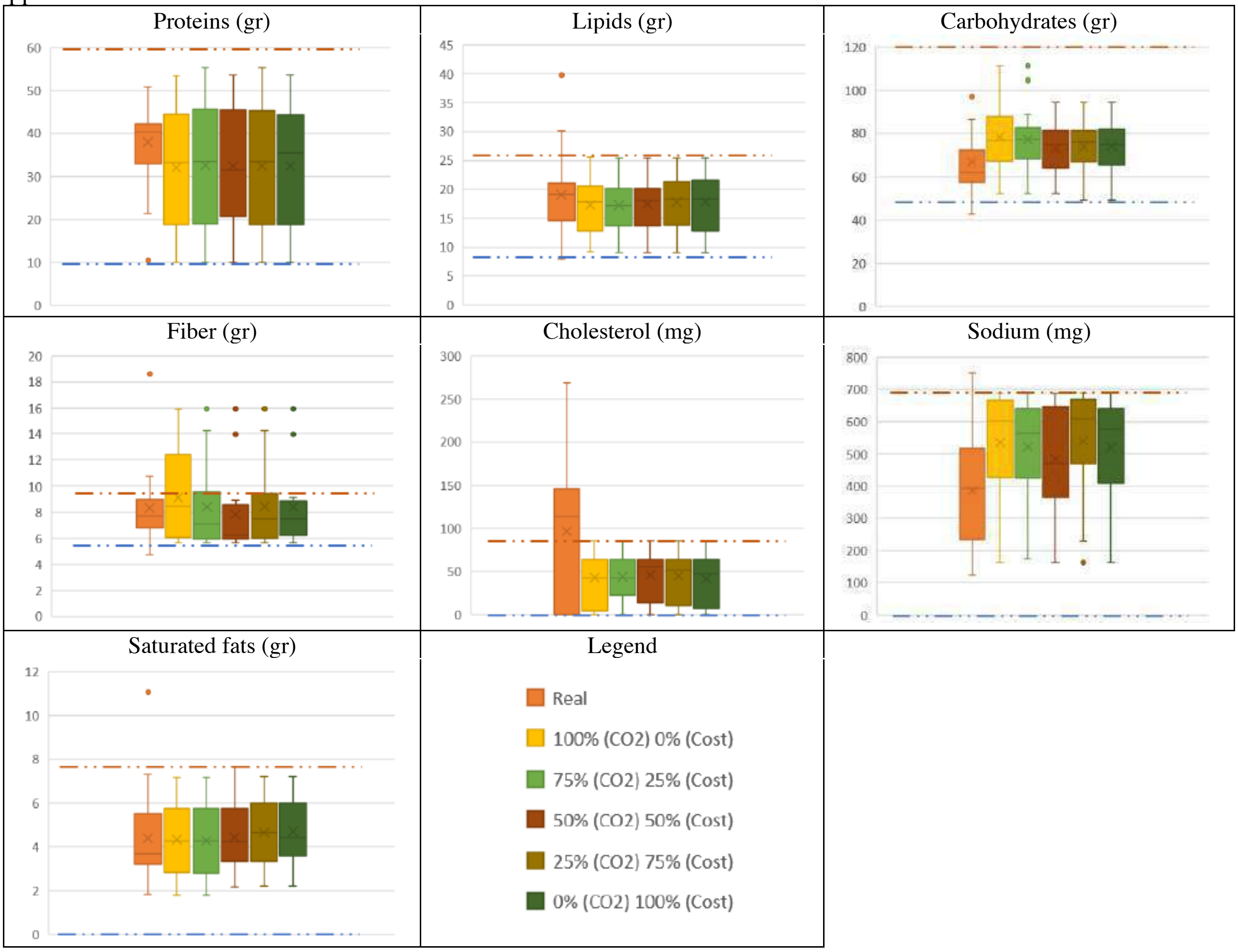


Table 1. Starter's selection.

Description		Real	100% (CO2) 0% (Cost)	75% (CO2) 25% (Cost)	50% (CO2) 50% (Cost)	25% (CO2) 75% (Cost)	0% (CO2) 100% (Cost)
Betarraga Con Cebolla Y Zanahoria	Beetaraga With Onion And Carrot	1	2	3	0	2	0
Repollo Morado Con Pimentón	Red Cabbage With Paprika	1	0	0	0	0	0
Chilena	Tomato With Onion	2	0	0	0	0	0
Apio Con Palta/ Arveja Con Cebolla/Repollo Con Aceituna	Celery With Avocado/ Pea With Onion/ Cabbage With Olive	1	0	0	0	0	0
Lechuga Con Habas	Lettuce With Beans	1	0	0	0	0	0
Crema De Verduras	Vegetables Cream	1	0	0	2	1	2
Tomate Con Cilantro	Tomato With Cilantro	1	0	0	0	0	0
Consomé De Vacuno	Beef Soup	1	4	4	4	3	4
Mix De Repollo	Cabbage Mix	1	0	2	4	4	4
Lechuga Con Zanahoria Y Palmito	Lettuce With Carrot And Palm Heart	1	0	0	0	0	0
Lechuga Con Choclo	Lettuce With Corn	1	0	0	0	0	0
Betarraga Con Cilantro	Beetaraga With Cilantro	1	2	1	1	2	1
Espinaca Con Zanahoria	Spinach With Carrot	1	3	4	4	2	2
Tomate Con Poroto Verde	Tomato With Green Beans	1	0	0	0	0	0
Brocoli Con Coliflor	Broccoli With Cauliflower	1	0	0	0	0	0
Lechuga Con Espinaca	Lettuce With Spinach	1	0	0	0	0	0
Consomé De Ave	Chicken Soup	2	4	3	2	2	1
Porotos Verdes Con Choclo	Green Beans With Corn	0	1	0	0	0	0
Betarragas Con Cebollla	Beets With Onions	0	1	1	1	2	2
Repollo Con Betarraga	Cabbage With Beet	1	0	0	0	0	2
Apio Con Zanahoria	Celery With Carrot	0	1	0	0	0	0
Sopa De Fideos	Noodle Soup	0	1	1	1	1	1
Pizza Vegetariana	Vegetarian Pizza	0	1	1	1	1	1

Table 2. Dessert's selection.

Description		Real	100% (CO2) 0% (Cost)	75% (CO2) 25% (Cost)	50% (CO2) 50% (Cost)	25% (CO2) 75% (Cost)	0% (CO2) 100% (Cost)
Manzana	Apple	4	1	1	1	0	0
Sémola Con Leche	Semolina With Milk	1	4	4	4	4	4
Naranja	Orange	3	0	0	0	0	0
Jalea Con Fruta	Jelly With Fruit	1	3	0	0	0	0
Pera	Pear	4	0	0	1	0	0
Piña	Pineapple	2	0	0	0	0	0
Brazo De Reina	Swiss Roll	1	2	0	1	2	1
Leche Asada	Milk-Based Dessert	1	1	4	4	3	3
Bavarois	Bavarois	1	0	0	0	0	0
Mousse De Frambuesa	Raspberry Mousse	0	1	0	0	0	0
Jalea De Piña	Pineapple Jelly	0	4	4	4	4	4
Mote Con Huesillo	Mote With Huesillo	0	3	2	0	0	0
Jalea Marmol	Marble Jelly	0	1	1	1	3	3
Jaleas Tricolor	Tricolor Jellies	0	0	2	2	0	0
Calabaza En Tacha	Pumpkin-Based Dessert	0	0	2	2	3	3
Durazno	Peach	1	0	0	0	0	0
Plátano	Banana	1	0	0	0	1	2

Based on available studies, the diets that generate the highest emissions are those that have a lower cost and are therefore more affordable for the population, promoting their consumption and negative impact on environment on a larger scale. However, we show that it is possible to develop diets that seek to safeguard both objectives. Future research considers the multi-objective optimization as well as including the maximization of the number of servings to be delivered in the objective function.

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Influence of the preparation mode on the environmental performance of food products: A case study on pizzas

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Context

Human food is responsible for significant environmental impacts and the agricultural phase is recognized as a major contributor to these impacts. As a result, many studies have focused on the environmental impacts of agricultural food production and processing (Borges Soares et al., 2021), but to our knowledge, very few have focused on the environmental impacts of the food preparation process at home. In general, this stage is not taken into account in the literature, although what can happen at this scale can be significant. Therefore, in this study we sought to determine the impacts of these home practices on the environmental profiles of food products.

Objectives

The objectives of this study were to compare the environmental impacts of two pizzas processed in three scenarios of preparation modes (industrial, homemade by assembling industrial products, and homemade including pizza dough and tomato sauce preparations). The variability of the practices and equipments used by the panel were taken into account as well as their perceptions of the environmental impacts for each of the three scenarios.

Methodology

Pizza preparation scenarios

We compared the environmental performances of a ham-cheese pizza and a cheeses pizza produced in three different scenarios representative of the following situations.

1- Industrial pizza. The consumer buys an industrial pizza at the supermarket and bakes it at home.

2- Assembled pizza. The consumer buys at the supermarket an industrial pizza dough, an industrial tomato sauce, and all the toppings (cheeses, ham, vegetables). He/she assembles the pizza at home before baking it.

3- Homemade pizza. The consumer buys at the supermarket all the ingredients needed to make the pizza dough (flour, yeast, oil, salt), to make the tomato sauce (e.g., tomato puree, tomato concentrate, oil, salt, sugar, garlic, herbs of Provence, oregano), as well as all the toppings (cheeses, ham, vegetables). He/she prepares the dough and the tomato sauce at home and assembles the pizza before baking it.

The recipes of pizza prepared with scenarios 2 and 3 were formulated to be as similar as possible to the recipe of the industrial pizza. For each type of pizza, the nutritional profile and caloric density were similar across all scenarios.

Recruitment of participants

69 participants representative of the French population (in terms of gender, age, and socio-

professional categories) were recruited to prepare and eat the pizzas at home according to the different scenarios. The raw materials for pizzas were provided to all participants each week. Each participant prepared and consumed the 6 pizzas over three different weeks in a randomized order and filled in the associated questionnaires.

Questionnaires

The objectives of the questionnaires were mainly to collect the data needed to build the life cycle inventory, as well as the perceptions of consumers for each pizza.
Questionnaire 1: data on the equipment used by participants and their habits (e.g., model and brand of the fridge and oven, distance between their home and the supermarket).
Questionnaire 2: data on the preparation process of each of the 6 pizzas (e.g., cooking time, equipment used, cleaning method used to wash the dishes).
Questionnaire 3: data on the consumers' perceptions regarding the 6 pizzas.

Environmental impact - Life Cycle Assessment (LCA)

The system perimeter included all steps from the agricultural production of ingredients to the consumption of the pizzas at the consumer's home, including waste management. The functional unit (FU) used was 1 ready-to-eat-pizza. The inventory data were estimated from the responses of the 69 consumers to the different questionnaires. The main flows considered were materials (pizza ingredients and packaging materials), energy flows (electricity and gas), wastes (pizza packagings), water consumption related to equipment cleaning and transport. LCAs were conducted on SimaPro 9.1.0.11 software using the "EF 3.0 Method (adapted) V1.00 / EF 3.0 Normalization and Weighting Set" (Fazio et al., 2018). LCAs were performed using a baseline scenario weighted by the actual situation of each households. For example, if X% of the participants reported using an electrical equipment for the dough making, a ponderation of X% was allocated to the electrical consumption linked to the equipment use. The average equipment power and use time reported by the participants were used to estimate this electrical consumption. 69 LCAs were also performed for each pizza in order to represent the 69 consumers and were then used for the comparison of the 6 pizzas including the variability of consumers' practices.

Results and discussion

Hotspots definition

For each of the 6 pizzas, baseline scenario was used to study the hotspots of pizza preparation and consumption. On average for all 6 pizzas, the main contributor to the environmental impacts of pizzas was the agricultural production of the ingredients for most environmental indicators. However, for the most electricity sensitive environmental indicators such as ozone depletion, ionising radiation, and resource use fossils, pizza oven cooking appears as the main hotspot. It could therefore be said that the choice of ingredients as well as the oven use time to bake the pizza are interesting levers to reduce the environmental impacts of pizzas for each of the 3 scenarios.

Influence of the consumers' practices on environmental impact of food products

First results showed that consumer practices can be very different from one to another. Therefore, we also studied the influence of consumer practices on the environmental impacts of the pizzas. The most impacting practices on the environmental impacts of pizzas are detailed below.

Cooking time. The oven use time (including oven pre-heating and pizza cooking) can vary greatly, from 10 to 50 minutes, depending on the participants. The reduction of oven use time from 50 to 10 min can reduce the environmental impacts of the pizza from 5% for less-energy sensitive indicators such as land use to 60% for higher-energy sensitive indicators (ionising radiation, ozone depletion, resource use fossils). Therefore, oven use time including pre-heating is an important lever for reducing the environmental impacts of pizzas, especially on electricity sensitive indicators.

Transport from the supermarket to the consumer home. The average transportation of the pizza from the supermarket to the consumer's home did not have a large contribution to the environmental impacts of pizzas, except for the indicator resource use, minerals and metals. However, some parameters can increase the influence of this step such as the distance between the consumer home and the supermarket, the transportation means, and the frequency of grocery shopping. For exemple the pizza impact on the resource use minerals and metal indicator is decreased by almost 80% when the distance consumer home–supermarket is 1 km instead of 16 km and by more than 30% when using a small gasoline car instead of a large diesel one (for an average distance home–supermarket). However, the parameter that seems to have the highest influence on the environmental impacts of pizza linked to its transport is the frequency of grocery shopping. Indeed, the environmental impacts of the pizza bought as part of a grocery basket for half a week is from 15% to more than 80% lower than when the pizza is bought alone depending on the indicator. This is due to the allocation factor to distribute the environmental impacts between the different items bought at the same time in the case that pizza is not bought alone. Therfore, it can be said that optimizing the trip to the supermarket by buying not only one food product is a good way to reduce its environmental impacts.

Pizzas leftovers management. After consuming the pizza, some participants had leftovers. Keeping the leftovers in order to consume them later avoid consuming some other food. On the opposite, throwing leftovers away implies that some other food will be needed for the next meal of the participant which would have been avoided by saving the leftovers. Therefore, the daily environmental impacts of the participant food consumption will be increased when leftovers are thrown away and the calories they could have provided replaced by some other food. However, the reheating of pizza leftovers can increase significantly the impacts of the pizza on environmental indicators sensitive to electricity consumption when the oven use time is high. Therefore, from an environmental point of view, keeping leftovers is better than throwing them away but the consumer has to be careful with the oven use time, or use a microwave for which the electrical consumption is lower due to a lower use time.

Comparison of the 6 pizzas environmental impacts

Differences of environmental impacts were observed between the 6 pizzas prepared and consumed by the 69 consumers. Some environmental indicators seem to be especially impacted by the pizza family (ham-cheese/cheeses). This is the case for climate change and land use, which are known to be sensitive to the agricultural production. For these two indicators, cheeses pizzas have higer environmental impacts than ham-cheese pizzas independently of the scenario. However, the scenario can have an influence on environmental indicators sensitive to the electricity consumption such as ionising radiation and resource use fossils. Indeed, for these two indicators the homemade pizzas have higer impacts than other pizzas because they require more electricity to prepare. Nevertheless, no pizza had higher environmental impacts than others on all indicators and therefore there is no one best option in terms of environmental performance according to our results.

Consumer perception

The consumer perception regarding the environmental impacts of the 6 pizzas they consumed were assessed. To do so, the consumers had to rank the different pizzas from the one they thought had the lowest environmental impacts to the one they thought had the highest. Figure 1 shows the average ranking of each pizza.

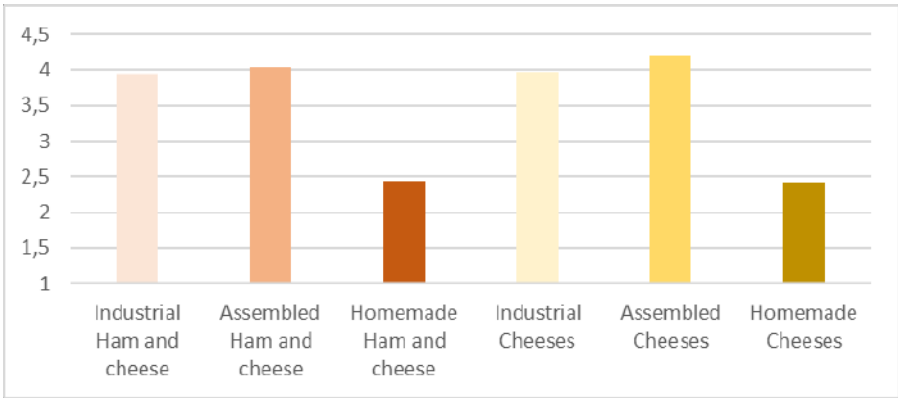

Figure 1. Average ranking of the pizzas by the 69 consumers to the question "Rank the 6 pizzas from the one with the lowest impact on the environment to the one with the highest impact on the environment". The lower the ranking number, the lowest the environmental impact is perceived.

The homemade pizzas were perceived as the ones with the lowest environmental impacts for both ham-cheese and cheeses pizzas. The consumers also had to rank the 6 pizzas according to their preferences. It appeared that homemade pizzas were the preferred ones. This shows that the perception of the pizzas' environmental impacts by participants is correlated to their preferences. This also shows that consumers tend to have erroneous perception of the environmental impacts of the pizzas they consumed because LCA results did not highlight that homemade pizzas had lower environmental impact than others, they even tend to have more impacts on electricity sensitive indicators.

Conclusion

These results gave us a first insight into the effect of the difference in food preparation modes on the environmental impacts of products. The consumers practices are very variable from one consumer to another and this can have high influence on the food products environmental impacts. However, this is never included in food LCAs which can lead to miss a large proportion of the environmental impacts of the food product. Similar studies on a wide choice of products and with more details on the reality of the consumer stage (e.g. with on-site measurements) would be helpful in order to deepen knowledge on the impact of production scenario of food on its environmental impacts. This would allow recommendations to be made to consumers for more sustainable food choices and home practices. In any case, our results showed that the use stage should not be neglected in food products LCA studies and that further research in this area is needed.

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Are athletes environmental champions? LCA case study in sports nutrition

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Introduction:

Nutritional sciences have been focused on the specific composition of nutrients to ensure the best dietary recommendations for the population. However, recently new interest has been raised to integrate the environmental impact when evaluating dietary guidelines. Several countries have included sustainability recommendations for their national dietary guidelines addressing the general population but some population groups are still understudied. Dietary requirements differ for each target population (e.g. children, pregnant women, and elderly). For example, while the recommended daily allowance (RDA) for protein for the general population is 0.8-1g/kg body mass (BM)/day, for active populations such as athletes, the RDA increases to 1.6g/kg BM/day (Thomas et al., 2016). Considering these higher protein requirements for athletes, do not integrate sustainability guidelines, if omnivorous diets are followed with increased meat higher environmental impacts (EnvI) should be expected. In addition, athletes have higher energy intakes so they match their higher energy expenditure from exercise training and competition, which potentially could increase the EnvI of their diets. The purpose of this research was to analyze the EnvI of athletes' diets following the validated Athlete's Plate® (AP) nutrition education tool (Reguant-Closa et al., 2019) to identify environmental hotspots that could be used to modify/reduce the total EnvI of their diets, while still meeting dietary requirements.

Methodology:

The study aimed to quantify the environmental impact of 216 plates created following the AP® nutrition education tool for three training loads (easy (E), moderate (M) and hard (H)) at the United States Olympic Training Center in Colorado Springs. To evaluate the EnvI of the AP® a life cycle assessment (LCA) was performed according to the SALCA methodology (Gaillard & Nemecek, 2009). Inventories included farm to plate impacts (agricultural production, transport, storage, packaging and cooking), but did not include the waste at the retail and consumption stage. Four environmental impact categories were included in the LCA analysis: global warming potential (GWP), exergy (characterizing the use of natural resources), eutrophication, and ecotoxicity. For the nutritional evaluation, energy, carbohydrates, protein, fat and fiber were evaluated using Computrition Software (Hospitality Suite, v.18.1, Chatsworth, CA, USA). More methodological details can be found in the two published papers (Reguant-Closa et al., 2019; Reguant-Closa et al., 2020).

Results:

Animal protein represented 73% of the total protein content of the plates (mainly coming from meat) vs the 27% of plant-based proteins. Meat was the largest animal protein source found on the plates. As animal proteins, and specially meat and red meat, are one of the major contributors of the EnvI a detailed analysis of the EnvI and meat content of the plate were performed. Figure 1 shows the contribution of each meat type found on the plates at the different impact categories studied. On average, chicken meat was the predominant meat found on the plates for all training intensities (E=125.4g; M=118.0g; H=95.9g) compared to beef (E=7.4g; M=19.1g; H=40.4g). Consequently, chicken was the meat with the highest EnvI in all environmental categories and for all training loads except for the hard plate where beef had a higher contribution. Protein content of the plates, especially for M (2.3±0.3g) and H (2.9±0.5g) plates, was significantly above the recommendations ($p<0.001$) (Thomas et al., 2016). Results show that energy, macronutrients and the EnvI categories increase with training load. On the contrary, fiber decreases with training load as is recommended by the AP tool (to facilitate digestion and avoid gastrointestinal discomfort with high training load). global Warming potential, exergy and eutrophication are driven mainly by meat while ecotoxicity is largely influenced by vegetable content on the plate. Figure 2 shows the results of each environmental impact expressed by plate.

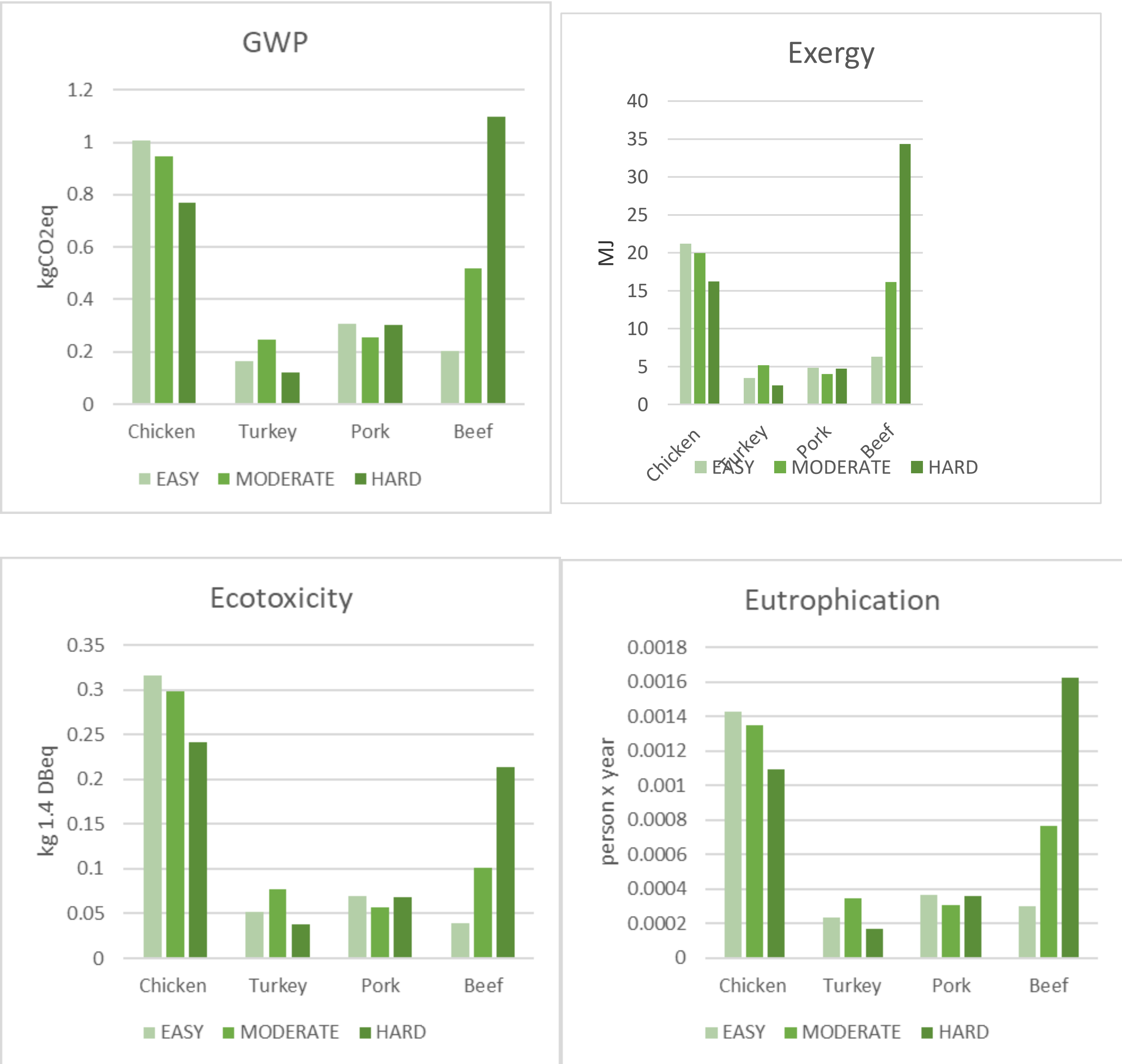

Figure 1: Environmental impact categories by training load and contribution of each meat type (mean values per plate)

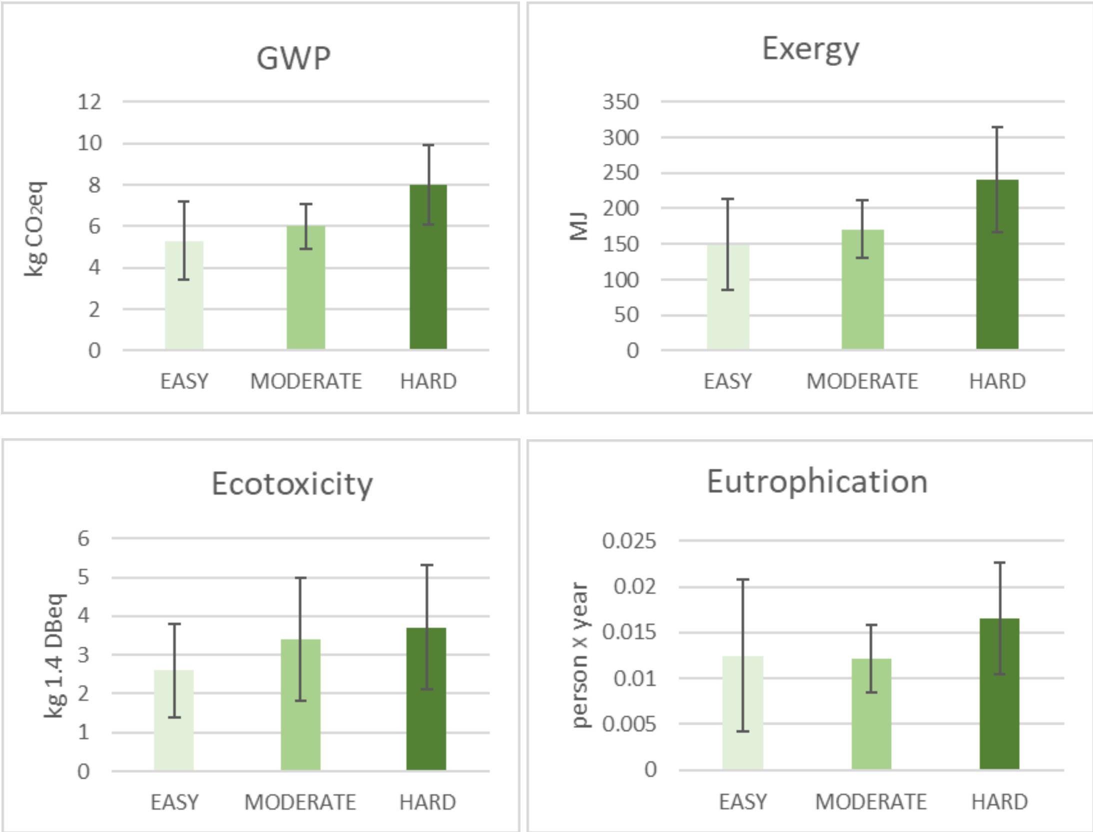

Figure 2: Environmental impact categories by training load (mean ± SD per plate)

Discussion and Conclusion:

The results of this study suggest higher CO_2eq for athletes' daily diets compared to other populations reported in the literature (Murakami & Livingstone, 2018). While athletes have higher energy requirements due to higher energy expenditure, the combination of foods on the plates could contribute to decrease EnvI as shown by the meat distribution though the different training loads (figure 1). In addition, protein intake, should not exceed recommendations, to ensure diets are efficient from a health, performance and environmental point of view. The study identified EnvI hotspots that should be addressed: 1) adjust macronutrient intake to the recommendations, especially protein intake; 2) replace animal by plant protein; 3) combine adequately plant-based proteins with animal proteins to ensure adequate amino acid profiles while avoiding protein excess; and 4) include education on environmental issues of food choices in using the AP® tool. Often dietary recommendations are defined without taking into account the EnvI. The results of this study highlight the importance of the integration of LCA when assessing dietary recommendations to ensure nutritional guidelines are in line with environmental recommendations for all populations.

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Assessing eco-efficiency of honey production using life cycle approaches

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Keywords: *Eco-efficiency; Life Cycle Assessment; Life Cycle Cost; Honey Production; Beekeepers.*

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Introduction

Honey bees play a key role in human health and the planet providing products such as honey, pollen, and protein-containing drone broods, while their pollination services make them a vital actor in food supplies (Ceyhan et al., 2017). The beekeeping sector has been identified as a low-cost venture with a high potential impact on improving the national economy related to other sectors. Notwithstanding its importance to society, the low production and environmental degradation are one of the key challenges that face this sector (Affognon et al., 2015).

Eco-efficiency concept combines economic and environmental aspects of productive systems, allowing to create more products or services whilst reducing environmental impacts throughout their life cycle (Čuček et al., 2015). Even though there are different ways to measure eco-efficiency, one of the most recognized is the ratio of life cycle cost (LCC) and the life cycle assessment (LCA) (Ibbotson et al., 2013). On the one hand, LCC provides an economic performance of the system under evaluation summarizing all costs associated with the life cycle of a product (Hunkeler, 2008). While on the other hand, LCA is a widely used methodology to evaluate the environmental impacts through the whole life cycle of products or services (ISO, 2006), being carbon footprint (CF) one of the most relevant indicator. Thus, the integration of LCC and LCA lies in the eco-efficiency analysis, allowing to identify opportunities to reduce environmental impacts and operating costs (Giusti et al., 2022).

Literature of eco-efficiency assessment in honey production systems is scarce. To the best our knowledge, only the study of Rebolledo-Leiva et al. (2021) evaluated eco-efficiency of honey production using LCA with Data Envelopment Analysis (DEA). In their study, a new method for combining CF and network DEA is proposed providing more detailed managerial insights for operational and environmental performance. In addition, there are no previous studies that deal with the eco-efficiency assessment in the beekeeping sector using life cycle approaches. In this context, the main aim of this study is to evaluate the eco-efficiency performance of honey production using CF and LCC. CF category is used as a measure of environmental performance because of its widely recognition in the agricultural context, while the total cost of honey production is used as a measure of the economic performance, focusing on the honey productive stage. This study attempts to unveil the resources with the higher environmental impacts and total cost of honey production.

Methodology

The data were gathered from 26 Chilean beekeepers through face-to-face interviews during the 2017 season. The geographical area corresponds to the Maule Region in the central zone of Chile, which has one of the largest number of hives and beekeepers in Chile (González, 2019).

i) Carbon footprint assessment

The CF assessment is conducted following the ISO guidelines (ISO, 2013). The functional unit (FU) considered is defined as 1 kg of honey produced, meanwhile the system boundary is set as a cradle to gate approach. In this sense, the life cycle inventory obtains the inputs of the following five agricultural factors: feeding, medication, transport, extraction, and use of disposable materials. While the output is honey produced. A detailed description concerning the managerial practices can be found in Vásquez-Ibarra et al. (2021). Moreover, Table 1 presents a summary statistic of the amount of inputs and outputs.

Table 1. Summary statistics of the amount of inputs and outputs of honey production per season.

	Feeding (kg)	Medication (kg)	Transport (kg)	Extraction (kWh)	Disposable materials (kg)	Honey (kg)
Average	2119.1	14.8	569.6	15.0	2.0	4753.8
Maximum	8494.0	65.1	3168.0	73.8	4.7	22,000.0
Minimum	99.0	0.1	34.2	2.0	0.5	600.0
Std dev.	2001.7	18.6	763.2	14.6	1.1	4968.4

The CF is determined using the ILCD v.1.0.8 2016 midpoint impact assessment method (EC-JRC, 2011), using the software OpenLCA v.1.7.0. Background processes were obtained from the Ecoinvent v3.3 database. Furthermore, beekeeping process produce further products and services, as wax, propolis, pollination, etc., accounting for an average 34% of the total income of the beekeepers. Thus, an economic allocation procedure is conducted to allocate environmental burdens to the honey product.

ii) Life cycle cost

As the LCA approach, the LCC analysis follows a four-step approach to determine the economic performance, considering the five agricultural factors defined in the previous section. In the LCC, the third step corresponds to cost aggregation, where occurs the computation of the accumulated costs of each life cycle stage (Sanyé-Mengual et al., 2018). The LCC was performed using MS Excel software.

Finally, once the CF and LCC have been calculated, then eco-efficiency index is determined as the ratio between the economic value and the CF for each beekeeper analyzed, following Eq. (1).

$$Eco-efficiency = \frac{total\ cost\ (USD)}{carbon\ footprint\ (kg\ CO_{2-eq})} \tag{1}$$

Results and discussions

Figure 1 presents the total CF during the season of all beekeepers evaluated. According to this figure, the average CF of honey production is 1315.5 kg CO_{2-eq} per season. When focusing on the CF per FU, an average value of 0.43 kg CO_{2-eq} is found. Figure 1 also shows that beekeeper 17 is the largest contributor with 3640.3 kg CO_{2-eq}, mainly due to the feeding (93%). This beekeeper reported the highest amount of feed consumed during the season evaluated (8494 kg) and per kg of honey (4.72). On the contrary, beekeeper 23 presents the lowest CF (314.2 kg CO_{2-eq}) during the season. This could be explained by the lowest quantity of inputs consumed (10% lower than the average of the sample).

In addition, the main contributor to CF is widely feeding activity, accounting for 71%, followed by diesel used for transport with 17% and medications with 9%, on average. Electricity and disposable materials contribute less than 5% altogether.

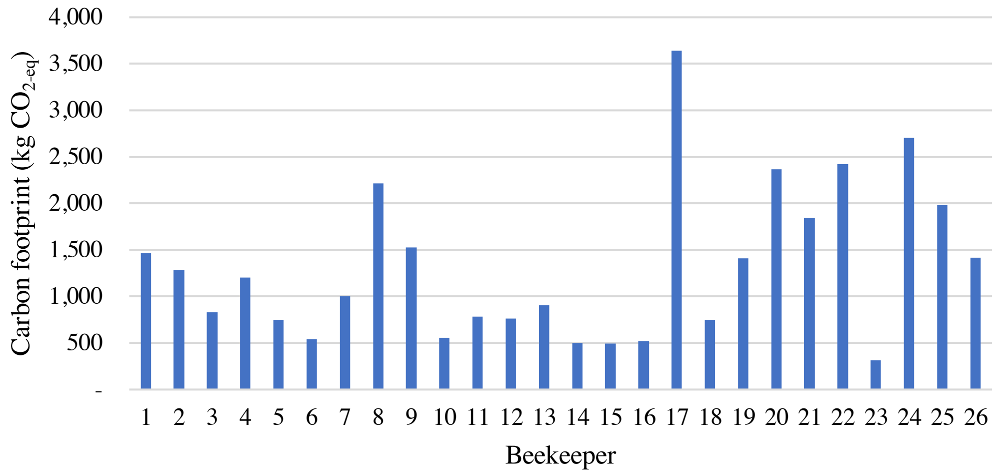

Figure 1. Total carbon footprint of Chilean beekeepers during a season.

Focusing on the total cost of honey production, Figure 2 presents the total cost for all beekeepers evaluated. According to this figure, the total cost per beekeeper is 2562.3 USD during the season, ranging from 564.0 to 6552.8 USD. When focusing on the total cost per FU, an average value of 1.4 USD/kg of honey is obtained. Figure 2 also shows that beekeepers 17 and 24 obtain the highest performance with 6519 and 6553 USD respectively. However, the main contributor is different for both beekeepers; while transport represents 65% of the total cost for beekeeper 24, feeding account for about 80% in beekeeper 17. On the contrary, beekeeper 1 presents the lowest total cost (564 USD), since this beekeeper presents one of the lowest total costs in all inputs.

In addition, on average, the main contributor to the total cost during the evaluated season is feeding with 47%, followed by medication with 25%, and diesel used for transport with 23%. Electricity and disposable materials contribute less than 5% altogether.

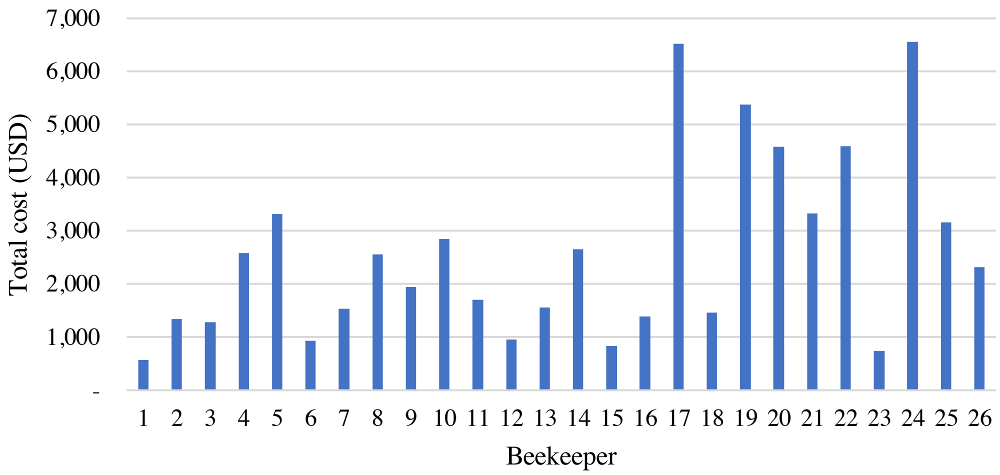

Figure 2. Total cost of honey production of Chilean beekeepers during a season.

Concerning the eco-efficiency index, the average value obtained is 2.16 USD/kg $CO_{2\text{-eq}}$. Beekeeper 14 presents the highest value (5.27 USD/kg $CO_{2\text{-eq}}$) mainly due to the medicines used, since this input presents the highest total cost (133 USD) and lowest CF value (0.56 kg $CO_{2\text{-eq}}$) during the season. Even though it is interesting to highlight that this beekeeper obtains the highest honey production level. On the contrary, beekeeper 1 presents the lowest index (0.38 USD/kg $CO_{2\text{-eq}}$) which could be explained since this beekeeper reports the lowest total costs. Concerning the eco-efficiency index of each input, medicines show the highest value because their high total costs (640 USD/season) and lowest CF generation (113 kg $CO_{2\text{-eq}}$), giving an average eco-efficiency index of 5.7 USD/kg $CO_{2\text{-eq}}$, followed by disposable materials (3.8 USD/kg $CO_{2\text{-eq}}$) and transport (2.6 USD/kg $CO_{2\text{-eq}}$).

According to the above, there are two main factors that beekeepers should focus in order to reduce their eco-efficiency assessment: medicines and disposable materials. In particular, medicines are also identified as one of the main contributors to CF and total costs. As explained in the study of Vásquez-Ibarra et al. (2021), beekeepers use chemical and alternative medicines to avoid, reduce or mitigate the impact of pests. In this sense, beekeepers spend on average 2523 USD in chemical medicines, such as *amitraz, flumagilin* and *flumethrin,* while they spend only 11 USD in alternative medicines, such as *oxalic acid* and *thymol*. Thus, a first recommendation could be replacing chemical medicines with high cost, by those alternatives with lowest cost. On the other hand, regarding disposable materials, currently beekeepers spend on average 121 USD and generate 31 kg $CO_{2\text{-eq}}$. Thus, in order to decrease eco-efficiency indexes, they could extend the life cycle of disposable materials, as gloves, suits and smokers, allowing to reduce the cost associated with this input. Finally, since feeding is the main contributor to CF generation and total cost, beekeepers could also focus on this input, even though their eco-efficiency index has not been found as high as medication and disposable materials. To address the environmental profile of feeding, Vásquez-Ibarra et al. (2021) identified that beekeepers should focus on an adequate amount and type of feeding.

Conclusions

This study analyses the eco-efficiency of honey production from 26 Chilean beekeepers using CF as an environmental indicator and LCC approach for the economic performance. Results reveal that feed is the main contributor to the total cost and CF. Therefore, new feeding strategies are required to reduce their environmental and economic impacts of this resource. Otherwise, medicines and disposable materials present the highest eco-efficiency indexes since their high total cost. This study is a first approach to evaluate eco-efficiency of honey producers using CF and LCC approach. In this sense, further studies could evaluate additional environmental categories in order to obtain a broader environmental performance and consequently a wide eco-efficiency analysis.

Acknowledgments

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Pursuing sustainability in the dairy sector: Water-Energy-Food nexus score for dairy farms

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Introduction

Milk provides a source of proteins with a high biological value (Marangoni et al., 2019). Studies have shown that people who consume dairy products tend to include more fruits, vegetables, fish, nuts or whole-grain breads in their diet and follow a more active lifestyle (FEN, 2020). Among the main producing countries in Europe, with almost 5% of the share, Spain ranks eighth (Augere-Granier, 2018). Despite this, milk consumption by Spaniards has been steadily decreasing, down to milk consumption values around 70 L per capita annually (MAPA, 2021). This trend could be explained due to food intolerances or an increment on plant-based diets (Munekata et al., 2020). In addition, other possible causes may be behind this change in behaviour, as consumers are more aware of environmental and animal welfare issues, which could eventually lead to animal-free eating patterns (Kolbe, 2018). At Spanish level, Galicia, with more than 6,500 livestock farms, constitutes the largest producer with almost four tenths the milk marketed during the period 2016-2020 (MAPA, 2020). Considering the environmental impacts associated to diets, Cambeses-Franco et al. (2022) reported that dairy products were a major contributor in certain European and American dietary patterns in terms of greenhouse gas (GHG) emissions, water demand and energy consumption. In particular, dairy farming stand out for being both resource-consuming and pollution-generating (Pandey and Singh, 2021). As a point of concern in animal welfare, mastitis is one of the most common infectious diseases with significant contributions in monetary terms (Bhakat et al., 2020). In the context of promoting environmentally friendly production strategies, the European Green Deal aims to achieve net zero GHG values for agricultural and livestock systems by 2050 (European Commission, 2019). Therefore, environmental and food profiles with respect to dairy farm performance should include and involve different sustainability perspectives to identify best practices and possible environmental trade-offs between them. In this regard, the Water-Energy-Food nexus (WEF) emerges as a framework tool to consider the complex interconnections between water demand, energy requirements and food provision (Zhang et al., 2018). Thus, the objective of this work is to evaluate the level of sustainability of milk production for a set of farms settled in Galicia (NW Spain) under the WEF nexus philosophy. In this way, the integration of GHG emissions, water demand, energy consumption and food loss (FL) in a single score could support, through an easy interpretation, the decision-making process for stakeholders in the form of an ecolabel.

Methodology

The productive data of 100 livestock farms located in Galicia was collected through face-to-face surveys, corresponding to a one-year production period (2020). This data comprise all relevant processes related to milk production on the farms, from direct consumption flows such as cleaning

products, electricity consumed and waste management (e.g., plastics, cardboard, wastewater). Other inputs such as agrochemical use (pesticides and fertilisers), seeds for crops cultivation, fuel and lubricant oil for farm machinery need to be included. With such information, the WEF nexus scores of the dairy farms have been calculated following a four-step procedure:
i) Indicator selection: With the purpose of understanding the trade-offs related to the WEF nexus along with the food supply chain, life cycle thinking is crucial (Del Borghi et al., 2020). Therefore, with the aim of estimating the life-cycle environmental impacts of milk production, the selection of three life cycle indicators: carbon footprint (CF), water footprint (WF) and energy footprint (EF) were considered. These indicators have been already taken into consideration when assessing a food system following a WEF nexus philosophy (Laso et al., 2022).
ii) Indicator assessment: The environmental footprints (CF, WF, and EF) are calculated using the Life Cycle Assessment (LCA) methodology following a cradle-to-gate approach and using the Ecoinvent database v3.8 for the modelling of the background processes (Wernet et al., 2016). In addition, as the case study is a multi-product system, where meat and milk are produced, a mass allocation method was taken into account to distribute the environmental burdens. In order to transform the inventory data into environmental impacts, the Life Cycle Impact Assessment (LCIA) method must be chosen. Accordingly, for the calculation of the CF indicator, the IPCC-100 years (2021) method was used, following the recommendation of the International Dairy Federation to achieve a common approach in the CF assessment of the dairy sector (IDF, 2015). Regarding the WF, the Available WAter REmaining (AWARE) method (Boulay et al., 2018) was used in line with the Product Environmental Footprint Category Rules (PEFCR) developed by the Joint Research Centre of the European Union, to measure the environmental performance of dairy products throughout their life cycles (EDA, 2018). In terms of energy requirements, one of the most appropriate LCIA methodologies is the Cumulative Energy Demand (CED) (Frischknecht et al., 2007), since it is aligned with the PEFCR. On the other side, for the calculation of the FL index, the proportion (in percentage) of waste milk (infected with mastitis) compared to the total milk produced was considered using **Eq 1**.

$$FL\ (\%) = \frac{waste\ milk\ from\ mastitis\ (l)}{total\ milk\ produced\ (l)} \cdot 100\ (\mathbf{Eq\ 1})$$

iii) Normalisation: In this step, the indicators are normalized into a range from 0 to 1 in order to overpass the problem regarding the different units of measure: kg of CO_2 equivalent (kg CO_2e), m^3, MJ and the percentage value (%) for the CF, WF, EF and FL, respectively. This normalisation is carried out using **Eq 2**.

$$\mathrm{X}_{\mathrm{n}_{\mathrm{ij}}} = \frac{\mathrm{X}_{\mathrm{max}_\mathrm{i}} - \mathrm{X}_{\mathrm{ij}}}{\mathrm{X}_{\mathrm{max}_\mathrm{i}} - \mathrm{X}_{\mathrm{min}_\mathrm{i}}}, \forall\ \mathrm{j}\ (\mathbf{Eq\ 2})$$

Where
i: indicator, i = {CF, WF, EF, FL}.
j: dairy farm evaluated, j = {1, …, 100}
$\mathrm{X}_{\mathrm{n}_{\mathrm{ij}}}$: normalised value of each indicator i of farm j.
X_{ij}: value of the indicator i of farm j.
$\mathrm{X}_{\mathrm{max}_\mathrm{i}}$: maximum value of the indicator i.
$\mathrm{X}_{\mathrm{min}_\mathrm{i}}$: minimum value of the indicator i.
iv) Weighting and integration: For each farm, the normalised footprints are integrated into one single value (WEF nexus score), through a weighting sum of the four footprints, whose range is between 0-100. For this purpose, all footprints are considered to be equally relevant (**Eq 3**).

$$\mathrm{WEF}_{\,j} = \left(\mathrm{CF}_{\mathrm{n}_\mathrm{j}} \cdot \mathrm{W}_{\mathrm{CF}}\right) + \left(\mathrm{WF}_{\mathrm{n}_\mathrm{j}} \cdot \mathrm{W}_{\mathrm{WF}}\right) + \left(\mathrm{EF}_{\mathrm{n}_\mathrm{j}} \cdot W_{\mathrm{EF}}\right) + \left(\mathrm{FL}_{\mathrm{n}_\mathrm{j}} \cdot \mathrm{W}_{\mathrm{FL}}\right)\ (\mathbf{Eq\ 3})$$

Being

WEF_j: WEF nexus score of farm *j*.
$CF_{n_j} WF_{n_j} EF_{n_j} FL_{n_j}$: normalized footprint of farm *j*.
W_{CF}, W_{WF}, W_{EF}, W_{FL}: weight of CF, WF, EF, and FL, respectively (equal to 25%).

Results and discussions

The results (**Figure 1**) show that the WEF nexus score has an average punctuation of 74, varying from 45 (farm 66) to 92 (farm 13). Therefore, based on this value, it is possible to differentiate four groups of farms (from worst to best results): D (from 45 to 56), C (from 57 to 68), B (from 69 to 79) and A (from 80 to 92).

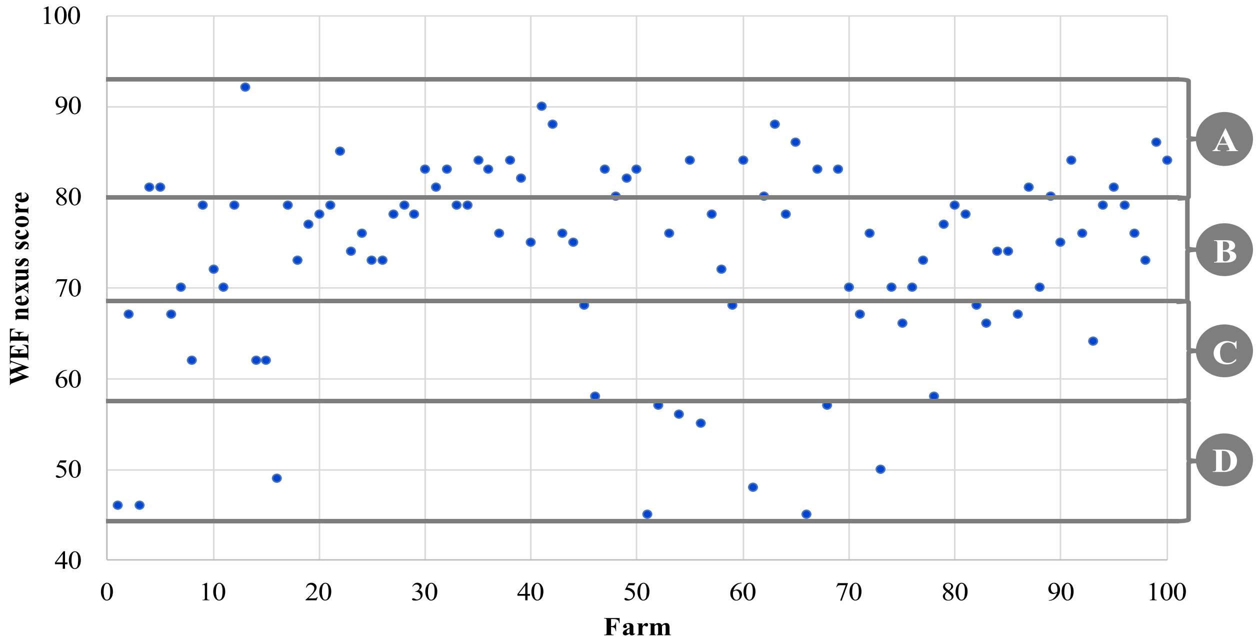

Figure 1. WEF nexus scores of the 100 dairy farms divided by four groups (from worst to best results): D (from 45 to 56), C (from 57 to 68), B (from 69 to 79) and A (from 80 to 92).

Once the group of farms with the lowest scores (group D) has been identified, it is interesting to know what their range of improvement would be until they can be categorised as the highest scoring farms (group A). On average, group A has 35 points more than group D, this would mean that the latter group would have to reduce their impacts by approximately 32%, 54%, 47% and 67% for their CF, WF, EF and FL, respectively. With this objective, due to the fact that most of the indicators have been calculated following an LCA methodology, it has been possible to detect the origin of the hotspots of the environmental impacts: as far as CF is concerned, emissions in the field related to manure and agrochemicals contribute to more than half of the total impacts, the second one being the commercial fodders used to meet the cows feed demand. On the other hand, for WF and EF, forages account for about 60% and 80% of each footprint, respectively. Consequently, one of the solutions could be to improve the performance of dairy cows, since although group A provides a daily feed ration for each animal of 5.5 kg more compared to group D, the latter implies (per kg of feed supplied) 0.66 L of milk while group D only represent 0.59 L. Another possible solution may be to modify the ingredient composition of the commercial feed used by each farm, as this in turn could also help to improve the WEF nexus score in terms of FL, although this should also be improved through the implementation of an animal welfare system, where not only the feeding of the animals is considered, but also the rest periods. However, more detailed studies are needed, because the improvement proposals should also be evaluated from a nutritional and economic point of view.

Conclusions

This study represents a good starting point for the implementation of a pioneering eco-label that integrates the environmental and food fields in the dairy sector and involves all actors in the supply chain through a single value easily understandable by the general public: from 0 (worst) to 100 (best). In addition, with appropriate modifications, the WEF nexus approach could be applied to other food production activities. However, stricter green policies are needed to encourage an increasing number of dairy production systems to become more and more involved in accounting for their environmental burdens with the objective that such certificates can materialize. In line with the above, it is vital to conduct further studies to standardize a set of indicators that are better adapted to each food sector, as well as to integrate other socio-economic indicators, with the aim of bringing the methodology in line with sustainable development along the entire food supply chain.

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Revisiting regionalized water scarcity characterization factors for selected watersheds along the hyper-arid Peruvian coast using AWARE

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The aim of this study was to provide regionalized water scarcity characterization factors (CFs) for seven watersheds along the hyper-arid Peruvian coast using the Available Water Remaining (AWARE) method (Boulay et al., 2018). The novelty of this proposal is twofold: a) it is the first attempt to regionalize an environmental impact method to the Peruvian context; and, b) it provides water scarcity CFs differentiating between surface water and groundwater.

The regionalization of water scarcity CFs was carried out according to the AWARE method, as described in Boulay et al. (2018). This method is based on the inverse of available water remaining (AMD_i, $m^3m^{-2}month^{-1}$) per unit of area and time in a given watershed. AMD_i represents the water remaining available once the water demands (human and ecosystem) are met. Thereafter, the CF ($m^3_{world\ eq.}\ m^{-3}$) is obtained normalizing AMD_i using the consumption weighted-average of AMD_i over the whole world ($AMD_{world\ avg}$, 0.0136 $m^3m^{-2}month^{-1}$). The CFs in AWARE go from 0.1 (minimum water scarcity in the watershed) to 100 (maximum water scarcity in the watershed).

Thus, the regionalization of the CFs to the Peruvian context was based on three approaches: a) a shift from native resolution scale (0.5° x 0.5°) employed by AWARE to hydrological units (HUs) defined by the Peruvian National Water Authority (*Autoridad Nacional del Agua* - ANA) (ANA, 2008); b) the substitution of water availability and demand from WaterGAP (Pastor et al., 2014; Schmied et al., 2014) to primary data provided by official water balance studies; and, c) the differentiation between availability and demand for surface water and groundwater.

In this study, seven HUs in the Department of Lima, located in the Pacific basin, were considered: *Chillon, Rimac, Lurin, Chilca, Mala, Omas*, and *Cañete*. Selection criteria were based on the high water stress and low water supply of this hydrographic region, which harbors a third of Peru's population and 40% of economic activities (ANA, 2019a; Llauca et al., 2021). Moreover, these HUs were selected according to data quality and availability in national databases in terms of water availability and demand.

Water availability data for the *Chillon, Rimac,* and *Lurin* watersheds were collected from ANA (2019), which considers a time series from 1965 to 2018, whereas data for the *Cañete* watershed was obtained from ANA (2019b), considering a 1926-2019 time series. Finally, water availability for the remaining watersheds were obtained from ANA (2015), using the period 1965-2013. Data on human water demand were obtained from the same bibliographic sources. The reference year for water demand reported for the *Chillon, Rimac* and *Lurin* watersheds was 2017, 2015 for *Chilca, Mala* and *Omas,* and 2019 in the case of the *Cañete* watershed. The values of the aforementioned parameters were collected both for surface water and groundwater. Due the lack data of availability and demand for groundwater in the *Cañete* watershed, the CFs for groundwater were not estimated for this watershed.

As aforementioned, the regionalization of CFs included the substitution of environmental water requirement (EWR) from Pastor et al. (2014) to ecological flow recommended by ANA (2016). According to ANA (2016), the ecological flow for superficial water is the monthly flow that is exceeded 95% of the time during a period of 20 years. Meanwhile, regarding the EWR for groundwater, 65% of groundwater recharge was considered to be equivalent to EWR (Hybel et al., 2015). Moreover, in order to normalize the proposed CF for groundwater, the calculation of $AMD_{world\ avg}$ for groundwater was carried out. It was calculated using the value of global groundwater recharge provided by Wada et al. (2010), global groundwater demand from Wada (2016) and EWR based on Hybel et al. (2015). A final value for $AMD_{world\ avg}$ of 0.0026 $m^3m^{-2}month^{-1}$ was obtained.

Results revealed that regionalized annual surface water CFs, in descending order, were as follow: *Rimac* (84.2), *Chilca* (83.9), *Omas* (70.6), *Lurín* (69.8), *Chillón* (52.3), *Cañete* (41.7), *Mala* (41.6)[1]. Regarding the regionalized monthly surface water CFs, these reached a value of 100 from June to November in all watersheds assessed, except for *Mala*, in November. However, in the remaining months (December to May) results were variable. For instance, the river *Rimac*, which is the main river that crosses the city of Lima, CFs were only lower than 100 in February and March. Another watershed with a similar trend was *Chilca*, which only showed CFs lower than 100 from January to March. In contrast, the *Mala* and *Cañete* watersheds presented CFs lower than 100 over the six-month period, from December to May. These trends are in line with previous studies, which have highlighted the period from May to November as the driest months for all the watersheds studied (ANA, 2019a, 2019b, 2015). These results reflect the high pressure that surface water is subject to in the watersheds analyzed, which has been repeatedly underestimated in Life Cycle Assessment (LCA) studies based on the CFs reported by AWARE, due to the high difference between the regionalized CFs with the native AWARE CFs, mainly in the months from June to December. Differences between regionalized CFs and native AWARE CFs have also been reported in Brazil (Andrade et al., 2020) and Australia (Bontinck et al., 2021).

Regarding groundwater CFs, results indicated that the aquifers in *Lurin, Rimac*, and *Chillon* watersheds experienced high pressure, with maximum throughout the entire year. For the *Omas* and *Chilca* watersheds maximum CFs were obtained from April to December, representing a similar trend to surface water. However, the aquifer in *Mala* showed the lowest levels of pressure, with CFs below 13 throughout the year. In this regard, AWARE is known for its low ability to differentiate levels of water scarcity in regions with water demands higher than availability (UNEP/SETAC, 2016). However, despite this limitation, the high CFs in every month for some HUs suggest the urgent need to reduce the pressure in the region, reducing associated environmental, economic and social impacts.

In conclusion, the proposed regionalized water scarcity CFs for surface water of the watersheds evaluated were different when compared with native AWARE CFs, showing more coherence with the context of the hyper-arid Peruvian coast. Moreover, groundwater CFs revealed the high vulnerability of the aquifers, mainly in *Lurin, Rimac* and *Chillon*, all in the vicinity of the city of Lima. In this sense, the regionalization of AWARE CFs to the Peruvian context may be an opportunity to improve the representativeness of the results of LCA studies when reporting water scarcity results. Finally, the high values obtained for regionalized CFs warn of strong pressures on water resources in the area, for which major regulation in water distribution and better strategies to improve the water use efficiency

[1] All characterization factor (CF) values reported in the following unit: $m^3_{world\ eq}.\ m^{-3}$

are urgent. Future research should focus on the identification of other methods to calculate groundwater CFs in order to compare those obtained in the present study.

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Environmental impacts of food in Germany with a focus on biodiversity impacts and water scarcity

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Keywords: *German food consumption, biodiversity, water scarcity, ecoregion factors, planetary boundaries*

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Objective. Food consumption, i.e., agricultural production is the main driver for the shift of four out of nine planetary boundaries that are beyond or within the zone of uncertainty: biosphere integrity, land-system change, freshwater use, and biogeochemical flows (Campbell et al. 2017).
However, even though environmental impacts of German food consumption have been analyzed several times in recent years (Eberle & Fels, 2016, Meier, 2014; Schmidt et al., 2019), impacts on biodiversity and impacts due to freshwater use, have not been analyzed yet. One reason is that impact assessment methods for assessing the mentioned impacts have only been developed in recent years. While biodiversity and water scarcity impacts have been studied for several food products in the past, an assessment of these impacts on a country level is still missing.
Thus, the aim of this paper is to update the analysis of global environmental impacts of German food consumption for greenhouse gas emissions, water consumption and land use, and adding the assessment of impacts on terrestrial biodiversity and water scarcity footprint.

Methods. The analysis has been conducted using Life Cycle Assessment (LCA) according to ISO 14040 series (2006). The same approach has been chosen as in Eberle & Fels (2016), meaning that the modelling is based on the average German food basket at consumption level. The functional unit was defined as the food consumption for one year for all German citizens. Consumption in this study encompasses the food products that are eaten as well as the food waste occurring on household level. All relevant material flows upstream via retail, processing and animal husbandry to agricultural production were examined. The composition of the German food basket was based on consumption statistics from BMEL (2017-19) and FAO (2020a-c). Food losses and waste were considered for every step from agriculture to consumption. Ecoinvent v3.6, GEMIS 5.0 and susDISH have been used to model the background processes. Blue water consumption was based on Mekonnen & Hoekstra (2010).
In order to obtain a more stable statistical data basis, the used data was averaged over three years with a temporal reference of 2017-19, where available. Following the goal of the study, the impact categories climate change, water scarcity, and biodiversity have been assessed. Furthermore, land use for agricultural production and blue water use as inventory indicators were analyzed.
To assess climate change impacts IPCC 2013 characterization factors were used, including emissions due to land use (LU) and direct land use change (dLUC). Water scarcity has been assessed using the AWaRe method with crop and country specific scarcity factors (Boulay et al., 2018). The BVI (Biodiversity Value Increment) method proposed by Lindner et al. (2019) has been chosen to assess biodiversity impacts. The BVI method can be used at different levels of detail. In this study a generic assessment has been conducted. The characterization factor in the method is based on two parameters: local quality of land use and the global contextualization using ecoregion

factors. To assess the local quality, the concept of naturalness, also called hemeroby (Fehrenbach, 2015), was used. The level of naturalness depends on production intensity of the agricultural cultivation. The assumption was made that all food consumed in Germany is intensively grown.
The data on product origin in this study as well as in most LCA studies using generic data is given at country level. In the BVI method a factor is used that depends on the ecoregion in which the product is cultivated. But the boundaries of countries and ecoregions rarely coincide. To overcome this challenge a novel dataset has been developed that provides production weighted ecoregion factors for 42 FAO crops at country level. To accomplish this, spatial production statistics from MAPSPAM (Yu et al. 2020) were matched to the ecoregions and aggregated on country level. The use of this crop weighted dataset is expected to be more precise for a generic assessment than using area weighted country ecoregion factors, since regional crop production intensities are not homogenously distributed within a country.

Results. The global environmental impacts caused by German food consumption are as follows: 216E+6 t of CO_2e are emitted (of which 46E+6 t CO_2e result from dLUC), 16.6E+6 ha of land is occupied each year, resulting in a biodiversity impact of 1.23E+6 BVI*ha*a and 2.401E+9 m³ of irrigation water is consumed, which causes a water scarcity footprint of 118.6E+9 $m^3_{worldeq}$.
Even though animal products (including meat, eggs, and milk products) only account for one third of the weight of the products, they cause almost two thirds (64 %) of the total greenhouse gas emissions, 81 % of emissions from dLUC, account for three quarters of land occupation (75 %) and are responsible for 76 % of the impacts on biodiversity. The rest is related almost completely to plant-based products. Fish and seafood cause only minor impacts, because of a low weight share in the German diet. Regarding water consumption and water scarcity footprint the picture changes. Here, plant products account for the largest fraction (82 % and 96 % respectively), especially citrus fruits and almonds.

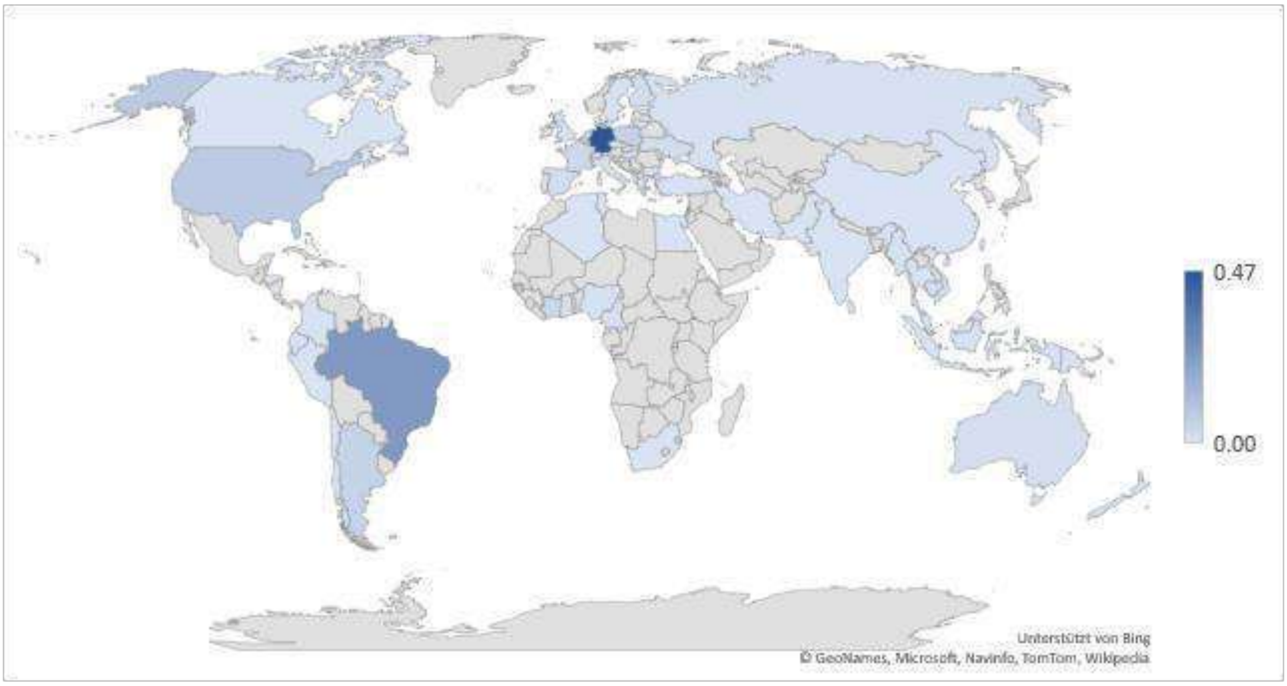

Figure 1: Global biodiversity impacts of the German diet; in 10^6 BVI*ha*a

Most THG emissions (excluding dLUC and LU) occur at the level of agricultural production (41 %), followed by animal husbandry (27 %) and consumption (19 %). Processing and retail do not account for high THG emissions. The two highest emissions at retail gate are related to meat products (sausages with 28.3E+6 t CO_2e and beef with 15.7E+6 t CO_2e), followed by cheese

(14.4E+6 t CO_2e). The highest emission connected to a plant-based product was found for cacao (5.8E+6 t CO_2e).
Emissions from dLUC are almost completely related to soy (96 %), mainly imported from Brazil (78 %) and Argentina (22 %). Soy was used only for feed in this study. The largest share of land is needed for wheat (14.7 %), followed by soy (14.3 %) and maize (10.6 %). The three main impacts on terrestrial biodiversity are also caused by these products, but in a different order: soy (30 %), wheat (15 %) and maize (12 %). This shift is explained by the local differences regarding ecoregion factors. The average soybean for the German diet is cultivated in regions with an ecoregion factor more than twice as high (0.267) as for the average wheat grain (0.129). Most land is occupied in Germany (49 %), followed by the United States of America (9 %) and Brazil (8 %). Like the shift in product ranking, the ranking regarding biodiversity impact encompasses the same three countries, but in a different order. The share of Germany is smaller with 38 %, while the share of Brazil is significantly higher with 20 %. Biodiversity impacts in the USA account for 7 % of the total global impacts. The global impacts on terrestrial biodiversity are shown in Figure 1.

Figure 2: Global water scarcity footprint of the German diet; in 10^9 $m^3_{worldeq}$

One quarter (568E+6 m^3) of the total water consumption is consumed in Spain for the cultivation of citrus products. That is almost twice as much as the amount used for maize (308E+6 m^3 or 13 %), which shows the second highest consumption. Considering local water scarcity, the effect is drastic. Citrus fruits alone account for more than one third (36 %) of the water scarcity footprint, followed by almonds with 11 % (9 % in the USA, 2 % in Spain) and peaches with 8 % (7 % in Spain, 1 % in Italy). Maize, on the other hand, which is second in terms of water consumption, only follows in tenth place (3 %). The largest water scarcity footprint was found to be caused in Spain with 61 %, followed by the USA with 12% and Italy with 11 %. The global impacts on water scarcity are shown in Figure 2.
Food waste accounts for 15 % of the GHG emissions, 16 % of emission from dLUC, 16 % of the occupied land and biodiversity impacts as well as 17 % for water consumption and 18 %water scarcity footprint.

Discussion and Conclusions.
This paper confirms observations of previous studies regarding climate impacts, direct land use

change and occupation. However, it provides new insights into water scarcity and biodiversity impacts resulting from the German food consumption. The results show that GHG emissions, land use and impacts on terrestrial biodiversity are mainly depending on the consumption of animal products. To reduce these impacts, it is necessary to reduce the consumption of meat and other animal products, mainly beef and processed products like sausages and cheese. The water scarcity footprint assessment on the other hand shows that most of the impact is caused by only a few plant-based products. This does not mean that animal products are generally better than plant-based products regarding the water scarcity footprint. It depends on the product and its origin. The water scarcity characterization factor for citrus in Spain (74.41) for example is about 35 times higher than in Brazil (2.1). It is also important to keep in mind that water consumption data is from 2010. Since then, water availability as well as water consumption probably changed by a considerable margin for some regions.

The biodiversity assessment shows that, like water scarcity, large optimization potentials exist regarding products and origins due to the ecoregion factor. For example, the ecoregion factor for soy production in Italy is 0.047, while the factor in Brazil is almost 8 times as high with 0.368.

Furthermore, the results display that most impacts on biodiversity and water scarcity caused by the German diet are caused outside of Germany. 62% of the impacts on biodiversity are caused outside of Germany, one third of them in the Americas. In the case of water scarcity, even more than 99% of the impacts are caused outside of Germany. This shows that the environmental impact of the current diet in Germany takes place largely at the expense of other countries.

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Water scarcity mitigation in China's rice production: closing yield and harvest area gaps

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Abstract

The spatial pattern of irrigation consumption greatly determines water use sustainability and food security. Over the past decades, China's rice production area has experienced a substantial change in spatial distribution, which has exacerbated national freshwater scarcity. To support the development of guidelines for sustainable water use in rice cropping, the potential for achieving a downscaled freshwater use boundary while maintaining China's current production levels has been explored (Lan et al., 2021). It has been found that, to operate within the boundary defined by a water scarcity index, national irrigation for rice cropping should reduce by 10% in water-scarce regions, implying a 10% loss in national rice production without further intervention. However, by scenario analysis, it was found that the production losses can be reduced to around 7% by closing yield gaps, and fully compensated by closing harvest area gaps in water-rich regions. Closing both the yield and harvest area gaps enables a 3% increase in the national rice production (6.9 million metric tons). The water-rich regions suitable for double-rice systems show a high potential to increase rice production. The spatial redistribution of rice production under these scenarios resulted in a reduction in the national water-scarcity footprint related to rice cropping of 52-55%. These results demonstrate that, to reach the downscaled water use boundary and ensure food security, national redistribution of rice production combined with closing yield and harvest area gaps is necessary and urgent.

Keywords: *sustainable agriculture; freshwater use; water footprint; cropping intensity; cropping redistribution.*

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Rationale and objective

It seems that current global blue water consumption (surface and groundwater) is within the freshwater use boundary (Steffen et al., 2015). However, there is a growing demand to downscale this boundary, as water scarcity is a local or regional phenomenon (Huang et al., 2020a; Ridoutt and Pfister, 2010). Agriculture accounts for the majority of the world's water consumption. At present, many of the world's intensive agricultural production areas, such as the North China Plain, are facing water scarcity. It is imperative to optimize the spatial pattern of global irrigation consumption to meet the goals of food security and sustainable water use (Davis et al., 2017).

Rice is one of the staple grain crops in China, accounting for 28% of the global rice supply, and is known to be irrigation-intensive. Few studies have examined the spatial patterns of water consumption for national rice cropping, which may put pressure on China's freshwater when rice production occurs in regions of high water scarcity. Over the past decades, China's rice production area has experienced a substantial change in spatial distribution. This has exacerbated national freshwater scarcity because of the mismatch in the spatial and temporal distributions of arable land and water resources in China (Huang et al., 2020b). Our previous study assessed the potential to meet a downscaled water use boundary by closing yield gaps of China's national rice production using county-level data only. Yu et al. (2017) found that closing the harvest area gap, defined as the harvest area that can be gained if existing croplands are harvested as frequently as possible, is another effective measure to promote China's grain production. It is reported that there is substantial potential to increase rice cropping by converting single-rice to double-rice systems in southern China (Deng et al., 2019).

To date, the environmental implications of closing China's harvest area gaps have not been assessed, and those of closing yield gaps have only been assessed at a coarse scale. To fill these gaps, this presentation, which is based on a recent publication (Lan et al., 2021), assesses the potential of rice redistribution in China at a high spatial resolution by considering a downscaled water use boundary and the closing of both yield and harvest area gaps.

Approach and methodology

We downscaled the water boundary by applying a water scarcity index (WSI), which is related to the ratio of freshwater consumption to hydrological availability and ranges from 0.01 to 1 (Pfister et al., 2009). We calculated the WSIs following the method of Scherer and Pfister (2016). The sustainable water use boundary in an area with rice cultivation was defined as the water consumption level that results in a WSI of 0.5, which represents the threshold between moderate and severe water scarcity (Pfister et al., 2009). Three scenarios (i.e., Scenario 1—closing yield gaps, Scenario 2—closing harvest area gaps, and Scenario 3—closing both yield and harvest area gaps) were designed to redistribute China's rice production to meet the water use boundary. The analysis was carried out with a high spatial resolution of 5 arcminutes based on the data in 2010 (averaged from 2009 to 2011). FAO's AquaCrop model, implemented within an improved version of GeoSim (Huang et al. 2019), was applied to simulate rice yield and irrigation water consumption. These were then used to calculate yield gaps and water-scarcity footprints (WSFs), which are an indicator of the potential environmental impacts from water scarcity (Ridoutt and Pfister, 2010b). We compared the WSFs before and after the redistribution of rice production and examined the balance of rice production under the different scenarios. In this way, we explored whether China can remain within water sustainability limits while maintaining the current level of rice production. Details on data sources and methods can be found in our published work (Lan et al., 2021).

Main results

The estimated national potential yields ranged from 6.6 to 10.9 t ha^{-1}, while the actual yields varied from 4.3 to 6.7 t ha^{-1}. The average potential yield of single-rice crops was 7.9 t ha^{-1}, while that of double-rice crops was 6.9 t ha^{-1} for each round of cultivation. Converting single-rice to double-rice systems will increase the annual yield. The annual potential yield from double-rice crops was 13.8 t ha^{-1}, which is 75% higher than that of the single-rice crop. The national harvest area gap was approximately 6.0 million ha, accounting for 21% of the national rice harvest area in 2010. Considering water availability, the harvest area gap in the water-rich regions was 4.7 million ha.

To reach the downscaled water use boundary, the national consumption of irrigation water for rice production would need to be reduced in water-scarce regions by 7.3×10^9 m^3, which is approximately 10% of the national irrigation water consumption for rice in 2010. The water-rich regions (WSI < 0.5) had the potential to increase irrigation by 1.5×10^{12} m^3, which is far greater than the reduction target for the water-scarce regions.

A reduction in irrigation within the water-scarce regions implies that the associated rice production would also be decreased. Based on the current crop yields, the total rice loss in the hotspot regions was estimated at 10% of the national production in 2010. However, using scenario analysis, we found that the production losses can be reduced to approximately 7% by closing yield gaps, and fully compensated by closing harvest area gaps in water-rich regions (Fig. 1). Closing both the yield and harvest area gaps enables a 3% increase in the national rice production (6.9 million metric tons)

(Fig. 1). The water-rich regions suitable for double-rice systems show a high potential to increase rice production. The national WSF for rice production in 2010 was 16.2 billion m^3 H_2Oe, whereas the total WSFs after redistribution were 7.3 (Scenario 1), 7.7 (Scenario 2) and 7.8 billion m^3 (Scenario 3). The spatial redistribution of rice production under the three scenarios resulted in a reduction in the national WSF related to rice cropping of 52-55% (Fig. 2).

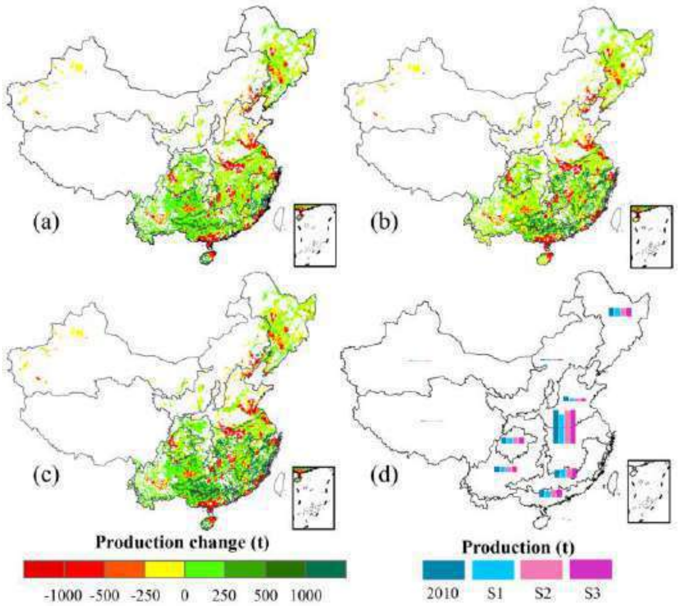

Fig. 1. Redistribution of rice production. (a) Scenario 1 (S1), (b) Scenario 2 (S2), (c) Scenario 3 (S3), and (d) comparison of the redistributed production with production in 2010 at the agro-ecological zone level. The black outlines indicate the boundaries of China's first-order agro-ecological zones.

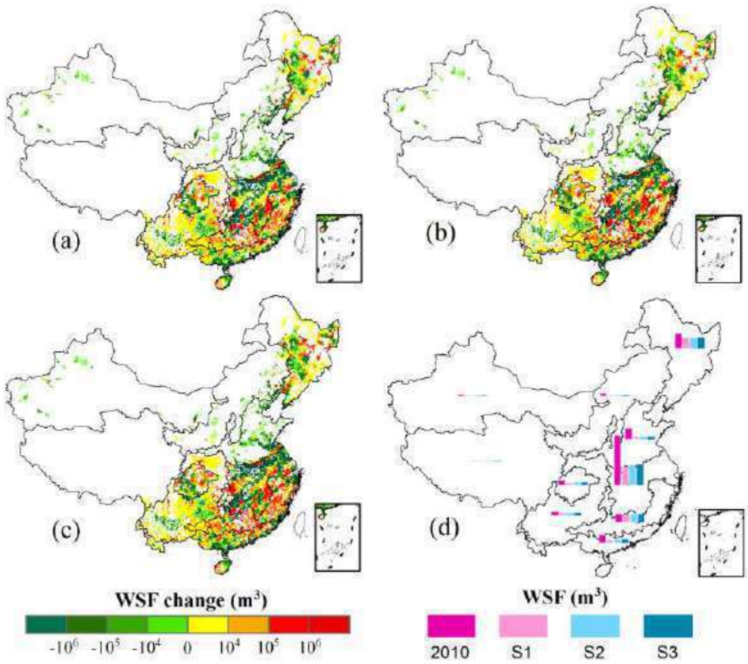

Fig. 2. Water-scarcity footprints (WSFs) in 2010 and under different scenarios. (a) Scenario 1 (S1), (b) Scenario 2 (S2), (c) Scenario 3 (S3) and (d) comparison of the WSFs after redistribution with the WSF in 2010 at the agro-ecological zone level. The black outlines indicate the boundaries of China's first-order agro-ecological zones.

Discussion and conclusion

As many countries in the world face the challenges of water and food security, where and how food production occurs has emerged as an important concern. This study illustrates the high potential for sustainable rice production by exploring opportunities in water-rich regions. Food production should carefully consider the regional water scarcity background. It is necessary to avoid aggravating unsustainable water consumption, which often occurs in regions of high water scarcity. To reach the downscaled water use boundary, rice redistribution is urgent and possible. We identified a substantial potential to balance rice production and water use by closing both the yield and harvest area gaps in water-rich regions. Particularly, converting the current single-rice systems to double-rice systems shows high potential. National policies on land use are advised to encourage the promotion of rice production in water-rich regions that are suitable for double-rice cropping. Using rice production as a case study, we demonstrate the broader value of integrating food production with a water use boundary for sustainable development.

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Assessing water scarcity impacts of food product in harmonized LCA – focus on life cycle inventory

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Keywords: water scarcity; AWARE; life cycle inventory analysis; water; PEF; LCA

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Abstract

Product Environmental Footprint (PEF) have been launched to harmonize LCA calculation methods and to make the results comparable. AWARE method is recommended in PEF to assess water scarcity impact. Product category rules should be improved especially in terms of life cycle inventory to tackle the challenges related to harmonized water scarcity assessment. Three food case studies were analyzed and hotspots of the production chains were recognized. Observations were made on the life cycle inventory phases of the cases and challenges are raised up. PCR and PEFCR developers are recommended to define processes where spatial origin, primary data or geographically representative secondary data is obligatory and principles how geographically representative secondary datasets should be compiled.

Rationale and objective

Life cycle assessment is generally applied for improving the environmental performance of the production chain and communicating for the stakeholders. To enable fair play in the market, different approaches (ISO 14025 (type III environmental declarations), Product Environmental Footprint (PEF)) have been launched to harmonize LCA calculation methods and to make the results comparable. The execution of LCA may differ whether the purpose of the study is the improvement of the environmental performance of the product or public communication over the results (Usva, 2022).

Including impacts on water in food LCA studies is particularly important. The number of people living under water shortage has multiplied rapidly in recent decades (Kummu et al., 2010; Wada et al. 2011) and ecosystems suffer from inadequate flow in rivers (Jury and Vaux, 2007). Agriculture is the main water consumer globally, especially due to irrigation (FAO 2016). On the other hand, water-intensive agricultural goods are exported from water scarce countries to Europe (Dolganova et al., 2019).

AWARE method is a mid-point impact assessment method for assessing water scarcity footprint. It was launched under UNEP-SETAC Life Cycle Initiative and based on ISO14046 standard (Boulay et al., 2018). So far 19 LCA case studies on food products applying AWARE-method have been published (Web of Science in 14.9.2021) (Usva, 2022). However, AWARE as a consensus method, is widely accepted and recommended in several directions. European Joint Research Centre (JRC) recommends AWARE method as a characterization method for "User deprivation potential" (Sala et al., 2019). FAO recommends AWARE method (as one out of two methods) for livestock products (FAO, 2019). AWARE is also recommended for harmonized LCA purposes by European Commission (EC) for Product Environmental Footprint (PEF) Product Category Rules (PCR's) (EC, 2017). Due to this wide acceptance, it can be assumed that the number of AWARE applications for assessing water scarcity impacts within LCA framework, will multiply in the near future.

Water scarcity is included as one of the recommended impact categories in several PCR's under PEF-program (PEFCR) (EC, 2017). Life cycle inventory phase as well as the whole process of LCA is well instructed in PEFCR's (EC, 2017), but the application methods in life cycle inventory in terms of water scarcity assessment is not thought through to the end yet (Usva, 2022). Water scarcity as a phenomenon is local or regional. As a method, the water scarcity assessment is sensitive to the spatial location of water consumption. This aspect is not specifically considered in life cycle inventory instructions in PEFCR's. If the method harmonization is the case, a proper instruction should be included in the category rules.

A project "Development and harmonization of Life Cycle Assessment (LCA) for food products (LCAFoodPrint)", coordinated by Natural Resources Institute Finland, aims to harmonized LCA methodology for food products in Finland. The work is done in collaboration with wide range of food chain actors, research and Ministry of agriculture and forestry in Finland. As a part of the project water scarcity impact within LCA has been studied and a recommendation for the harmonized water scarcity assessment will be given. EC's Product Environmental Footprint has been selected as a starting point for the harmonization work.

The purpose of this paper is to present critical issues identified in AWARE method applications for food products in especially life cycle inventory phase. Accordingly, recommendations are made for harmonized life cycle assessment and product category rules, especially for PEFCR's.

Approach and methodology

The aim of the PEFCR is to increase reproducibility, relevance and consistency of PEF studies (EC, 2017). Single PEFCR's are defined for certain product category in accordance to the general guidance (EC, 2017). In the PEFCR's the minimum list of mandatory primary data is defined as well as the impact categories and models to be used (EC, 2017). Most relevant processes and elementary flows are identified (EC, 2017). In this paper, harmonized LCA refers to LCA, the result of which is to be openly communicated, and which is therefore carried out in accordance with the applicable PCR (or PEFCR). In this study the aspects to be considered in food/agricultural PEFCR's related to water scarcity assessment applying AWARE method, were identified. Especially the focus was on life cycle inventory phase.

Considering harmonized LCA in the purpose of communication, a repeatable, relevant and consistent LCA should be conducted. PCR should be accurate and detailed enough to guide in executing a LCA study with the desired characteristics. In the harmonized LCA the comparability of the result is specially important, sometimes even more important than the sensitivity of method or details in some parts of the life cycle (Usva, 2022). In harmonized LCA the level of total impact matters (Usva, 2022). Recommendations were given for PEFCR developers to fulfill these needs.

Three food LCA case studies from Finland including water scarcity assessment were analyzed: 1) milk from a rain-fed system (Usva et al., 2019), 2) coffee from irrigated and non-irrigated systems (Usva et al. 2020) and 3) broiler chicken consuming domestic and imported feeds (Usva et al., 2022). These food products represent both rain-fed and irrigated systems; domestic (Finland) production (milk); animal production with some imported feeds (broiler) and globally traded product (coffee).

The case studies and especially the life cycle inventories were analyzed, observations compiled and potential limiting factors in applying AWARE method for food products were identified (Usva 2022). The analysis is described in detail in Usva (2022). In addition, the hotspots of the case studies were identified to focus on essential parts of the chain.

Results and discussion

Analyzing the case studies showed that the geographical location of the water consumption is the main contributor to the water scarcity impact. The volume of consumed water has a remarkable impact too. These results are supported by e.g. Caldeira et al. (2018) who studied cooking oil systems in different countries. Irrigation, when applied, dominated the water scarcity results of case food products. The overall level of water scarcity impact was remarkably lower in rain-fed systems. In the rain-fed systems, the majority of water scarcity impact was due to fertilizer production in all case studies. More detailed results are provided in Usva (2022).

Due to strong spatial nature, the most critical observations on inventory analysis' of the case studies related to the spatial aspects. Traceability was one of the main challenges. The origin country was mostly known in terms of the agricultural inputs, but not for industrial inputs. In the case of unknown spatial origin, a characterization factor representing wider area, for example Europe or Globe, need to be selected. These characterization factors are relatively high inducing higher water scarcity impact of the product.

Even if the origins of inputs were known, a lack of geographically representative data was observed. Geographically non-representative datasets are a significant source of uncertainty. Geographically non-representative datasets can be modified more representative but may lead easily to inconsistency. Inconsistencies in inventories were found possible if inventories consisted on primary and secondary datasets compiled in different ways. For example, different principles on selecting characterization factors when the real location is not known, may lead to inconsistencies.

In terms of irrigation, modelled water volumes instead of primary data, are commonly used. It may lead to under- or overestimations and is a problem due to the significance of the irrigation in terms of food water scarcity impact.

Conclusions

The most important challenges related to water scarcity assessment of food products relate to traceability of the inputs, geographically representative datasets, inconsistent inventories and availability of primary data, especially related to water volumes in irrigation.

Accuracy and consistency of LCA case studies applying AWARE can be improved by focusing on life cycle inventory phase. Traceability in supply chains needs to be improved. The continuous work to produce more of geographically representative datasets is still needed.

For the purposes of harmonized LCA, more detailed calculation rules are needed in PEFCR's and other PCR's. Recommendation for the PCR's:

1. Define processes where primary data on the spatial origin of the input is obligatory.
2. Define processes where primary data is obligatory. Note, that in terms of water scarcity, these processes differ from other impact categories. Especially primary data on irrigation should be considered.
3. Define processes where geographically representative secondary data is obligatory and when e.g. "Global" processes can or should be used.
4. Define principles for compiling geographically representative secondary datasets.

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Historical trends in the spatial patterns of water and land footprints of the world's major crops

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Keywords: *water footprint; land footprint; life cycle assessment; crop production; global AquaCrop model*

Introduction

Reliable and high-resolution water and land use inventory data build a foundation for LCAs of food products. Therefore, it is important to utilize up-to-date datasets on the water (WF) and land (LF) footprints of crops in the life cycle inventory databases (LCI). The leading LCIs mostly apply the WF dataset by Mekonnen and Hoekstra (2011) which only provides the values around the year 2000 and contains several methodological limitations such as (i) crop growth and its response to thermal stress are not simulated; (ii) the water balance is simulated without considering capillary rise, which is relevant in areas with shallow groundwater; (iii) the green-blue water partitioning is performed in post-processing, which disregards the complex dynamics of green and blue water fluxes in the soil (Hoekstra, 2019). At the same time, LFs of crops are not well-studied yet, particularly concerning land bioproductivity. In this work, we simulate the historical changes in WF and LF of global crop production during 1990-2019 using state-of-the-art input data and the recently published global gridded crop model AquaCrop-Earth@lternatives (ACEA, Mialyk et al., 2022). The generated WF and LF datasets provide up-to-date LCI data inputs and allow for performing more accurate analyses.

Methods

ACEA is a global gridded version of FAO's water-driven and process-based crop growth model AquaCrop (Vanuytrecht et al., 2014). It is written in Python and based on open-source AquaCrop-OSPy version 6.1 (Kelly and Foster, 2021). The key features of ACEA are direct tracing of green and blue water fluxes in the soil, consideration of historical changes in rainfed and irrigated croplands, and efficient large-scale computation. For more details, please refer to Mialyk et al. (2022).

The main input data sources are:

- Soil and daily climatic data as used in the Inter-Sectoral Impact Model Intercomparison Project (Inter-Sectoral Impact Model Intercomparison Project, 2022).
- Crop parameters from AquaCrop's default files and crop-specific literature.
- Monthly gridded groundwater levels (Fan et al., 2013).
- Gridded rainfed and irrigated harvested areas from SPAM2010 (Yu et al., 2020).
- Annual production and harvested area statistics per country from FAOSTAT (FAOSTAT, 2022).
- Land suitability (Zabel et al., 2014) as a proxy for bioproductivity.

The simulation of crop WFs and LFs in ACEA has several stages. First, green and blue ETs as well as crop yields are modelled. Then, the latter is scaled together with harvested areas to fit the official national statistics from FAOSTAT. This allows accounting for historical agricultural developments which cannot be directly captured by AquaCrop, such as an increase in fertilizer use, cropland expansion, or impacts of socio-political instability. Finally, WFs and LFs are estimated. We estimate three consumptive WF components (green, blue from irrigation, and blue from capillary rise) and three LF classes depending on land bioproductivity (highly, moderately, and poorly productive lands).

Both WFs and LFs are simulated for more than 100 crops (covering 99% of global harvested areas) in the 1990‑2019 period at 5 x 5 arc minute spatial resolution (~ 8.3 km x 8.3 km). The analysis is performed at the global scale, for each year, from the unit perspective (in m^3 for water or m^2 for land per tonne of a crop) and from the perspective of total production (in m^3 or m^2).

Results and discussion

Global trends

Preliminary results for 17 major crops (covering 75% of the global harvested area), which represent six crop groups (cereals, oil crops, sugar crops, fibre crops, roots, and pulses), show a total WF of $4{,}100\times10^9$ m^3 and a total LF of $10{,}400\times10^9$ m^2 in 2019. Compared to 1990, the WF and LF increased by 22% and 19%, respectively (Figure 1). Throughout the whole study period, cereal and oil crops were the dominant groups and currently, their share is more than 80% in both footprints. Among all crop groups, oil crops experienced the largest increases in both footprints (+100% for WF, +90% for LF).

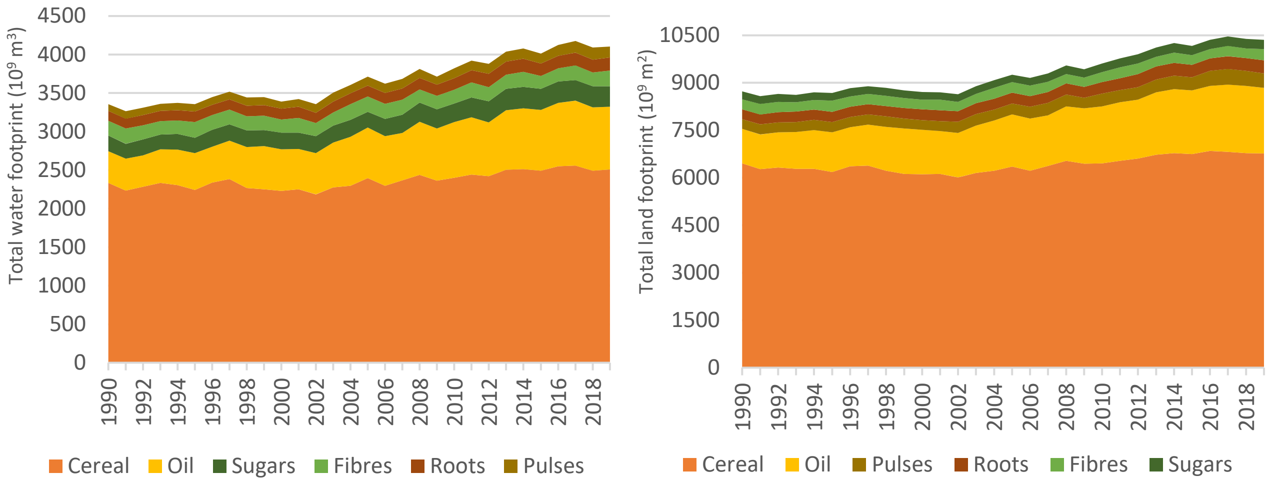

Figure 1: Total annual water (left) and land (right) footprints of six crop groups during 1990-2019, from the perspective of total production. The crop groups are sorted in ascending order.

These increases in total WFs and LFs of all crop groups are opposite to the trends observed in unit footprints, as shown in Figure 2. The unit footprints have reduced in a range from 13% to 34% driven by crop yield gains, irrigation expansion, and cultivation of more productive lands (Figure 3).

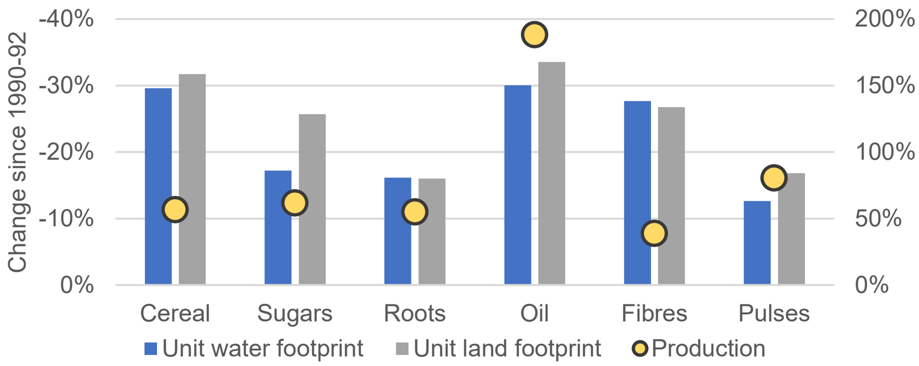

Figure 2: Historical change in unit water and land footprints (left axis) and total production (right axis) of six crop groups from 1990-92 to 2017-19.

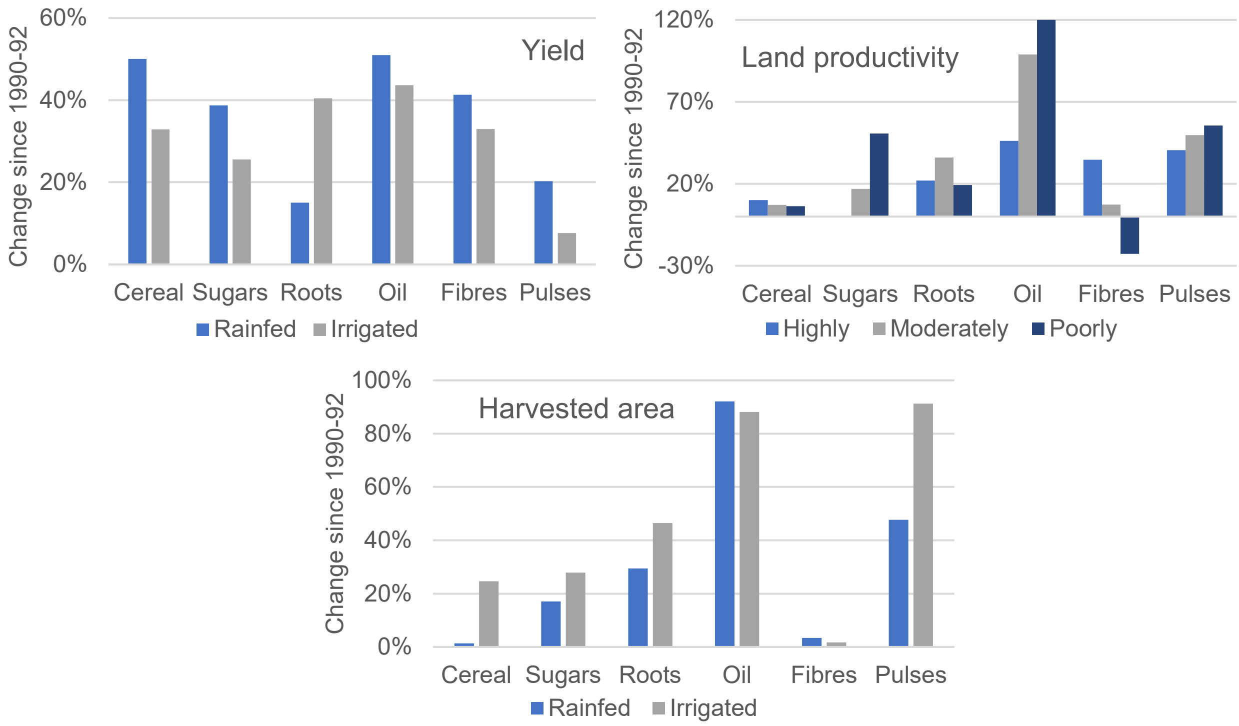

Figure 3: Historical change in crop yield, land productivity, and harvested areas of six crop groups from 1990-92 to 2017-19.

Current footprint compositions

In 2017-2019, the total WF of 17 simulated crops was composed of 84% green water, 14% blue from irrigation, and 1.5% blue from capillary rise. The dominant role of green water is confirmed by previous literature which reports it in the range from 87% (Mekonnen and Hoekstra, 2011) to 90% (Tuninetti et al., 2015).

The largest shares of each WF component in the total WF are observed for the next crops:

- Green water (>95%): cowpea, cassava, sorghum, soybean, and millet.
- Blue water from irrigation (>25%): rice, cotton, sugarcane, and sugar beet.
- Blue water from capillary rise (>2.5%): rapeseed, sugar beet, wheat, and sunflower.

Our estimates of unit WFs substantially differ from Mekonnen and Hoekstra (2011) as shown in Figure 4. On average, our results are 14% smaller in the same time period (1996-2005), ranging from +7% for potato to -35% for cassava. This can be explained by different extents of rainfed and irrigated areas and application of the process-based crop model with direct green-blue water partitioning in our study. A similar observation was done by Mialyk et al. (2022).

The total LF, in 2017-2019, is composed of 15.3% highly productive, 66.3% moderately productive, and 18.4% poorly productive lands. The larger share of moderately productive lands is due to their wider availability. The largest shares of each LF class in the total LF of each crop are observed for the next crops:

- Highly productive lands (>20%): soybean, rice, and maize.
- Moderately productive lands (>75%): cassava, sunflower, and rapeseed.
- Poorly productive lands (>25%): millet, barley, cowpea, and wheat.

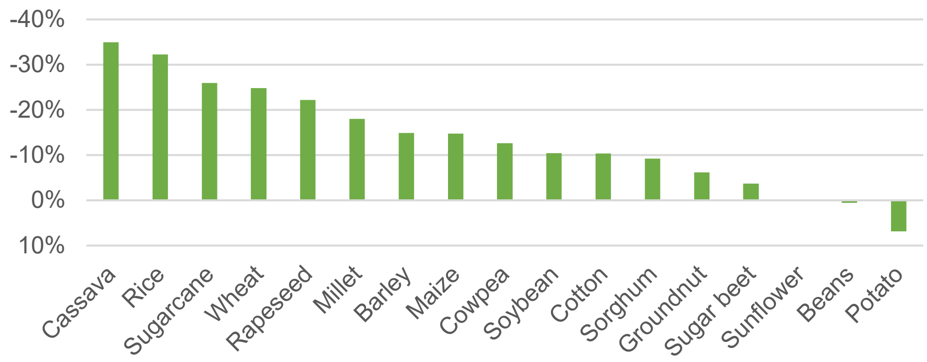

Figure 4: Comparison of average unit water footprints of 17 simulated crops during 1996-2005 in this study to respective values from Mekonnen and Hoekstra (2011). Negative values indicate smaller values in our study.

Conclusions

To have reliable LCAs of food products, up-to-date inventory datasets on crop WFs and LFs are needed. In this study, we aim at providing such datasets for more than 100 primary crops simulated by a state-of-the-art gridded crop model during 1990-2019. Preliminary results for 17 major crops already indicate substantial reductions in unit WFs and LFs of all crop groups since 1990. Such trends are likely to persist once the rest of the crops are simulated. The final datasets will be available at various spatiotemporal resolutions (e.g. annual averages of rainfed and irrigated crops at national and basin levels) creating opportunities for updates of the current LCI databases and new types of analyses.

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Water scarcity footprint of sugarcane production in the state of São Paulo, Brazil

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Keywords: *Water depletion; AWARE; regionalization; sub-perennial crop; irrigation; supply chain.*

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Motivation and goal

Brazil is the world's largest producer of sugarcane, with an annual production of 758 million tons in 2020. This crop generated a revenue of 60.8 billion reais (R$), equivalent to 13% of the total Brazilian agriculture sector revenue in the same year (IBGE, 2022).
To make this production possible, there are four types of irrigation management for sugarcane adopted in different Brazilian regions: i) full: which aims to supply close to 100% of the water deficit (400 to 1,000 mm/year); ii) supplementary: aims to supply around 50% of the water deficit (200 to 400 mm/year); iii) fertigation: consists of the reuse of effluents from the agro-industrial process such as vinasse and residual water; and iv) salvage: the same principle as fertigation, only here the effluents from ethanol industry are diluted in low volumes of water from reservoirs (ANA, 2019; 2021). According to the Brazilian National Agency for Water and Sanitation (ANA), the volume of water used over a year in one hectare for supplementary/full irrigation is, on average, equivalent to that applied in 25 ha of fertigation/salvage.
The state of São Paulo (SP) is the major sugarcane producer in Brazil, with approximately 56% of the production volume. In 2020, the state reached a production of 431.5 million tons of sugarcane, enough to be considered the region that produced the most sugarcane in the world (IBGE, 2022). The sugarcane water demand in SP is around 311 mm of water per plant cycle, and fertigation and salvage are the predominant irrigation management for this crop in this state (ANA, 2019a; 2021). Considering the large sugarcane cultivation area in SP, this state accounts for the highest irrigation water demand in Brazil for this crop production. As a result of the water crisis that recently reached the state of São Paulo, as well as concerns about future crises due to climate change, the awareness about the damage that such events can bring to the agricultural sector has risen.

Thus, it is crucial to assess the Water Scarcity Footprint (WSF) of sugarcane in SP to support political decisions and management practices. This paper aims to analyze the WSF of sugarcane in SP, providing information on hotspots to producers and a baseline for elaborating water security policies and strategies to mitigate impacts from sugarcane production in this state.

Methods

The WSF was calculated for 1 kilogram of sugarcane produced in SP. The scope was cradle to farm gate.

The inventory of SP sugarcane production, available in the Ecoinvent 3.6 database (Folegatti Matsuura and Picoli, 2018), was updated in 2021, modifying: i) average from years 2015-2020 sugarcane yield (CONAB, 2021a); ii) area percentages occupied by 1-year cropping cycle, 1.5-years cropping cycle, and renovation (CONAB, 2019); iii) area percentages for mechanized harvest (CONAB, 2020); iv) agrochemicals consumption (Agrianual, 2020); v) consumption of agro-industrial residues: vinasse – estimated based on volumes of ethanol produced (CONAB, 2021b)– and filter cake – estimated based on the amount of sugarcane processed (CONAB, 2021a); vi) irrigation water demand, obtained from the Brazilian National Agency for Water and Sanitation (ANA) database (direct communication). Regarding irrigation efficiency, the ANA based its calculation on the technical coefficients of water use for irrigated agriculture (ANA, 2019b).

The Brazilian states and countries that produced or exported at least 60% of the inputs consumed in sugarcane production were identified through research in the official Brazilian databases (Table 1). This procedure was carried out to make possible the subsequent attribution of characterization factors (CF) for each region and calculate the WSF of the inputs. It was assumed that the whole production chain of each material was located in the same region.

Input	Participation of regions in production
Glyphosate	64% - China, 36% - USA
Gypsum	100% - Pernambuco/Brazil
Limestone	100% - Minas Gerais/Brazil
Packaging for fertilizers	53% - Minas Gerais/Brazil, 25% - Canada, 21% - Russia
Packaging for pesticides	63% - SP/Brazil, 20% - China, 17% - India
Pesticide unspecified	63% - SP/Brazil, 20% - China, 17% - India
Phosphate fertilizer (P_2O_5)	58% - Morocco, 18% - China, 15% - Mato Grosso/Brazil, 9% - Rio Grande do Sul/Brazil
Potassium fertilizer (K_2O)	69% - Canada, 31% - Belarus
Nitrogen fertilizer (N)	65% - Russia, 16% - Qatar, 7% - Algeria, 6% - China, 6% - Mato Grosso/Brazil
Diesel B10	100% - Brazil

Table 1. Origin of sugarcane inputs (percentage of consumption and main producing countries and states).

For inputs from national regions, the SIDRA database was used (IBGE, 2021) for calculating input production (kg/year) of the last three or five years available in the historical series (most recent year: 2018). Regarding imports by country and total, the COMEXSTAT database was used (MDIC, 2021) to calculate the average of the last five years available (2015-2019) for each input.

Water consumption was compiled and grouped into three parts: i) water consumption in the supply chain of each crop input; ii) other water consumption in sugarcane production (water for diluting pesticides in spraying); and iii) consumption of water for sugarcane irrigation. Water consumption for i) was calculated from the balance between the volumes of water withdrawn and returned to the ecosystem. The water consumption for spraying (200 L/ha) was calculated based on expert estimates. It is noteworthy that for cases i) and ii), the final value of water consumption refers to the water volume used in the input chain to produce one kilogram of sugarcane.

Regarding the computation of water consumed in case iii (crop production), monthly values for sugarcane irrigation (salvage) for the municipalities were obtained through formal communication with ANA. In the municipalities where there was no salvage irrigation, the consumption of freshwater (blue water) from a source for irrigation was zero, and, with this, it was understood that only fertigation with vinasse from ethanol production (reuse water), filter cake and ash (residues from the ethanol plant) were applied.
The water scarcity footprint was calculated by multiplying water consumption by the CF of the corresponding region where crop inputs were produced, and sugarcane was cultivated. Monthly and annual CFs of the AWARE model (Boulay et al., 2018) were used and, for reasons of sensitivity, the monthly and annual CFs of this model regionalization for Brazil (AWAREBR) (Andrade et al., 2019). The WSF value of irrigation water at sugarcane farms was calculated using the weighted sum of the monthly WSFs per municipality in relation to the sugarcane production in each municipality. Data regarding sugarcane production at the municipality level was from IBGE (2022).

Results and discussion

The results showed that about 95% (1.29E-04 m³/kg sugarcane) of the total water consumed in sugarcane production came from the supply chain, especially from nitrogen fertilizer production. Water for dilution of pesticides in spraying corresponded to 3% (4.2E-06 m3/kg) of the total water consumed in the sugarcane chain, while irrigation contributed to only 2% (3.2E-06 m3/kg) (Figure 1a).

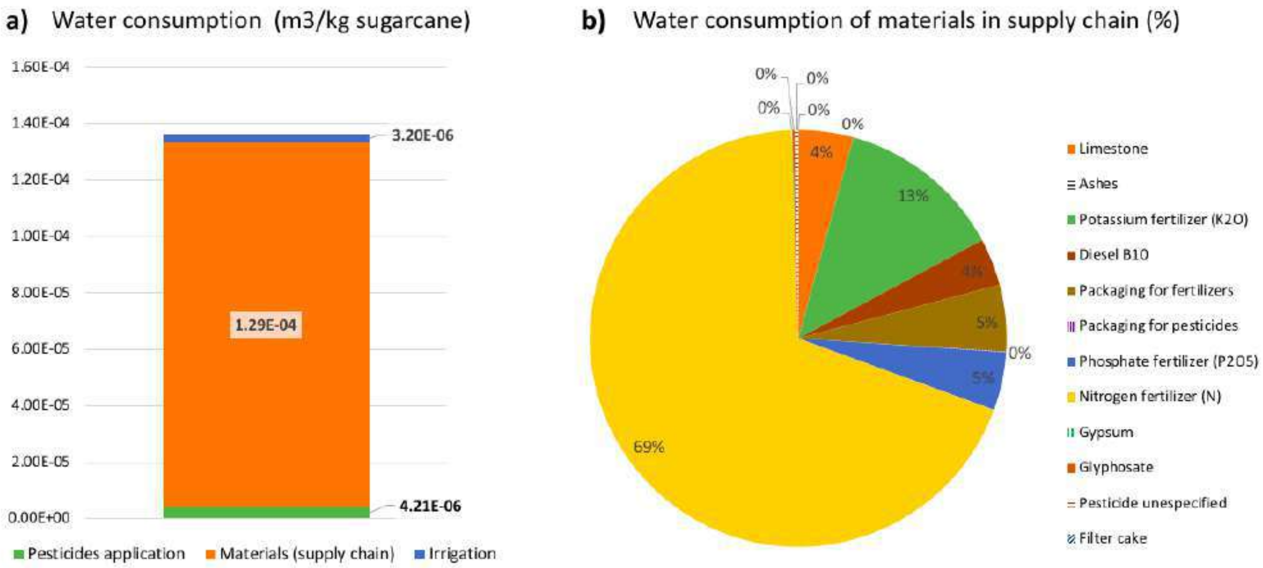

Figure 1. a) Water consumption in sugarcane production in São Paulo (m³/kg); b) Water consumption of inputs used in the sugarcane production (m³/kg).

Regarding freshwater consumption for irrigation, it varied throughout the year and was concentrated in only 20 municipalities, while the remaining applied fertigation using vinasse and wastewater from the ethanol industry. It reached a maximum value of 3.95 m³/ha.month in August in the municipality of Itapura, and a minimum of zero, meaning there is no freshwater demand throughout the year in 625 municipalities (97% of the SP total).
The annual WSF (m^3/kg) of sugarcane in the state of São Paulo ranged from 2.81E-03 (AWAREBR) and 2.56E-03 (AWARE) (Figure 2a). The consumption of materials used in sugarcane production was the main responsible for this footprint (2.79E-03 with AWAREBR characterization factors and 2.55E-03 with AWARE factors). Nitrogen fertilizer accounted for 74-80% of the total impact (Figure 2b).

The WSF of sugarcane irrigation ranged from 2.09E-05 (AWAREBR factors) to 2.37E-06 (AWARE factors). The highest impact was in August, using both AWAREBR and AWARE FCs; the lowest values were in February when using the FCS AWAREBR and in March, using the FCs AWARE.

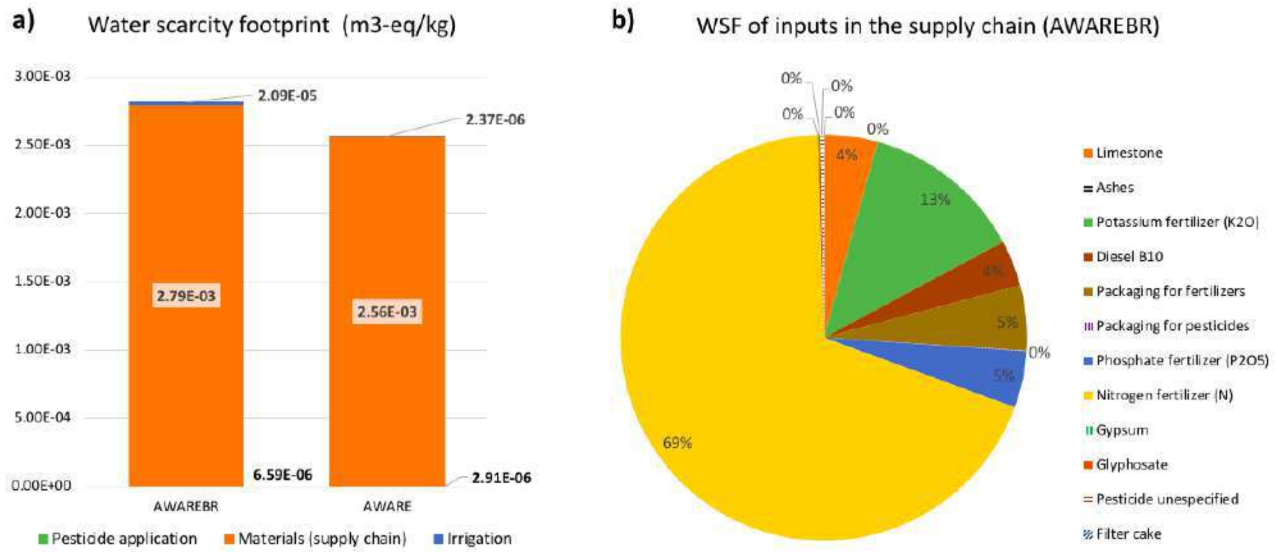

Figure 2. Water scarcity footprint of sugarcane production in São Paulo. a) overall impact (m^3/kg), considering AWARE and AWAREBR FCs; b) share of impact per material (AWAREBR)

The irrigation water consumption and, consequently, the WSF related to irrigation were due to the practices adopted by producers in the state of SP. This situation was emphasized by Dolganova et al. (2019), who pointed out that even though Brazil was responsible for 14% of all sugarcane imported by the European Union (EU), the country represented only 0.2% of the WSF of EU sugarcane imports. In comparative terms, the maximum consumption value observed in SP farms was 3.95 m^3/ha.month, while Kaemai et al. (2021) reported that sugarcane produced in Thailand (the fourth largest producer in the world) applied from 8248 to 18556 m^3/ha, depending on the region in which it was produced. In India (the world's second-largest producer), the cultivation phase had a blue water demand of 0.175 m^3/kg (Hiloidhari et al., 2021), while in SP, the consumption was 2.81E-03 m^3/kg.

Conclusions

The present study used a consistent and reproducible procedure to calculate the water scarcity footprint of sugarcane production in the state of São Paulo. This procedure can be used in other WSF studies of crops.

The highest water consumption came from the production of sugarcane inputs and the lowest from irrigation at sugarcane farms. In terms of WSF, the most significant footprint was also related to inputs supply chains, in particular nitrogen fertilizer, showing the importance of reducing this input in sugarcane production or using other sources of nitrogen to fulfil the crop needs, such as waste streams from local crop and food producers.

Acknowledgement

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Life cycle assessment of novel plant products compared to animal products

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Objective of the study

Meat and animal products have been identified as a major driver of environmental impacts in the food sector. Traditional simple vegan products like legumes often show considerably lower environmental impacts but are less accepted by consumers. In the last years a huge increase of processed plant products which serve as direct alternatives to animal products can be observed. Novel meat and dairy alternatives refer to meat- and milk-free food products that have a similar taste, haptic experience, appearance, and nutritional value to traditional meat and dairy products.[1] They include, among others, products such as Quorn, soy vegetable mince, vegetable drinks, yoghurt, cheese, creams, beyond meat burger and planted chicken. Little is known about their environmental impacts. The ESU world food database (ESU-services 2022) has been extended in the last years for several such products. Here we present the direct comparison for different animal-based food items with their vegan or vegetarian counterparts based on an assessment in the framework of developing scientific basis for Swiss dietary recommendations (Jungbluth et al. 2022).

Methodology

The life cycle inventories are based on single projects, literature research and published studies for single products. All data have been harmonized with the LCI methodology applied for the ESU database (like the ecoinvent methodology). The data are fully documented in EcoSpold format. Here we discuss the environmental impacts from farm to shop (incl. food losses). The home transport, storage, and preparation at home is not included here. Sometimes there might be slight differences at this stage which are not considered.

Generally, several definitions for a functional unit can be found in LCA studies for food products. Often quite different products e.g. a beef and vegan burger, are compared just on the basis of mass. This might give wrong incentives for an unhealthy but more environmentally friendly nutrition if the content of nutrients differs considerable.

Another easy to apply measurement is the impact per energy content (kcal) of food. This reflects a main purpose of satisfying the hunger with the food. On the other side it can be argued that in Western societies there is often an overconsumption and thus the energy content is not the limiting factor for a healthy diet. It might even be a disadvantage to consume as much energy as possible for the lowest impact if this leads to overweight in the population.

The main function of food is to provide nutrients, many of which cannot be determined from weight or energy content. It was therefore deemed necessary to apply other functional units. The main conflict seems to be the provision of nutrients with animal products, which often show a quite high

1 https://www.sciencedirect.com/science/article/pii/S2095809920303192

environmental impact. Therefore, the following nutrients that are difficult to get without meat and animal products are investigated in more detail[2]:

- 64 g protein at the supermarket[3]
- 4 µg vitamin B12 at the supermarket
- 1.5 g omega-3 fatty acids[4] at the supermarket
- 1 g of calcium at the supermarket
- 15 mg iron[5] at the supermarket
- 150 µg iodine at the supermarket
- 14 mg zinc[6] at the supermarket
- 1.4 mg riboflavin (vitamin B2)[Fehler! Textmarke nicht definiert.] at the supermarket
- 15 µg vitamin D at the supermarket
- 70 µg selenium at the supermarket

Results of the datasets can be evaluated with different life cycle impact assessment (LCIA) methods. For this paper we present the results for the Swiss ecological scarcity method (BAFU 2021), global warming potential and the European Footprint.

Results and discussion

Table 1 shows the reduction potential for the total environmental impacts of the daily nutrient intake. The base line is the environmental impact due to the necessary daily provision of nutrients with an animal-based product. The reduction potential is investigated for the direct replacement with plant-based products.

Food items providing the nutrients in an eco-efficient manner are marked in green, while those with an inefficient provision are marked in yellow or red.

It must be noted that within the groups of food items there might be considerable differences concerning environmental impacts per portion and the nutrients per portion. For some plant-based alternatives there are products on the market with enrichments for certain nutrients. So far it is difficult to analyze the environmental impacts of such pure nutrients. This adds to the uncertainty of these evaluations.

Proteins and iron can be replaced very efficiently with several plant-based products and reductions of up to 90% for the environmental impacts can be achieved. It is more difficult to replace vitamin B12, which seems to be only possible with plant-based alternatives with added vitamin B12. For calcium, plant-based alternatives there are also good options.

The number of servings necessary to provide the daily amount of nutrients is shown in Table 4. Milk and hard cheese are the only food items providing the necessary calcium with less than 5 servings a day. Plant based drink as alternative to cow milk can be a good option. Calcium supplements e.g. in milk alternatives might be an environmentally friendly way to meet the daily demands.

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2 https://www.sge-ssn.ch/media/Merkblatt-Vegane-Ernaehrung-2021.pdf

3 Represents the recommended daily intake for a person weighing 80 kg

4 Represents 0.7% of energy intake of a 2000 kcal diet

5 Represents the recommended daily intake for women between 19-51 years old, the recommended intake for men is lower

6 Represents the recommended daily intake for men, the recommended intake for women is lower

Conclusion

Meat alternatives (and legumes which are often the base for meat alternatives) are an effective substitution to the consumption of meat. Comparing highly processed meat substitutes with red meat, the substitutes deliver all nutrients more environmentally friendly than meat. For dairy and egg products, many substitutes are available.

In a global perspective, environmental impacts are an important cause of health impacts and premature deaths. From an environmental perspective a replacement of animal-based products with plant-based products is necessary.

Plant based proteins are often used as an eco-efficient means for providing the necessary daily nutrients. A possible obstacle is the number of portions necessary to achieve a certain nutrient input. The present policies of retailers to promote vegan or vegetarian products mainly/exclusively for the group of consumers with high environmental awareness and willingness to pay is also questionable. It would be very welcome if such products became mainstream and were no longer offered only to a certain target group.

Further improvements can be expected by substituting even more animal-based products with plant-based products. As diets might include many of these substitutes, it might be necessary to supplement such products with essential nutrients. So far, the environmental aspects of the production of such additives are not fully known and need further investigation.

Table 1 Reduction potential to achieve the daily nutrient intake for the replacement of animal-based food items with plant-based food items (Swiss ecological scarcity method)

Reduction potential of environmental impact	64 g protein	4 µg vitamin B12	1.5 g omega-3 fatty acids	1 g of calcium	15 mg iron	150 µg iodine	14 mg zinc[4]	1.4 mg riboflavin (vitamin B2)	15 µg vitamin D	70 µg selenium
Drink instead of cow milk	46%	-5%	70%	-2%	na	-37%	44%		-92%	-96%
Instead of red meat …										
Legumes	-81%	na	-46%	-98%	-96%	930%	-19%	51%	na	na
Meat subsitutes, vegan, minimally processed	-87%	17120%	-77%	-98%	-87%	-88%	-43%	105%	na	-97%
Meat subsitutes, vegan, highly processed	-82%	11%	-94%	-97%	-89%	na	na	na	na	na
Egg-based meat alternatives	-61%	99%	-63%	-95%	-46%	na	-88%	na	na	na
Instead of poultry …										
Legumes	-70%	na	-25%	-98%	-97%	6%	-89%	-74%	na	na
Meat subsitutes, vegan, minimally processed	-79%	2245%	-68%	-97%	-95%	-55%	-76%	43%	na	-87%
Meat subsitutes, vegan, highly processed	-72%	-85%	-91%	-97%	-96%	na	na	na	na	na
Egg-based meat alternatives	-40%	-73%	-48%	-94%	-79%	na	-95%	na	na	na
Instead of eggs …										
Legumes	-59%	na	168%	-63%	-76%	1640%	-69%	33%	na	na
Meat subsitutes, vegan, minimally processed	-72%	16307%	15%	-58%	-60%	636%	-31%	634%	na	-66%
Meat subsitutes, vegan, highly processed	-62%	5%	-68%	-43%	-65%	na	na	na	na	na
Egg-based meat alternatives	-17%	90%	86%	-10%	69%	na	-86%	na	na	na
vegetable oil instead of fish										
omega 3 rich	na	na	-94%	2489%	na	na	729%	na	na	na
omega 3 poor/ other oils	13140%	na	-89%	4293%	4147%	na	na	na	na	na
omega 9 rich	na	na	-100%	na	2217%	142734%	na	na	na	na
Vegan cream instead cream	-35%	na	-67%	407%	-98%	na	na	na	na	na

Table 2 Reduction potential to achieve the daily nutrient intake for the replacement of animal-based food items with plant-based food items (European Footprint 3.0)

Reduction potential of environmental impact (EF 3.0)	64 g protein	4 µg vitamin B12	1.5 g omega-3 fatty acids	1 g of calcium	15 mg iron	150 µg iodine	14 mg zinc[4]	1.4 mg riboflavin (vitamin B2)	15 µg vitamin D	70 µg selenium
Drink instead of cow milk	29%	-17%	50%	-14%	na	-45%	27%		-93%	-96%
Instead of red meat …										
Legumes	-94%	na	-83%	-99%	-98%	-91%	-92%	-89%	na	na
Meat subsitutes, vegan, minimally processed	-89%	14410%	-81%	-98%	-89%	-90%	-52%	72%	na	-97%
Meat subsitutes, vegan, highly processed	-83%	3%	-94%	-97%	-90%	na	na	na	na	na
Egg-based meat alternatives	-62%	93%	-64%	-96%	-48%	na	-88%	na	na	na
Instead of poultry …										
Legumes	-91%	na	-78%	-99%	-99%	-68%	-97%	-92%	na	na
Meat subsitutes, vegan, minimally processed	-83%	1813%	-74%	-98%	-96%	-63%	-80%	17%	na	-90%
Meat subsitutes, vegan, highly processed	-75%	-86%	-92%	-97%	-96%	na	na	na	na	na
Egg-based meat alternatives	-43%	-74%	-51%	-95%	-81%	na	-95%	na	na	na
Instead of eggs …										
Legumes	-87%	na	-17%	-88%	-93%	441%	-90%	-59%	na	na
Meat subsitutes, vegan, minimally processed	-76%	13836%	-2%	-64%	-66%	525%	-42%	523%	na	-71%
Meat subsitutes, vegan, highly processed	-64%	-1%	-70%	-47%	-67%	na	na	na	na	na
Egg-based meat alternatives	-18%	86%	82%	-12%	66%	na	-86%	na	na	na
vegetable oil instead of fish										
omega 3 rich	na	na	-94%	2197%	na	na	636%	na	na	na
omega 3 poor/ other oils	2684%	na	-87%	365%	631%	na	na	na	na	na
omega 9 rich	na	na	-96%	na	916%	68473%	na	na	na	na
Vegan cream instead cream	-55%	na	-77%	252%	-99%	na	na	na	na	na

Table 3 Reduction potential to achieve the daily nutrient intake for the replacement of animal-based food items with plant-based food items (Global Warming Potential 100a)

Reduction potential of environmental impact (GWP)	64 g protein	4 µg vitamin B12	1.5 g omega-3 fatty acids	1 g of calcium	15 mg iron	150 µg iodine	14 mg zinc[4]	1.4 mg riboflavin (vitamin B2)	15 µg vitamin D	70 µg selenium
Drink instead of cow milk	40%	-9%	62%	-6%	na	-40%	38%	1296%	-92%	-96%
Instead of red meat …										
Legumes	-95%	na	-86%	-100%	-98%	-93%	-93%	-91%	na	na
Meat subsitutes, vegan, minimally processed	-88%	15314%	-79%	-98%	-88%	-89%	-49%	83%	na	-97%
Meat subsitutes, vegan, highly processed	-79%	31%	-92%	-97%	-87%	na	na	na	na	na
Egg-based meat alternatives	-62%	94%	-64%	-95%	-47%	na	-88%	na	na	na
Instead of poultry …										
Legumes	-89%	na	-73%	-99%	-99%	-62%	-96%	-91%	na	na
Meat subsitutes, vegan, minimally processed	-74%	2838%	-60%	-97%	-94%	-44%	-70%	79%	na	-84%
Meat subsitutes, vegan, highly processed	-54%	-75%	-85%	-94%	-93%	na	na	na	na	na
Egg-based meat alternatives	-18%	-63%	-30%	-92%	-72%	na	-93%	na	na	na
Instead of eggs …										
Legumes	-84%	na	6%	-85%	-91%	591%	-88%	-47%	na	na
Meat subsitutes, vegan, minimally processed	-60%	22849%	61%	-41%	-43%	929%	-4%	927%	na	-52%
Meat subsitutes, vegan, highly processed	-29%	94%	-41%	5%	-36%	na	na	na	na	na
Egg-based meat alternatives	27%	188%	182%	37%	158%	na	-78%	na	na	na
vegetable oil instead of fish										
omega 3 rich	na	na	-95%	1826%	na	na	517%	na	na	na
omega 3 poor/ other oils	2935%	na	-86%	407%	697%	na	na	na	na	na
omega 9 rich	na	na	-96%	na	775%	58933%	na	na	na	na
Vegan cream instead cream	-59%	na	-79%	217%	-99%	na	na	na	na	na

Table 4 Number of servings per food items to achieve the daily nutrient intake

Number of servings	64 g protein	4 µg vitamin B12	1.5 g omega-3 fatty acids	1 g of calcium	15 mg iron	150 µg iodine	14 mg zinc[4]	1.4 mg riboflavin (vitamin B2)	15 µg vitamin D	70 µg selenium
Milk for drinking, 200g	10	9	1	4	na	8	18	3	150	30
Red Meat - Beef, Veal, Lamb, Pork, horse, 110g	3	1	0	96	6	56	3	4	8	8
Poultry, 110g	2	8	1	120	24	22	12	8	14	3
Fish, omega-3 poor, 110g	3	1	2	35	16	2	19	16	6	3
Shellfish, 110g	4	1	3	26	8	1	7	14	na	na
Fish, omega-3 rich, 110g	3	1	0	77	21	3	30	10	2	na
Eggs, 110g	5	3	0	19	8	3	11	4	8	3
Legumes, 60g	4	na	2	15	4	133	7	12	na	na
Meat subsitutes, vegan, minimally processed, 110g	2	727	1	12	5	40	11	46	na	2
Meat subsitutes, vegan, highly processed, 110g	3	6	0	20	5	na	na	na	na	na
Egg-based meat alternatives, 110g	4	6	1	19	14	na	2	na	na	na
Milk alternatives, 200g	20	11	2	6	38	7	35	70	18	2
vegetable oils, omega 3 rich, 10g	na	na	0	33333	na	na	4200	na	na	na
vegetable oils, omega 3 poor/ other oils, 10g	1600	na	1	6897	3000	na	na	na	na	na
vegetable oils, omega 9 rich, 10g	na	na	0	na	3000	30000	na	na	na	na
Cream, 30g	94	48	1	43	1000	39	187	30	121	na
Cream alternatives, 30g	85	na	0	303	25	na	na	na	na	na

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Replacement of global dairy production with cellular agriculture

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Keywords: *dairy production; cellular agriculture; system expansion; food production systems, multifunctional systems; by-products*

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Introduction

Cellular agriculture is a technology that enables meat and other agricultural products to be cultivated in a bioreactor from cells instead of producing livestock (Mattick, 2018). It is a technique that has the potential to improve animal welfare, boost human health, and reduce the environmental impact of meat production. At the same time, it has the potential to increase energy consumption and consequently greenhouse gas emissions, because it substitutes biological processes with chemical and mechanical ones (Mattick, 2018). Assessments comparing meat alternatives with different meats has been done earlier (e.g., Smetana et al., 2015), but animal production systems are multifunctional, providing also other edible and inedible products. One of the most multifunctional systems is dairy cattle, which produces milk, meat and numerous other products - a bovine animal's edible parts account for only 45-47 percent of its live weight, and other parts of the animal are used for a variety of purposes, including pet foods, animal feeds, leather goods, biogas, biodiesel, fertilizers, and so on. To replace such a multifunctional system with cellular agriculture, alternative production of the other materials is also needed. Therefore, the aim of this study is to compare climate and land use impacts of global dairy production and cellular agriculture on a system level by implementing system expansion in attributional LCA.

Materials & Methods

The system level comparison is done following principles of system expansion, by including all the functions provided by dairy production system and creating equivalent system where milk and meat is produced by cellular agriculture and other functions are replaced with Ecoinvents (Wernet et al., 2016) market dataset of substitutable product. The compared systems as are presented in Table 1.
The systems were scaled to be equivalent to global annual milk production, based on global milk production in 2015-2020 (FAO, 2022). The environmental impacts and production of milk in relation to live animal foe slaughtering was derived from Ecoinvent database. The data concering amounts, usages and further processing of animal by-products was derived from companies, and environmental

impacts were assessed with Ecoinvent database and literature sources. Processing of by-products was included to the point where they are ready to use, i.e., substitutable. The processing and yields of by-products are presented more detailed in Kyttä et al. (2022).

in the cellular agriculture system, the environmental impacts of cultured meat were assessed based on data from Tuomisto et al. (2022) by changing the energy consumption to global energy (Ecoinvent). The data concerning cultured milk, which is oat milk supplemented with cultured milk proteins, was derived from Mazac et al. (2022). The substitutes of animal by-products are presented in footnote of Table 1.

Table 1. Compared systems of annual Finnish dairy production and cellular agriculture system, including all the products produced by each system and the alternative products added to each system to make the systems equivalent. The amounts of pet food and feed alternatives differs from the outputs of dairy system due different protein content. MBM = meat and bone meal, N = nitrogen, P = phosphorous

Products in dairy system	Dairy cattle system	Products in cellular system	Cellular agriculture
Milk, t	690 790 936	Milk, t	690 790 936
Meat/edible offal, t	9 868 442	Meat, t	9 868 442
Leather, t	148 621	PVC [a], t	148 621
Pet food/feed, t	5 363 439	Pet food/feed [b], t	6 619 182
MBM, N t	60 935	N fertilizer [c], t	60 935
MBM, P t	38 047	P fertilizer [d], t	38 047
Biodiesel, t	513 932	Diesel [e], t	513 932
Biogas, methane m3	328 155	Natural gas [f], m3	328 155
Digestate, N t	11 890	N fertilizer [c], t	11 890
Digestate, P t	1 783	P fertilizer [d], t	1 783

[a] market for PVC (ecoinvent), [b] market dataset for pet food (created), [c] market for N fertiliser (ecoinvent), [d] market for P fertiliser (ecoinvent), [e] market for diesel (ecoinvent), [f] market for natural gas (ecoinvent)

Results

The system level comparison results to notably lower global warming and land use impacts of cellular agriculture system, being only 37% and 3% of the impacts of dairy cattle system (Fig.1). Majority of the impacts of cellular agriculture originates from the production of cultured milk. Even though dairy cattle produce variety of by-products, the impacts of processing them, and also the impacts of replacing these products with alternatives are very low.

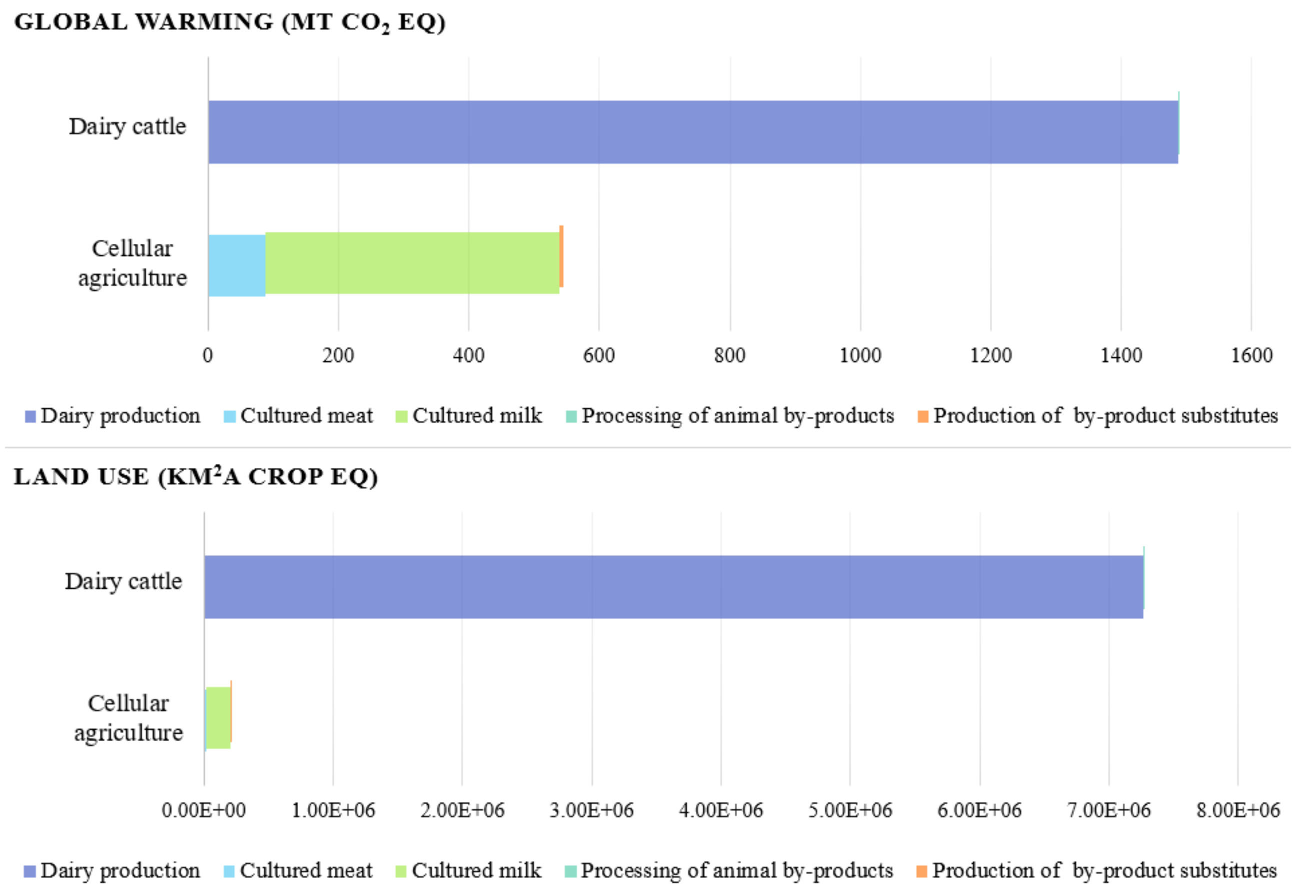

Fig 1. Global warming (Mt CO_2 eq.) and land use (km^{2}a crop eq.) impacts of expanded dairy and cellular agriculture systems.

Discussion

The results show potential to reduce the global warming impacts over 0.9 Gt CO_2 eq and the land use impacts around 7 million km^{2}a crop eq in total, by replacing the current dairy production by cellular agriculture. As the global greenhouse gas emissions from food production are estimated to be around 6.3-7.1 Gt CO_2 eq in total (without the emissions from land use change) (Willett et al., 2019) and the total agricultural land use in 2019 was around 47 million km^2 (FAO, 2022), replacing global dairy production with cellular agriculture would reduce the global agricultural emissions by 13-14 % and land use by 15 %. In addition, the saved land area has potential to sequester carbon and maintain natural habitats through alternative land uses, e.g., afforestation and habitat conservation.

However, this assessment is based on global averages and does not consider the regional differences in production systems, nor the feasibility of change in production technologies in different regions. Also, the assessment contains considerable uncertainties regarding the representativeness of the data used in the LCA. Therefore, further assessments with regional considerations are needed.

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A Comparative Life Cycle Assessment of Pork Meat and Plant-Based, Meat Alternative Patties

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Rationale and Objective

Increasing awareness of environmental issues related to food and the proliferation of plant-based meat alternatives have prompted evaluations of the potential environmental impacts of meat and plant-based alternatives. Most studies evaluating the reduction of meat consumption conclude that potential environmental impacts will decrease (Aston et al., 2012; Baroni et al., 2007; Goldstein et al., 2017). Few, however, have evaluated tradeoffs between nutritionally complete diets and potential environmental impacts (Liebe et al., 2020; White & Hall, 2017). The objectives of this work were to (1) perform a scan-level, "field-to-fork" comparative LCA of the global warming potential (GWP), cumulative energy demand (CED), water use (WU), and land use (LU) of three plant-based meat alternative patties: Beyond Burger (BB), Impossible Burger (IB), and Veggie Burger (VB), with that of ground pork; and (2) estimate the nutrient density of each of product.

Approach and Methodology

The LCA was conducted using SimaPro© 9. The functional unit was 1 kg of consumed product. The system boundary was cradle to grave ("field-to-fork"), and included raw material extraction, processing, packaging, purchase, preparation, consumption, and disposal of each product and packaging materials in a typical U.S. household. Environmental impacts embodied in the foreground infrastructure were excluded from the analysis; however, background processes such as electricity generation from the ecoinvent v3.7 database included an accounting of infrastructure.

Inventory data were obtained from a combination of sources including laboratory analyses completed at Colorado State University, publicly available nutrient composition databases (*i.e.*, USDA National Nutrient Database for Standard Reference), peer-reviewed literature (including a prior cradle-to-grave LCA of pork completed by the authors), and industry reports (*e.g.*, for calculation of retail space allotted to each product). Where data were incomplete, proxy lifecycle inventory datasets were identified from ecoinvent v3.7. A 1% cut off criterion was chosen for all inputs; however, if data were readily available, they were included. Where allocation of inputs is required, the allocation procedures follow the ISO 14044 hierarchy. The primary audience for this LCA was the pork industry (growers, processors, packaging companies, and retailers).

Environmental impacts assessed included GWP, CED, WU, and LU. Global warming potential was evaluated using the 100-year IPCC 2013 (IPCC, 2013) emissions factors. The IMPACT World+ midpoint method (Bulle et al., 2019) was used for CED and LU, and the ReCiPe 2016 (H) method was used for WU (Huijbregts et al., 2017). Uncertainty analysis was conducted using Monte Carlo simulations with a 95% confidence interval. The products varied in the amount of cooking loss, defined as the loss of product weight during cooking, which had potential implications for the results. As such, sensitivity analyses were conducted to estimate the impacts of cooking loss assumptions on all impact categories. Cooking loss was measured by laboratory analysis and was 19.2, 11.5, 12.5, and 31.3% loss for BB, IB, VB, and ground pork, respectively. To account for dependence and sensitivity of the electricity requirement at the processing facility on environmental impacts, a sensitivity analysis for a 20% reduction in processing electricity demand was also estimated for all impact categories.

Recipes for the plant-based meat alternative products were proprietary. As such, a linear optimization was used to estimate ingredient quantities. The optimization imposed the predominance order of ingredients based on the order listed on the package label. The objective function for the optimization was to minimize the sum of relative deviation from the nutritive value of one serving of each product (per the product label) and the total weight of the serving. The final nutritional composition of the recipe estimated by the model was compared with the results of the laboratory analysis for accuracy.

The Nutrient-Rich Foods (NRF) Index (Fulgoni et al., 2009) was used to estimate the nutrient density of each product on a raw and cooked basis. The nutrient profiles included 9 (NRF 9.3) (protein, fiber, vitamin A, vitamin C, vitamin E, calcium, iron, magnesium, and potassium) or 15 nutrients to encourage (NRF 15.3) (all 9 NRF 9.3 nutrients plus monounsaturated fat, vitamin D, thiamin, vitamin B-12, folate, and zinc), and 3 nutrients to avoid (saturated fat, added sugar, and salt).

Main Results and Discussion

Pork was found to have the highest impact for all impact categories assessed, while VB had the lowest for all categories assessed. Global warming potential ranged from 5.4 to 12.2 kg CO_2-eq/kg consumed. Among the plant-based patties, IB had the highest GWP and VB the lowest. The IB also had the highest CED among the plant-based patties—driven primarily by electricity consumption during processing (49% of the total impact). After pork, BB had the highest WU and LU, followed by IB, primarily due to differences in the type of packaging used (namely, polyurethane packaging for BB).

The sensitivity analysis indicated that differences in cooking loss affected the results across all impacts but did not affect the overall interpretation of the result. The GWP and CED for IB were most sensitive to a 20% reduction in processing electricity demand, resulting in a 7.4 and 9.1% reduction in impact, respectively. The cooked nutrient density analysis yielded conflicting results depending upon the number of nutrients considered. Using the NRF 9.3 metric, VB was the most nutrient dense due to a relatively low saturated fat content. Pork NRF 9.3 values were the lowest for this metric because of high saturated fat content. BB, the next most nutrient dense by this metric, had a 27% greater NRF 9.3 value than pork. However, pork's NRF 15.3 value was 25% greater than that for BB due to inclusion of Vitamins D, B1, B2, B12, folate, and zinc, highlighting the importance of considering more complete nutrient profiles in comparative evaluations of nutrient density of foods. The IB was by far the most nutrient dense product using the NRF 15.3 metric due to the inclusion of synthetic vitamins in the recipe which were not accounted for in the NRF 9.3.

Conclusion

This study demonstrates an approach for considering lifecycle environmental impacts together with the nutrient density of food products. Pork had greater GWP, CED, WU, and LU than plant-based meat alternative burgers, but was the third-most nutrient dense product using the NRF 15.3 metric. Given the significant contribution of processing to the GWP and CED of the IB and high levels of sensitivity associated with modeling processing of emerging plant-based meat alternatives, it is critical that more industrially relevant-data are made available to the LCA community for future analyses.

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Carbon footprint of dairy sheep production in northern Spain through Ardicarbon assessment tool

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Rationale: Dairy sheep production is a significant sector for the Basque Country, with more than 134 thousand ewes and a milk production of about 10 million L yr^{-1}. The 50 % of the sheep milk production is destined to cheese industry for "Idiazabal PDO" (Protected Designation of Origen, European Quality label) production. The herds of Latxa breed have played an important environmental, social and economic role as core actor in rural areas, as for a large part of the year, feeding is based on grazing and the use of fodders that would otherwise be lost. It also maintains the landscape and the population in rural areas.

Furthermore, in recent years, Green Deal strategies (from Farm to Fork) are at the top of the European agenda. One of their main objectives is to reduce the environmental footprint of farm products as a key factor for farmers to obtaining incentives. For this purpose, it is essential to assess the environmental footprints of dairy sheep production to identify weak points of the production chain where to take actions for reducing the farm's environmental impact (FAO, 2010). The carbon footprint of the sheep milk production can be evaluated by using the Life Cycle Assessment (LCA) approach (De Boer, 2003). Nevertheless, it would be highly desirable to provide the dairy sheep sector with user-friendly tools owing to the difficulty associated with the LCA methodology.

Objective: The aim of this study was to analyse the carbon footprint of dairy sheep production in northern Spain based on the user-friendly and easy to operate ArdiCarbon tool, based on LCA analysis.

Approach and methodology:

ArdiCarbon is a multi-criteria calculator to measure greenhouse gas (GHG) emissions from sheep meat and milk production and identify the best mitigation options, in accordance with the 2006 IPCC and the 2019 Refinement IPCC guidelines. A module is available to assess the effect of the implementation of different Best Available Techniques (BATs) at farm level to evaluate the reductions in terms of nitrogen, phosphorus, ammonia and greenhouse gases emissions from livestock. The environmental sustainability analysis is complemented by the incorporation of social and economic perspectives.

ArdiCarbon adopts a multi-criteria life cycle approach covering climate change (CC), acidification potential (AP), eutrophication potential (EP), photochemical ozone formation (POCP) and particulate matter formation (PM). ArdiCarbon also provides a whole farm nutrient and energy balance and ammonia emissions (EMEP/EEA 2019). In addition, the tool accounts for benefits such as food and protein production, carbon sequestration and biodiversity analysis. ArdiCarbon offers the option to include soil carbon sequestration in the carbon footprint of both functional units (milk and meat), and a biodiversity assessment based on the Cool Farm Biodiversity (CFA, 2016) approach which allows farmers to score points depending on the actions involved in the farm. ArdiCarbon evaluates soil carbon sequestration (C_{seq}) according to the method developed by Petersen et al. (2013) and tested by Batalla *et al*. (2015) in 12 farms in Northern Spain. In order to estimate C_{seq}, the same coefficient (9.7%) is applied to carbon derived from crop residues and carbon deposited by the herd during the grazing period.

Ardicarbon reports the sustainability results of the analyzed farms through several dashboards. Concretely, there are three level to assess the sustainability: level 1, for a simplified analysis for a non-experienced user; level 2, for a more detailed analysis including socio-economic perspective, carbon sequestration and the biodiversity analysis; level 3, the most advanced analysis for an experienced LCA users. ArdiCarbon is currently being used in the framework of the LIFE GREEN SHEEP project with the aim to develop a common approach adapted to sheep meat and milk production and to reduce the carbon footprint of sheep meat and milk production. To that end, several tools such CAP´2ER, CarbonSheep, LCAsheep and ArdiCarbon. are being compared.

The ArdiCarbon tool, which makes possible to carry out in-depth analysis in a simple form of use, has been run on a typical dairy sheep farm in Northern Spain. ArdiCarbon is a flexible tool because it allows to upload the most updated and suitable emission factors. Thus, the last Spanish zootechnical documents for the calculation of the nitrogen and phosphorus balance of feed for the dairy and meat sheep sector have been implemented (Miteco 2019), as well as the 2019 Refinement to the 2006 IPCC Guidelines and the last EMEP/EEA guidebook (2019).

The study was conducted on a typical dairy sheep farm in Northern Spain (Gipuzkoa). The herd comprised 213 lactating ewes with a grazing period of 215 days per year. During the study period, 149 lambs were sold for slaughtering (a total of 1.639 kg live weight per year). The farm covered a total of 60,2 ha of land for farming, with 37 ha of natural grassland, 18.6 ha of mountain pasture and 4.6 ha of rangeland. In the present study, milk production was 31.029 L yr^{-1}, and the Functional Unit (FU) was defined as 1 kg of Fat and Protein Corrected Milk (FPCM), corrected at 6,5% fat and 5,8% protein according to Pulina *et al*. (2005). Electricity and fuel consumption were 4.799 kWh and 4361 L, respectively. The purchase of concentrates and fodder amounted to 110 t, without mineral fertiliser application.

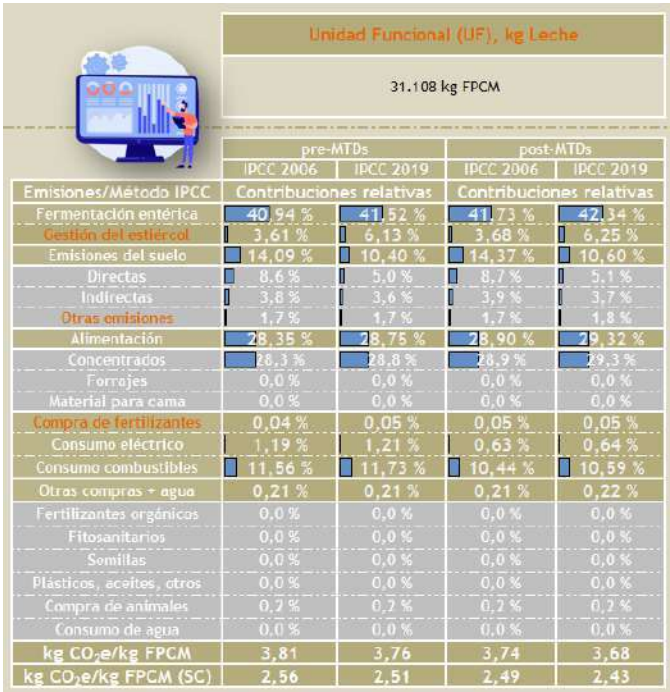
The system boundary was "from cradle to farm gate", including all "on farm" GHG emissions, as well as "off farm" emissions corresponding with the processing and the transport of all farm purchases (concentrates, forages, limestone, etc.). To consider all these off-farm emissions, a combination of emissions factors has been implemented in the ArdiCarbon tool (Ecoalim database, Guide GES´TIM+, 2020). Simulations were performed using the 2006 IPCC and the 2019 Refinement: without allocation and applying a mass allocation factor of 91 % to milk production. As no economic data is available, we performed a mass allocation procedure: it resulted in 91% to milk and 5% to meat. Finally, 100-year time horizon global warming potential (GWP) values reported by IPCC (2013) were applied.

The use of renewable energies such as solar panels and biomass (48% reduction), and the reduction of fuel consumption (15 %) where analysed as BATs to assess the reduction of carbon emission at farm level.

Results and discussion: Total emissions per kg FPCM are presented in Figure 1 with the relative contribution per pollutant sources. The results reflect that on average 40 % of the emissions come from enteric fermentation and 30 % from the bought of concentrates and fodder. N_2O emissions from soil are around 14 % or 10 % depending on the IPCC guideline selected, and mainly due to the nitrogen deposited at the pasture during grazing because there is not mineral fertilization. Electricity consumption and fuel consumption accounts for 1% and 11% respectively. Emission reduction when the BATs are implemented are depicted in the Figure 1. The values of milk CF estimated in the present study were within the range for dairy sheep production in northern Spain obtained by Batalla et al. (2015), from 2 to 5.2 kg with an average value of 3.2 kg CO_2eq per kg of FPCM. According to the same author, the contribution per sources shows that the enteric fermentation it is the biggest contributor to the total GHG emissions (39 %), followed by the purchase of concentrates. The present study highlights how the choice of IPCC methodology is not a key issue when carbon footprint is estimated in a wet region. In this regard, the 2019 Refinement IPCC decreased the CF due to the update of emission factors by a single 1,5 %.

It should be noted that there currently no consensus on how to account for carbon soil sequestration using the life cycle assessment (LCA) methodology, but when soil carbon sequestration estimate was included in life cycle assessment using the method developed by Petersen *et al*. (2013) and tested by Batalla *et al*. (2015), we observed lower values of GHG emissions per kg of FPCM. Thus, the carbon footprint values decrease 1.25 kg CO_2 eq/kg FPCM, a 33 % reduction on average. These results indicated the emission from dairy sheep farms can be considerably reduced through the carbon sequestration. Nevertheless, it needs to verify primarily on a common carbon accounting methodology although its measurement is strongly influenced by the models used in the carbon sequestration estimation (Arca *et al*., 2021)

Figure 1. The dashboard displays a summary of the greenhouse gas emissions contribution to carbon footprint from different sources, presented as percent (%) of total carbon footprint (kg CO2/kg FPCM).



	Unidad Funcional (UF), kg Leche			
	31.108 kg FPCM			
	pre-MTDs		post-MTDs	
	IPCC 2006	IPCC 2019	IPCC 2006	IPCC 2019
Emisiones/Método IPCC	Contribuciones relativas		Contribuciones relativas	
Fermentación entérica	40,94 %	41,52 %	41,73 %	42,34 %
Gestión del estiércol	3,61 %	6,13 %	3,68 %	6,25 %
Emisiones del suelo	14,09 %	10,40 %	14,37 %	10,60 %
Directas	8.6 %	5,0 %	8,7 %	5.1 %
Indirectas	3,8 %	3,6 %	3,9 %	3,7 %
Otras emisiones	1,7 %	1,7 %	1,7 %	1,8 %
Alimentación	28,35 %	28,75 %	28,90 %	29,32 %
Concentrados	28,3 %	28,8 %	28,9 %	29,3 %
Forrajes	0,0 %	0,0 %	0,0 %	0,0 %
Material para cama	0,0 %	0,0 %	0,0 %	0,0 %
Compra de fertilizantes	0,04 %	0,05 %	0,05 %	0,05 %
Consumo eléctrico	1,19 %	1,21 %	0,63 %	0,64 %
Consumo combustibles	11,56 %	11,73 %	10,44 %	10,59 %
Otras compras + agua	0,21 %	0,21 %	0,21 %	0,22 %
Fertilizantes orgánicos	0,0 %	0,0 %	0,0 %	0,0 %
Fitosanitarios	0,0 %	0,0 %	0,0 %	0,0 %
Semillas	0,0 %	0,0 %	0,0 %	0,0 %
Plásticos, aceites, otros	0,0 %	0,0 %	0,0 %	0,0 %
Compra de animales	0,2 %	0,2 %	0,2 %	0,2 %
Consumo de agua	0,0 %	0,0 %	0,0 %	0,0 %
kg CO_2e/kg FPCM	3,81	3,76	3,74	3,68
kg CO_2e/kg FPCM (SC)	2,56	2,51	2,49	2,43

Conclusions: It is concluded that ArdiCarbon is a user friendly and easy to operate tool to provide farmers, land planners, etc., with the best available methodology regarding the potential environmental impact of dairy sheep milk to perform an in-depth analysis of the carbon footprint of the dairy production in a comprehensive way, through and easy understanding of the LCA-based decision-making process.

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Expanded results of a systematic literature review:
Cradle-to-farm gate life cycle assessment of pig production

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Keywords:.
Life Cycle Assessment; Pig; Systematic review.

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Introduction:

According to current estimates, the livestock sector is responsible for 14.5% of annual anthropogenic greenhouse gas emissions, with pork production being responsible for 9% of the sector's emissions [23]. Greenhouse gas emissions from agriculture are primarily in the form of Methane (CH_4), Nitrous oxide (N_2O), and Carbon dioxide (CO_2) [24]. The impact potential of greenhouse gases are generally characterized and reported in Carbon Dioxide-equivalence (CO_2-eq). Emissions from agriculture can be calculated in varying ways depending on the source of emissions and data availability.
Organizations such as the Intergovernmental Panel for Climate Change (IPCC), the European Environment Agency (EEA) and the Food and Agricultural organization of the United Nations (FAO), provide methods for calculation of direct agricultural emissions [25–27]. The results of these calculations are commonly used as inventory data in pig production LCAs for animal housing and manure management, while results of field management calculations combined with databases are generally used as inventory data for feed production.

This paper provides supplementary results of the Gislason et al 2022 [28] literature review, which covered existing peer-reviewed cradle-to-farm gate Life Cycle Assessments (LCAs) of primary pig production with a functional unit of mass of animal live weight (kgLW). Other recent reviews have not limited their functional unit, the two most recent being published in 2021 [29], and in 2016 [30]. Furthermore, the Gislason et al 2022 literature review addressed a significant number of studies not assessed in prior reviews. As such, Gislason et al 2022 represents the most recent review of LCA studies focusing on primary pig production.

Methodology:

This study was created alongside the Gislason et al 2022 review and provides additional details on the acidification and eutrophication impact categories, which have not been presented in Gislason et al 2022. Some general trends from the Gislason et al 2022 review are also reported. The literature search was limited to the Web of Science and Scopus search databases, which resulted in a combined initial list of 1.116 papers before removal of duplicates. Relevant keywords were selected for the search strings in order to identify LCA studies focusing on primary pig production, targeting the studies' title, abstract and keywords (example of keywords: "footprint assessment" or "life cycle assessment"). A multi-step procedure was developed and implemented to systemically reduce papers considered as out of scope (further details in Gislason et al 2022).

Results:

A total of 55 studies were included in our review which were published between the years of 2005 and 2021, all of which defined their functional unit as mass of animal live weight.

A trend for an exponential increase in the number of publications was identified in the recent years, emphasizing a growing research interest in the subject. 26 contributing nations were identified, with most assessments from France (13), Denmark (8), China (6) and Spain (6). The inventory and scope differences of the compared systems were registered and grouped in five categories.

The studies that compared differences in technologies (manure management or housing system) or farming methods (vaccination or immunocastration), were 25 in total.

Comparison of different feeding methods (e.g. multiphase feeding strategies) or feed compositions, were registered in 16 of the studies.

Comparison of different nations or regions was registered in 10 of the studies.

Other types of comparisons included the farm size (5), temporal developments (3) and others/uncategorizable (8). Foreground inventories of the production system (e.g. manure management system, animal housing and building data, and energy use) were usually built up from a combination of data sources, mainly primary data (31), national data and statistics (28) and peer-reviewed literature (17). Sourcing of feed mixture data in the studies was commonly overcome by applying a combination of data sources and tools. Feed formulations were primarily sourced from peer-reviewed literature (20), primary data (18) and generated/optimized data (10).

A majority of studies did not report normalized or weighted results, with only two (2) studies presenting normalized results and three (3) reporting weighted results.

Commonly reported impacts were climate change (53), eutrophication (36), acidification (34), non-renewable energy use (24) and land use (21), although a total of 20 impact categories were identified. The objective of the 55 studies varied, although interest in feed comparison has increased in recent years. Improvement from feed changes were reported to achieve up to 35% reduction of CO_2-eq, although more commonly around 10%. Impact reduction from manure management and housing of animal varied considerably, although the inclusion of the anaerobic digestion within the system boundary was consistently associated with reduction of impacts, because of substitution of energy or natural gas from the generated biogas. Three (3) studies assessed temporal changes since the beginning of the 2000s to the 2020s, reporting CO_2-eq reductions between 32% and 36%. Four (4) studies conducted comparisons of different national production systems, where they reported that CO_2-eq increased between 16,5% and 84,4% when comparing the worst and best performing national production systems.

Climate change was the most commonly reported impact category, covered by 53 of the studies. The reported climate change impact ranged from -0,02 to 23,6 kg CO_2-eq per kgLW without land use changes (LUC). Feed was, on average, the largest source to the greenhouse gas emissions (23 – 92%). Often, the individual reviewed studies did not report the impacts from the housing (e.g. enteric fermentation) and manure management separately. Therefore, we decided to combine the impacts of these two groups as well. Housing and manure management was the second largest contributor (8-80%). Further details on information from this section can be found in Gislason et al 2022.

Acidification was reported in 34 studies in either an aggregated category (acidification potential), or as terrestrial acidification, and in one study as both acidification potential and accumulated exceedance. The mid-point indicator unit was either mass of sulfur dioxide equivalents (g SO_2-eq), or moles of hydrogen ion equivalents (molH^+-eq). 28 studies reported acidification potential, which ranged from 14,7 to 91,67 g SO_2-eq or 43 to 130 mmolH^+-eq per kgLW, depending on the unit used in the specific studies. Terrestrial acidification was reported in five of the studies, and ranged from 17 to 186 g SO_2-eq.

Eutrophication was reported in 36 studies, either as freshwater, marine, terrestrial or as an aggregated category (eutrophication potential). In particular, eutrophication potential was the most commonly occurring indicator, reported in 27 studies, mainly as mass of phosphate equivalents (g PO_4^{-3}-eq), ranging from 3,7 to 203 g PO_4^{-3}-eq per kgLW. Mass of nitrate equivalents (g NO_3^--eq) and phosphorus equivalents (g P-eq) were both reported a single time which ranged from 269 and 381 g NO_3^--eq, and between 8,58 and 8,85 g P-eq per kgLW.

Figure 1 displays acidification and eutrophication potential of studies which reported both impact categories, in g SO_2-eq for acidification and g PO_4^{-3}-eq per for eutrophication.

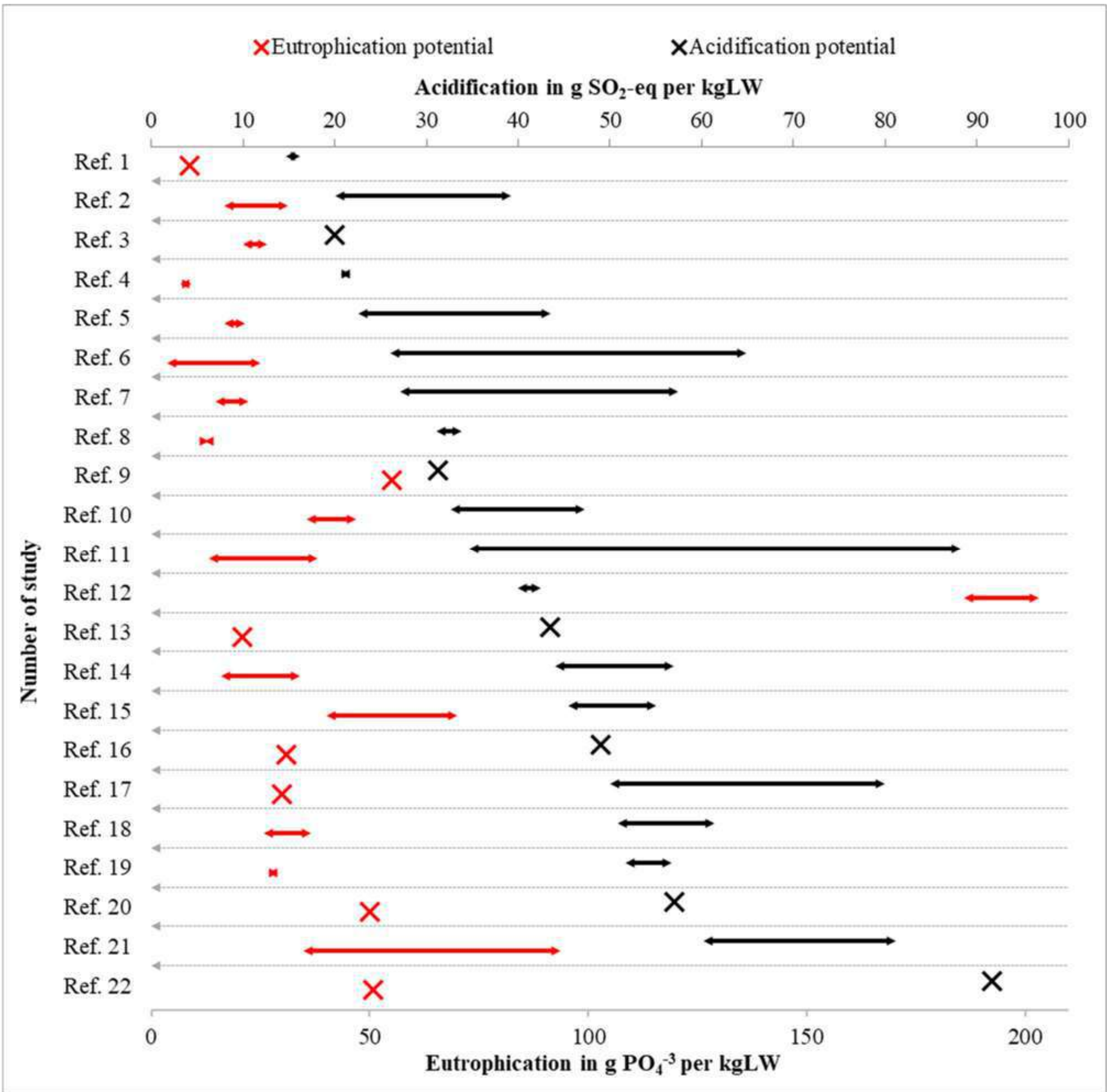

Figure 1: *Single values and ranges of acidification and eutrophication impacts reported in 22 studies. Acidification is reported in g SO2eq per kgLW, while eutrophication is reported in g PO4-3 per kgLW.*

The contribution of both acidification and eutrophication was reported in 10 of the studies.
The major contributors to acidification and eutrophication were feed, and housing and manure management, with only ~1% attributed to other activities. As such, impacts other than feed can be assumed to be attributed to manure management and housing of animals. Manure management and animal housing were on average the largest contributors to acidification, followed by feed. Contributions to eutrophication were on average distributed 50:50 between feed, and manure management and housing. Impact contributions from feed, presented relative to all other processes can be viewed in *Figure 2* for Acidification and *Figure 3* for Eutrophication.

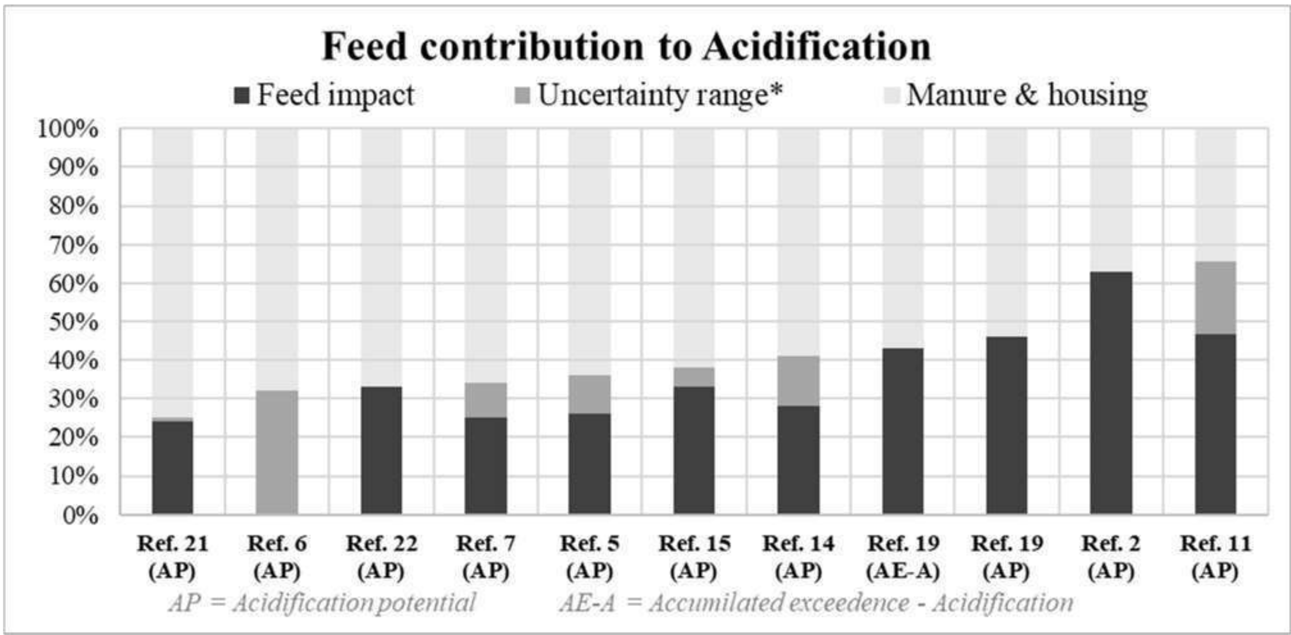

Figure 2: Acidification impact contribution of feed relative to manure management and housing.
**Uncertainty range suggests multiple comparisons were made, which presented different contributions depending on the system being assessed. This means that uncertainty range contribution is added to either feed or manure management & housing depending on the compared system.*

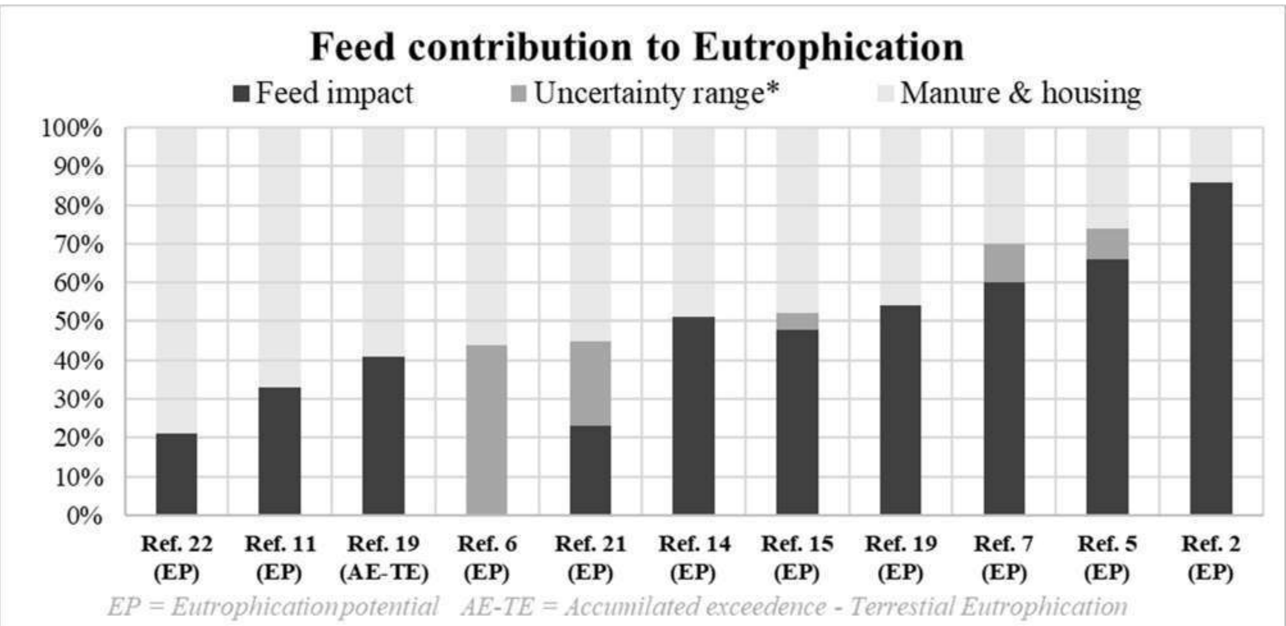

Figure 3: Eutrophication impact contribution of feed relative to manure management and housing.
**Uncertainty range suggests multiple comparisons were made, which presented different contributions depending on the system being assessed. This means that uncertainty range contribution is added to either feed or manure management & housing depending on the compared system.*

Discussion and conclusion:

Significant increase in publication of pig LCAs has been observed in recent years, with an increased interest in feed improvements and temporal assessments. Impact contributions to climate change, acidification and eutrophication varied significantly across different studies, as well as the LCA methodological choices (e.g. system boundary, dealing with multifunctionality aspects and impact assessment methods). A central issue which limits comparability within the LCAs of pig production mainly relate to differences in methodology selection (multifunctionality, inventory, LCIA method) and definition of system boundaries. As such, there is a general need for harmonizing the LCA methodology used to assess primary pig production. Data representativeness was generally high, with primary data or governmental statistics commonly being used. The large contributions from feed, housing of animals and manure management to climate change, acidification, and eutrophication, suggests these should be focus areas of research investigating impact reduction.

Takeaway points:

- The reported impacts for Climate Change, Acidification and Eutrophication varied considerably across the studies
- Climate Change impact was reported between -0,02 and 23,6 kgCO_2-eq per kg live weight of animal
- Acidification impact was reported between 14,7 and 186 gSO_2-eq per kg live weight of animal
- Eutrophication impact was reported between 3,7 and 203 gPO_4^{-3}-eq per kg live weight of animal
- Feed production and manure management and animal housing are the main contributors to climate change, acidification, and eutrophication.
- Feed improvements were reported to decrease CO_2-eq by up to 35%
- The suggested areas for impact reduction relate to the feed production, the housing of animals and the manure management systems

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Meat sheep production simplified LCA: comparison and evaluation of different tools to estimate carbon footprint across Europe

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Keywords: *Milk, meat, enteric methane, Green Sheep LIFE*

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Rationale and Objective LIFE Green Sheep (LIFE19 CCM/FR/001245) has been targeting a common Carbon Footprint (CF) assessment methodology at European level. In order to simplify the life cycle inventory, tools to estimate CF in dairy and meat sheep farm have already been developed in European countries such as France (CAP'2ER), Spain (ArdiCarbon) and Italy (Carbonsheep), and Ireland (Sheep LCA). Nevertheless, they are specifically adapted to local production systems in terms of collected inputs and algorithms used in the impact assessment. Consistent data inventories and shared plans of mitigation practices for sheep production farming at European level requires aligned approaches and tools. The objective of this study was to compare 3 tools, already available in Europe, to estimate the carbon footprint of meat sheep farming systems.

Approach and Methodology The 3 tools compared were: CAP'2ER (C2E; "Institute de l'Elevage, France); ArdiCarbon (AC; Neiker, Spain); and CarbonSheep (CS; Univ. of Sassari, Italy). For the comparison in this study all tools were set at level 1 of model detail for simplified estimates, which were based on aggregate inputs from farms. Collected inputs and impact assessments performed by models were based on customized algorithms and emission coefficients of IPCC (2019) for animal and farm emissions to increase the tool flexibility at country level. Algorithms and equations to estimate animal requirements, food intake and excretion, coefficients adopted to calculate emissions from each hotspot or emission source and allocation formulas were not modified before run the models for the estimate comparison. The LCA boundaries of the analysis were from cradle to farm gate. The comparison was performed collecting data from 3 sheep farms in France, Spain and Ireland (n=9). Basic inputs required to run each tool (79 for C2E, 80 for AC and 49 for CS) were collected from the 9 farms copying the life cycle inventory of flock consistency, crops and pasture areas, fertilizers, purchased feed, fuel and electricity, and farm outputs of meat sold from suckling lambs, fattening lambs and culled animals. The model runs enabled assessment of aggregated emissions from the following categories: total CF allocated to milk, enteric methane, manure management, crops and fertilizers, feed purchased, electricity, fuel and other purchased inputs. Emissions were expressed per kg of CO_2eq./kg of carcass weight. A total of 27 estimates were obtained running each tool for the 9 farms. The model evaluation was performed from differences between C2E vs. AC, C2E vs. CS and AC vs. CS analysed as mean bias and the root mean square error of prediction (RMSPE) (Tedeschi, 2006).

Results and Discussions Collected inputs proceeded from a broad range of farm conditions. The farms involved in the study had 756±682 ewes, 103±57 ha, and produced 17.2±19.1 tons of meat per year. Most of the farms had semi-extensive farming systems with animals having access to pasture. The estimated of CF of the 3 models were presented in Figure 1 and resulted equal to: 33.3, 30.9, and 31.2 kg of meat for C2E, AC and CS, respectively. All emissions were allocated to meat. All tools reported high incidence of animal emissions (enteric methane and manure) on the total CF in line with the literature evidences. The differences in CF expressed as mean bias were 2.4 for C2E-AC, 2.1 for C2E-CS and -0.3 for AC-CS. It indicates that values predicted by the tools were very similar among them even if CS and AC showed more similar estimations compared to other combinations. The mean bias alone does not indicate the comparability of tools estimate since it compensates negative and positive differences. When differences were evaluated as RMSPE, it was higher than the mean bias, and equal to 6.55, 4.62 and 3.52 for C2E-AC, C2E-CS and AC-CS, respectively. When the RMSPE of each hotspot were expressed as percentage of the CF it was possible to observe that differences were due to enteric methane (51%, 96% and 113%) and to manure management (73, 49% and 103% of RMSPE for C2E-AC, C2E-CS and AC-CS respectively). It indicates that CF values were similar but compensating effects among differences emission hotspots were observed.Detected differences mainly relies on emission coefficients adopted for crops and feed purchased and on allocation formulas.

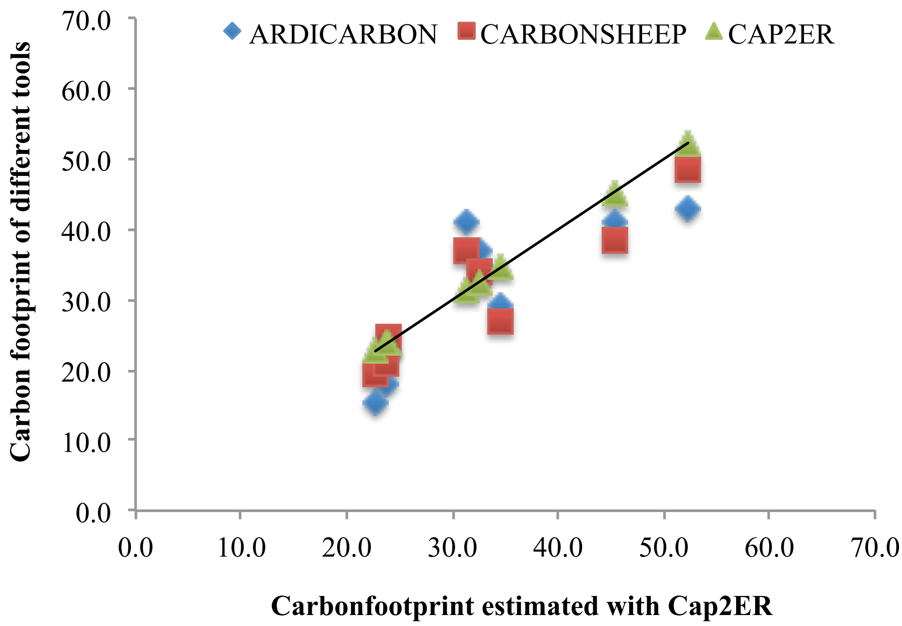

Figure 1. Estimated of Carbon Footprint performed with CAP'2ER (C2E), ArdiCarbon (AC) and CarbonSheep (CS), for meat sheep farms across Europe. CAP'2ER is represented as the equivalence line.

Conclusions The comparison indicated that the three tools performed similar estimates but algorithms and emission coefficients adopted need a careful alignment before run common estimates at European level to detect differences among hotspots.

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Comparative life cycle assessment of shrimp production chains involving different types of farming systems

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Keywords: *Aquaculture intensification; Recirculating aquaculture systems; Earthen pond farming; Mangrove-shrimp aquaculture; Alternative shrimp feed; Sustainable Production and Consumption*

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Keywords: *Recirculating aquaculture systems; Alternative diets; Semi-intensive pond production, Mangrove-shrimp farming; Sustainable aquaculture*

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Rationale

Global farmed shrimp production increased rapidly from less than 9000 tons in 1970 to 4 million tons in 2018 with an annual increase of 3−5% (FAO, 2019). The US is one of the main markets for shrimp, with 90% of the product imported from overseas (USDA 2019). To meet the growing demand for shrimp in the US, rapid expansion and intensification of shrimp aquaculture could, however, exert severe damages to the environment. Therefore, there is a strong need to support the US shrimp production with more sustainable farming practices.

Objectives

The goal of this life cycle assessment (LCA) study was to evaluate the environmental performance of shrimp (*Litopenaeus vannamei*) production from cradle to Chicago market through (*i*) identifying the environmental hotspots of a local indoor shrimp farm, (*ii*) examining the environmental consequences of six alternative shrimp feeds, and (*iii*) comparing the environmental profiles of three shrimp production chains operated with different farming systems and production intensity.

Approach and methodology

The shrimp production chains start from feed ingredient production through feed processing to shrimp farming, with shrimp larvae reared separately. After harvest, shrimp are then processed and packaged before transportation to market. The local (Midwestern) intensive production chain (IPC) is based on a shrimp farm in Indiana that applies a recirculating system involving wastewater treatment and requires high feed and energy inputs. The interregional semi-intensive production chain (SPC) is based on an earthen pond system located in Alabama that uses moderate feed and energy inputs and manure fertilization with limited wastewater treatment. The oversea extensive production (EPC) is based on a mangrove-shrimp symbiosis system in Vietnam that does not need feed and energy inputs. The foreground data in the life cycle inventory were collected from on-site operation (IPC) and literature (SPC and EPC), and the background data, including fertilizers, energy carriers, transportation modes, packaging materials, *etc.* were adapted from the Ecoinvent database v3.0. The midpoint impacts, including global warming potential (GWP), freshwater eutrophication potential (FEP), and terrestrial acidification potential (TAP) were calculated using the ReCiPe 2016 Midpoint (E) v1.02 method.

Results and discussion

Feed production and farming stages were the major contributors to the terrestrial acidification potential (TAP; 55% and 25%, respectively) and global warming potential (GWP; 43% and 28%, respectively), which agreed with the study of Badiola et al. (2018) on the environmental performance of RAS. The freshwater eutrophication potential (FEP) was dominated by shrimp farming (89%). Polyculture of aquatic animal with plant, i.e., aquaponics, has been demonstrated to be an economical solution to reducing the energy demand per unit of food produced by intensive farming (Chen et al., 2020). The P emission through wastewater discharge from farm was the main contributor to the FEP, however, separating the solid part of the wastewater (i.e., sludge) for disposal as landfill was found to markedly decrease the total FEP by five times (data not presented). For the impacts associated with processing and packaging, paper box was responsible for 67% of the TAP, 86% of the FEP, and 67% of the GWP, and ice accounted for 29%, 13%, and 26%, respectively.

In Feed C and six alternative feed mix, soybean meal was found to be a major ingredient affecting and causing the most variation of the environmental performance of shrimp feed in this study (e.g., contributing the highest FEP to Feed C). While soybean meal was reasonably assumed to be produced using domestically (US) supplied soybean, the environmental impact of soybean largely varies with its country of origin. For example, the GWP of 1 kg soybean meal from Argentina (6.7 kg CO_2 eq.) and Brazil (5.3 kg CO_2 eq.) are considerably higher than that from the US (0.5 kg CO_2 eq.), mainly because the large variation in the LULUC CO_2 emission associated with soybean production in different countries.

The environmental performance of two shrimp production chains based on semi-closed (Alabama) and open (Cà Mau) farms were analyzed and compared with the IPC. Different from the IPC, the farming stage accounted for the highest TAP (51%) and GWP (58%) and FEP (65%), mainly due to the electricity use. Feed production had the second largest contribution to the TAP (28%) and GWP (16%) because Feed S contains a significant proportion of poultry by-product meal. Farming also contributed markedly to the total FEP because of the high N and P emissions generated by the fertilizers (urea and triple superphosphate) used. The EPC had a very different environmental profile (Figure 1) from the IPC and SPC because of the mangrove-shrimp farm involved, on which feeding and cultivating conditions are fully controlled by natural environment and no additional material or energy inputs are required for its operation, resulting in no associated impacts generated. However, mangrove deforestation for farming resulted in a high GWP (12,600 kg CO_2 eq.). The farming stage also showed a negative FEP (−13 kg P eq.), indicating that in addition to the uptake of eutrophicating substances (N and P) in the effluent from shrimp cultivation, the planted mangroves played a nutrient-removing role for the surrounding water bodies. The EPC had the lowest TAP and FEP, which were 46−68% and 203−311% lower than those of the IPC and SPC, respectively. Jonell and Henriksson (2015) reported similar results that extensive mangrove farming generated lower TAP and FEP than intensive and semi-intensive farming. However, the EPC was least sustainable in terms of GWP, indicating that the CO_2 emission due to LULUC in mangrove area outweighed the benefits of no resource input in the farming stage (Figure 2). The SPC produced the highest TAP and FEP, mainly due to the intensive electricity use on farm which was 9.6 times higher than that for the IPC.

Conclusion

This cradle to the market LCA study can provide shrimp farmers with a deep and clear understanding of the environmental impacts associated with their production, as well as the groundwork to design or adapt alternative farming practices with reduced environmental cost. Shrimp feed contributed the largest total TAP and GWP of IPC. The impacts of shrimp feed can be reduced by choosing feed formulae with lower FCR and avoiding poultry by-product and fish meals as the protein sources. However, replacing fish meal by plant proteins did not necessarily improve the environmental performance of the IPC. The GWP of the IPC highly depended on the origin of soybean meal included in the feed. Among the three production chains, the IPC had the highest FEP, which was dominated by P emission through wastewater discharge from shrimp farm. The intensive uses of electricity and fertilizers for pond cultivation made the SPC produce the highest TAP. Moreover, disposing sludge from recirculating systems as landfill and using renewable energy (*e.g.*, wind energy in the Midwestern US) are potential ways to improve the environmental performance of closed shrimp farming. While the 2030 Agenda for Sustainable Development states that aquaculture should contribute towards food security and nutrition goals (FAO, 2016), the results of this study can also guide consumers in the Midwestern US to make more informed decisions on the purchase of imported or domestically produced shrimp at markets.

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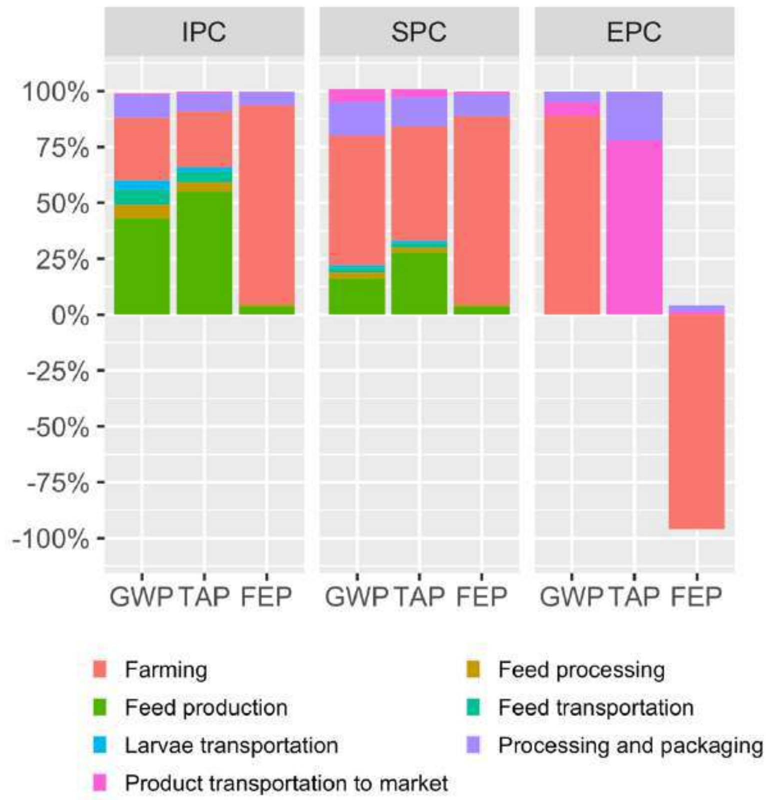

Figure 1. Environmental profiles of intensive, semi-intensive and extensive shrimp production chains.

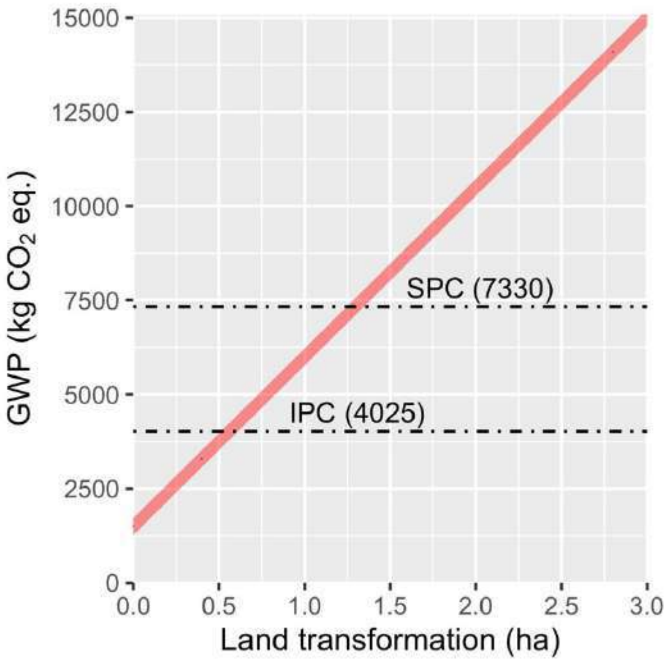

Figure 2. Effect of area of land transformation on total GWP of extensive production chain.

Life cycle assessment in aquaculture certification: Greenhouse gas screening tools for the Aquaculture Stewardship Council

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Keywords: *Aquaculture, Certification, Greenhouse gases, Screening assessment, Calculation software*

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Global aquaculture surpassed wild capture fisheries as a source of seafood for human consumption in 2013 and produced 88 million tonnes of fish and shellfish in 2020 (FAO, 2022). The industry continues to grow rapidly, providing highly traded products from a wide variety of species, production systems, locales, environments, and regulatory settings. High and growing demand for aquaculture products combined with local, regional, and global concerns of environmental impact have necessitated comprehensive certification schemes to hold producers and supply chain actors accountable against standards of practice, both environmental and social.

Greenhouse gas (GHG) emissions from food production systems are of increasing concern to multiple stakeholders, accounting for between a quarter and a third of global emissions (Crippa *et al.*, 2021; Vermeulen *et al.*, 2012). There is growing demand to incorporate aspects of climate responsible production into certification schemes of food products to reflect this recognized role. While aquaculture has been estimated to contribute just 0.5 per cent of global GHG emissions (MacLeod *et al.*, 2020), emissions intensity of aquaculture varies substantially by species and production system and high emissions can be driven by feed production, land use change underpinning feeds or farm siting, electricity demands of land-based systems, and air freight of products to market (Gephart *et al.*, 2021). Encouraging low GHG aquaculture production can contribute to climate change mitigation by providing lower-impact animal protein products compared with many land-based livestock systems, particularly ruminant animal production like beef (Hoegh-Guldberg *et al.*, 2019; Poore and Nemecek, 2018).

The Aquaculture Stewardship Council (ASC) is an ISEAL-certified provider of standards for aquaculture farms currently spanning eleven species groups (Table 1). ASC-certified farms currently produce annual volumes of approximately 2.4 million tonnes, roughly two thirds of which is certified under the Salmon Standard. Four of ASC's farm standards include requirements to calculate and report the GHG emissions associated with feeds and farm operations. Most standards also have requirements for farms to measure and record their on-farm use of energy, and the Bivalves Standard also requires management of equipment for energy efficiency. In addition to direct measurement requirements, life cycle GHG emissions from certified farms are also influenced by restrictions on conversion of mangroves and wetlands and requirements for responsible soy sourcing to avoid deforestation upstream in feed supply chains.

Numerous challenges have been identified in the historical implementation of GHG requirements in ASC's standards. These include limited expertise and capacity of smaller producers to undertake emissions calculations, uneven reporting of data, metadata, and methods, inconsistent methods applied across different suppliers, and conflicting approaches between established standards and guidelines. Standards have historically provided relatively limited and non-prescriptive guidance on a range of considerations such as scope of process inclusion, source of impact factors and other data, on-farm electricity generation, power purchase agreements, and treatment of carbon offsets.

Table 1. *Global aquaculture production, ASC-certified production, number of published LCA case studies, and estimated greenhouse gas emissions from feeds and farms associated with ASC-certified production. Values are grouped according to the eleven current ASC species standards.*

Species group	% of global production[a]	ASC production (tonnes)[b]	% of ASC production	# published LCA cases[c]	Estimated emissions (t CO_2-eq)[d]
Species for which ASC standards already require greenhouse gas calculation					
Salmon	3.4	1,570,000	65.6	27	4,140,000
Seabass, seabream, and meagre	0.9	51,000	2.1	6	314,000
Tropical marine finfish[e]	0.9	3,000	0.1	0	17,000
Flatfish	0.2	-	-	3	-
Species for which greenhouse gas calculation is a planned new requirement in the ASC Farm Standard					
Shrimp	7.7	337,000	14.1	13	1,921,000
Bivalves	18.6	166,000	6.9	10	34,000
Tilapia	7.3	113,000	4.7	11	462,000
Pangasius	0.6	104,000	4.4	8	415,000
Freshwater trout	1.1	43,000	1.8	22	126,000
Seriola and cobia	0.3	4,000	0.2	0	22,000
Abalone	0.2	2,000	0.1	0	500
Total	41.2	2,396,000	100.0	100	7,450,000

[a]Calculated from global aquaculture production volumes from FAO (2020) excluding plants.
[b]Estimated annual certified production volumes for 2021 as available at https://www.asc-aqua.org/what-we-do/how-we-make-a-difference/data-sharing/ascs-impacts-dashboard/
[c]Academic journal articles published up to 2020, data collected at www.foodlca.org, used for global analysis by Gephart et al. (2021).
[d]Calculated based on annual global ASC-certified production volumes and median global warming potential values for species groups from Gephart *et al.* (2021), adjusted to live weight equivalents.
[e]Includes groupers, snappers, pompano, barramundi, and croakers.

ASC's new Farm Standard, currently in development, will address some of these challenges and aim for more methodologically robust and consistent GHG data reporting as part of the audit process. To assist in this process, ASC is developing online screening calculators to connect producers with data and calculations needed to estimate life cycle emissions in accordance with the requirements of the new standard.

The objectives of these tools include: facilitating GHG calculations in line with the requirements of the Farm Standard; improving methodological consistency, transparency, and quality of data reported to ASC; identifying species, production systems, and practices associated with higher and lower rates of emissions; comparing certified products to other seafood products and land-based animal protein sources; informing further development of ASC's standards and climate-related initiatives; helping smaller producers by reducing costs and avoiding expertise insufficiencies associated with GHG modeling; and producing aggregated datasets that can be used for research purposes.

The initial scope of these calculators is based on availability of data and consistently recognized drivers of emissions in aquaculture systems, and includes inputs to production, processing, and transport of feed ingredients to feed mills, energy inputs to feed milling, transport of feeds to farm sites, and farm use of fuels, electricity, and select additional inputs (*e.g.,* liquid oxygen for recirculating aquaculture systems) (Figure 1). Future extensions will incorporate more system-specific sources of farm emissions, processing, and distribution of products. Functional units for the initial scopes are one tonne of feed leaving the mill and one tonne of live weight production at farm-gate. Data sources used to underpin emissions estimates include the Global Feed LCA Institute (GFLI; Blonk, 2020), which provides impact assessment results for a wide variety of primarily crop-derived feedstuffs and allows for multiple co-product allocation methods, in addition to Ecoinvent (Wernet *et al.*, 2016) and the UK government (DEFRA, 2022).

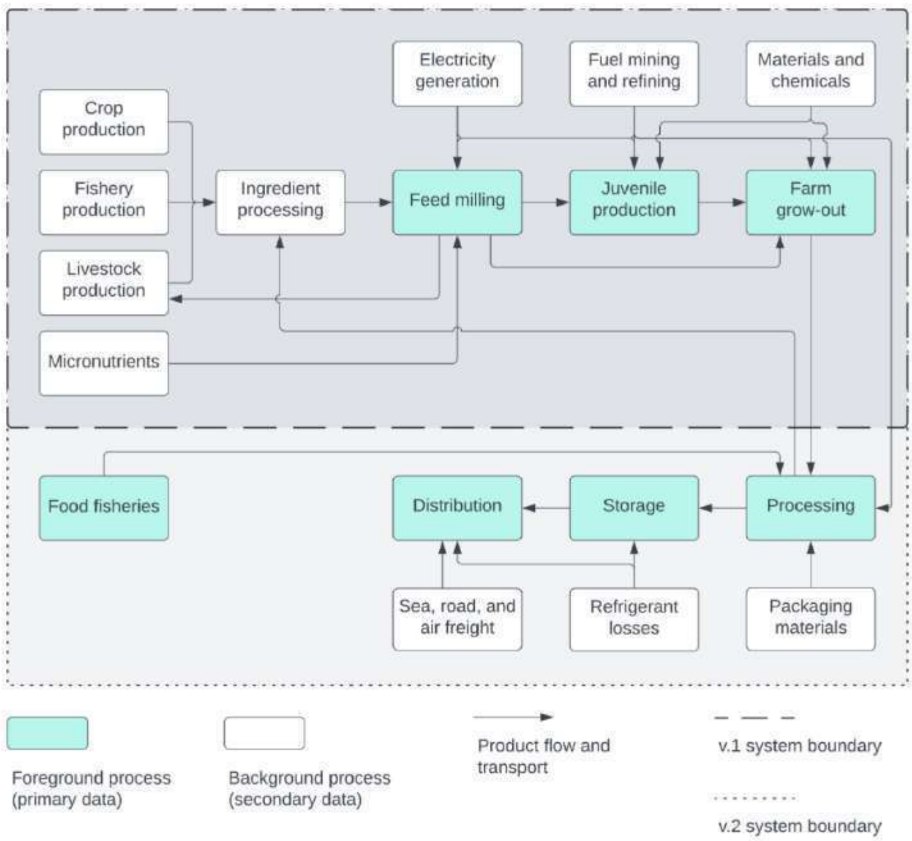

Figure 1. *Scope of life cycle stage inclusion for ASC's aquaculture GHG estimation tools, including current scope and planned future expansion (v.2) which extends past requirements of ASC standards.*

Results in the screening calculators are generated using both mass and economic allocation for the purpose of demonstrating methodological sensitivity, increasing transparency, and allowing for easier comparison with published studies and values generated following competing methodological standards. Results will be provided at a resolution appropriate for verification and submission to ASC as part of standard requirements, and include emissions by source (*e.g.* crop-derived feed inputs, feed processing, on-farm electricity, *etc.*), scope of emissions, and category (fossil, biogenic, or land use change) (Figure 2).

The calculators will help to identify key opportunities to reduce the impact of producers and products, demonstrate the effectiveness of supply chain changes or decisions in reducing impact (*e.g.,* avoidance of land use change in feeds or at farm site), see sensitivity of aquaculture model results to allocation choice, and model scenarios based on varying inputs and their sources. Allowing for a streamlined and simplified approach to calculating GHG emissions focusing on the most recognized drivers of impact will facilitate a more methodologically consistent and broadly relevant life cycle screening assessment across a wide number of species, production systems, and locales.

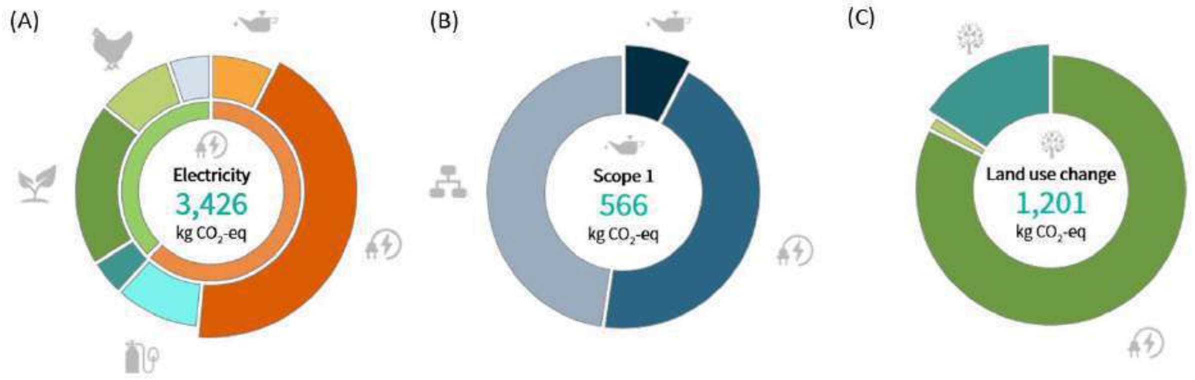

Figure 2. *Example characterization results from a prototype GHG screening calculator for a hypothetical salmon recirculating system using mass allocation and the national electricity grid of the Netherlands. Results are communicated according to general input type or emissions source (A), scope of emissions (B), and categorization as either fossil, biogenic, or land use change emissions (C).*

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Life cycle assessment of an Italian offshore aquaculture plant

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Introduction & Aim

Aquaculture is more and more considered as a major contributor to the growing demand in worldwide seafood production.
Sustainability has become a key question for aquaculture systems. Aquaculture imply environmental concerns related to the consumption of feed, the emission of nutrients and organic compounds into the water and, sometimes, the consumption of pesticides and antibiotics for pest and disease control (le Feon et al., 2021).
Even if originally developed for the evaluation of industrial processes, Life Cycle Assessment (LCA) approach has been more and more applied also to the agro-food sector. LCA allows the quantification of the potential environmental impacts related to a production process and/or a product. Consequently, it is the first step for an effective identification of mitigation solutions.
The study is part of the Project SIMTAP (Self-sufficient Integrated Multi-Trophic AquaPonic systems for improving food production sustainability and brackish water use and recycling). SIMTAP aims at designing and developing small-scale self-sufficient integrated multitrophic aquaponic systems where besides fish also other seafood and vegetables are produced by reducing the consumption of fishmeal and fish oil. In the context of the project, a comparison with commercial scale aquaculture plants is foresees to evaluate if the designed systems can be sustainable. In this study, the LCA approach was applied to quantify the environmental performances of an Italian aquaculture plant producing seabass and seabream.

Material and methods

In this study, Life Cycle Assessment was applied to assess the environmental impact related to seabream and seabass farming in an offshore aquaculture plant in Central Italy. The fishes are reared in sea cages, the rearing cycle reared from 14 to 18 months depending on the fish weight at the harvest and growing seasons. Juveniles of 3 grams are seeded while the fish harvesting size ranges from 400 to 600 grams. Feeds with different composition and pellet size are used during the fattening cycle depending on fish size.
The selected functional unit was 1 ton of fish at the fish farm gate. The system boundary (Figure 1) includes the following aspects:

- Manufacturing, maintenance, and disposal of the sea cages,
- Production of feed and other production factors consumed (e.g., fuel, electricity, juveniles),
- Rearing operations such as feeding, pest and disease control, management of predators (tuna, birds)
- All the emissions related to the process (e.g., nutrients emissions due to the metabolism of the fish during the entire production cycle, diesel related emissions).

Slaughtering of the fishes, packaging and distribution of the product were excluded from the system boundary.

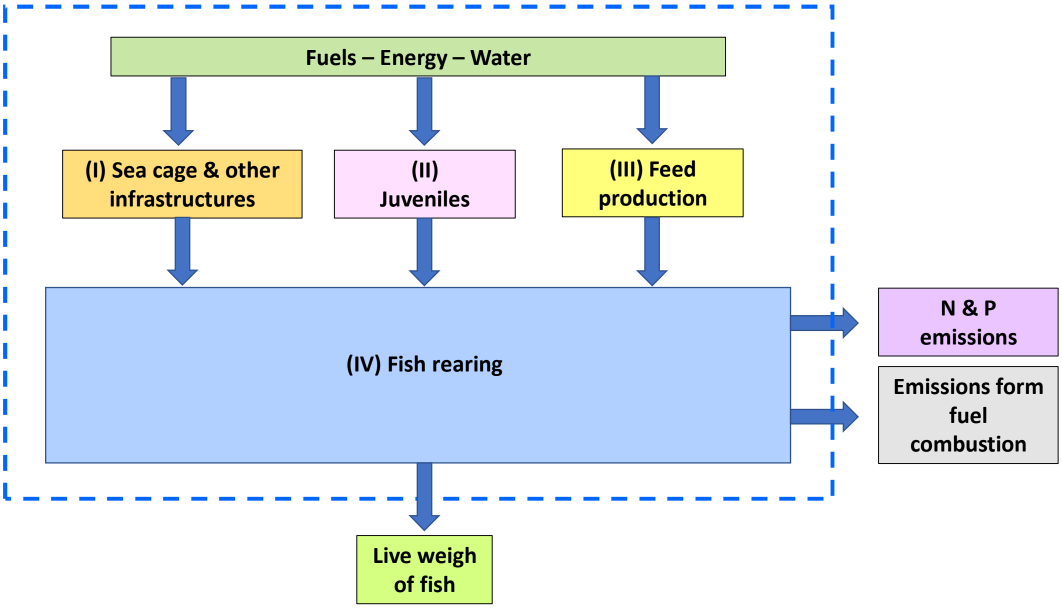

Figure 1 – System boundary

The inventory data was collected in commercial aquaculture plants in Central Italy. Primary data refers to the feed composition and consumption, direct energy and fuels use, material and lifespan of the sea cages as well as feed conversion rate and mortality. Secondary data was used with regard to the emissions of N and P compounds from fish (Cho et al., 1991), fry production (Garcia Garcia et al., 2019) and energy consumption for feed production (Garcia Garcia et al., 2019; Abdou et al., 2017). Background data about cages and other capital goods as well as about the component of the feed were retrieved from databases (Ecoinvent® and Agrifootprint).
The inventory data vas characterized using the ReCiPe 2016 Midpoint (H) V1.06 / World (2010) H and 15 impact categories (Global warming; Stratospheric ozone depletion; Ozone formation, Human health; Fine particulate matter formation; Ozone formation, Terrestrial ecosystems; Terrestrial acidification; Freshwater eutrophication; Marine eutrophication; Terrestrial ecotoxicity; Freshwater ecotoxicity; Marine ecotoxicity; Human carcinogenic toxicity; Human non-carcinogenic toxicity; Mineral resource scarcity; Fossil resource scarcity.

Results

Table 1 reports the absolute results for the two species and the relative variation (Δ) between the two species. Respect to seabass, seabream shows lower impact for all the evaluated impact categories mainly due to low mortality and a better feed conversion rate.
For European seabass (*Dicentrarchus labrax*), Gilthead seabream (*Sparus aurata*), the environmental results related to the environmental issues, as well as for most of the other considered impact categories, showed that aquafeed is the main environmental hotspots (Figure 2.) For the Climate Change impact category, aquafeed impact range from 55 to 70% of the total, while for acidification and eutrophication impact categories, the contribution of feed is second only to that of the emissions of N and P compounds. The analysis highlighted a strong relation between aquafeed conversion rate, amount of N and P emitted and, consequently, the impact on acidification and eutrophication.
The achieved results concerning contribution analysis are in agreement with previous studies

(Konstantinidis et al., 2020). For sea bass farmed in the Mediterranean region, Abdou et al. (2017) identified the main contributors to environmental impacts of marine fish farming in relation to rearing practices, Abdou et al. (2018) studied the influence of rearing practices and the contributions of production phases, Beltran et al. (2018) compared production systems. However, comparisons between farming processes in sea bass cage farming between different countries was less investigated (Jerbi et al., 2012; Abdou et al., 2018).

Table 1 – Environmental impacts for 1 kg of seabass and seabream (Δ = impact variation between seabream and seabass)

Impact category	Unit	Seabass	Seabream	Δ
Global warming (CC)	kg CO_2 eq	3416	2967	-13%
Stratospheric ozone depletion (OD)	kg CFC11 eq	0.016	0.013	-18%
Ozone formation, Human health (OF-hh)	kg NOx eq	16.063	14.129	-12%
Fine particulate matter formation (PM)	kg PM2.5 eq	6.943	6.076	-12%
Ozone formation, Terrestrial ecosystems (OF-te)	kg NOx eq	16.287	14.328	-12%
Terrestrial acidification (TE)	kg SO2 eq	25.913	22.314	-14%
Freshwater eutrophication (FE)	kg P eq	1.205	1.038	-14%
Marine eutrophication (ME)	kg N eq	113.27	91.43	-19%
Terrestrial ecotoxicity (TEx)	kg 1,4-DCB	9801	8348	-15%
Freshwater ecotoxicity (FEx)	kg 1,4-DCB	139.49	118.52	-15%
Marine ecotoxicity (MEx)	kg 1,4-DCB	131.19	113.36	-14%
Human carcinogenic toxicity (HT-c)	kg 1,4-DCB	309.63	294.66	-5%
Human non-carcinogenic toxicity (HT-noc)	kg 1,4-DCB	4249	3551	-16%
Mineral resource scarcity (MRS)	kg Cu eq	13.013	12.017	-8%
Fossil resource scarcity (FRS)	kg oil eq	1117	972	-13%

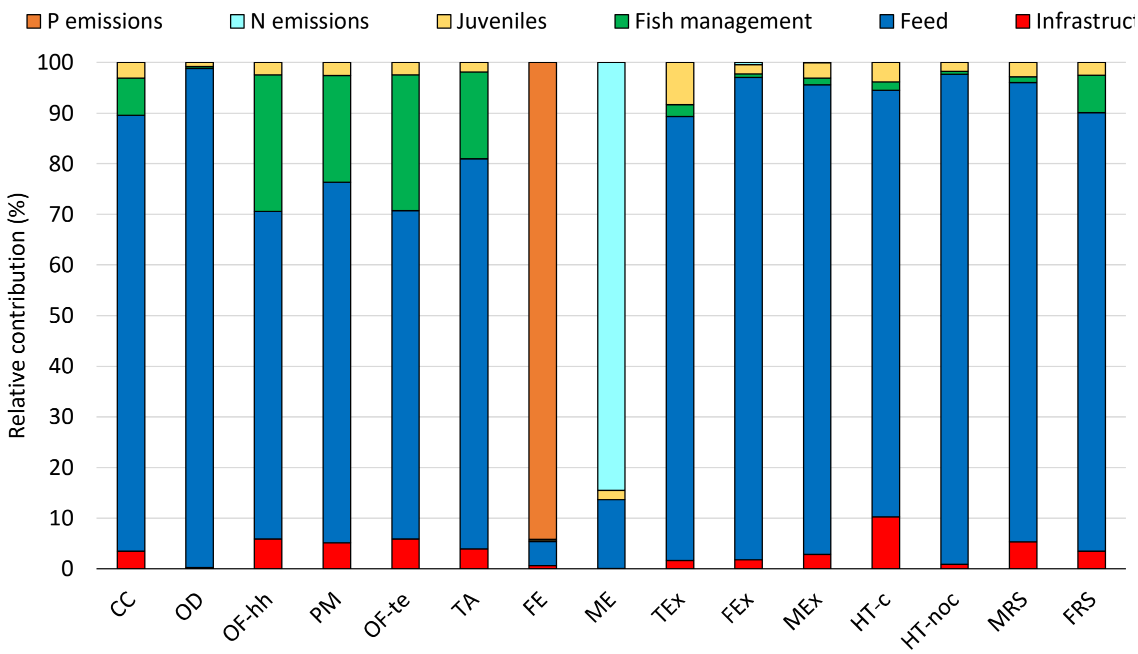

Figure 2 – Contribution analysis for seabream

Conclusions

Feeding is the main responsible of the environmental impact of seabream and seabass while the other consumed production factors play a less relevant role.

In a contest where the consumption of fossil carburant must be dramatically reduced, studying new sustainable fish diets is nowadays urgent. Following the example of the SIMTAP systems developed during the project SIMTAP, such new diets should be characterized by limited transportation impact (use of locally produced raw material and diets consumption) and maximizing the use renewable energy and protein sources (e.g., solar power and microalgae). Finally, besides the environmental performances also the economic and social ones should be evaluated for a more comprehensive assessment of the process sustainability.

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ECO-FORMULATION OF FISH FEEDS: A PROMISING EFFICIENT SOLUTION TO LIMIT AQUACULTURE IMPACTS ON THE ENVIRONNEMENT

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Context:

Aquaculture has been the main source of fish for human consumption since 2015. In 2018, it provided 53% of consumed fish, a percentage that is expected to increase over the long term as part of the solution to provide sufficient food and protein to more than nine billion people by 2050. Nevertheless, this expansion is not free of environmental impacts (Bohnes et al., 2019). Thus, a major challenge for aquaculture is to find new practices to make its development more environmentally friendly. One solution to limit these impacts is to use feed as a lever because it contributes the most to the impacts of fish production (Boissy et al., 2011). Aquaculture is also criticised for its heavy dependence on limited resources due to its massive use of fishmeal and fish oil. Multiobjective (MO) formulation, which aims for a compromise between lower cost and lower environmental impacts, appears to be a promising solution to reduce the environmental footprint of aquaculture production (Garcia-Launay et al., 2018). However, carnivorous fish, such as salmonids, are considered to be very sensitive to the composition of their diet, as illustrated by the negative impact of replacing fishmeal and fish oil with plants on growth (Lazzarotto et al., 2018). The objectives of this study were to design an eco-friendly trout feed (ECO-diet) using MO formulation and to compare its zootechnical and environmental performances to those of a commercial feed (C-diet) containing 16% fishmeal and 6.5% fish oil.

Material and methods:

Two isoprotein, isolipid and isoenergetic diets were formulated: a control diet (C-diet) and an ECO-diet, formulated using a multiobjective function adapted from Garcia-Launay et al. (2018) to minimize both the environmental footprint (climate change, non-renewable energy demand, acidification, NPPU, land occupation, eutrophication, water dependence, phosphorus demand), and price of feed. The digestibility of the diet was measured and a 12 weeks-growth trial was conducted (3 tanks per diet) on juvenile rainbow trout (initial body weight of 61 g ±1.4 g) to assess the consequences of these diets on growth performance, body composition and nutrient utilization. The experimental results were used in a LCA approach to estimate the environmental impacts of the diet and of 1 kg of body-weight gain at rearing facility scale. Emissions and impacts were calculated using SimaPro® software v8.3.0.0, with the attributional databases ecoinvent® v3 and AGRIBALYSE® including the ECOALIM dataset (Wilfart et al., 2016) for background data. Environmental impacts categories were those described by Wilfart et al. (2016) associated to NPPU and water dependence from Boissy et al. 2011 which are specific to aquaculture systems. Statistical analyses were performed using R software (v4.01). Results were expressed as mean ± 1 standard deviation. The normality of the residuals and homogeneity of the variances were checked using a Shapiro-Wilk test and Bartlett test, respectively. Then, data were tested by one-factor analysis of variance (ANOVA) to measure effects of diets on growth-performance and body-composition

parameters, and environmental impacts per kg of body weight gain. A Kruskal-Wallis test was applied to non-normal data. When a significant difference was observed, Tukey's range test was applied to compare least-square means. For all statistical analyses, the significance level was set at 0.05.
A mixed linear regression model with the tank as the random effect was used to determine effects of the diet, duration of the experiment, and their interaction on trout growth using the lmer function of the lme4 package of R.

Results and discussion:

MO formulation changed the composition of the diet greatly, which has decreased environmental impacts of the feed. It increased the number of ingredients used (from 16 to 23) but reduced the use of fishmeal and fish oil by half. MO formulation also led to the elimination of soy products, faba bean, and gluten meal in favor of processed animal co-products that have high protein contents and low climate change impact. Rapeseed oil also disappeared from the ECO-diet due to its major contribution to land use, eutrophication, and acidification and, to a lower extent, climate change (Figure 1). Unlike other studies, in which MO formulation was applied to pig and poultry feeds (Meda et al., 2021), the ECO-diet was less expensive than the commercial-type C-diet (-8%). Indeed, the C-diet was formulated as closely as possible according to current commercial practices, which consider both least cost and pre-set percentages of fishmeal and fish oil. This approach increased costs. The still high content of fishmeal and fish oil in the C-diet thus explains why the C-diet cost more than the ECO-diet, which was formulated without constraints on these two raw ingredients.
The ECO-diet had high digestibility, which differed little from that of the C-diet. Mean fish body weight after 12 weeks of growth did not differ significantly from that obtained with the C-diet, but analysis of fish growth curves (Figure 2) indicated that the ECO-diet could lead to lower growth in the long term. Based on these growth curves, fish fed the C-diet would require 5 more days of rearing to reach the size of a human meal portion (250 g), while those fed the ECO-diet would require 20 more days. The decrease in growth performance in the long term is probably mainly related to the decrease in feed intake. The lower protein and fat digestibilities of the ECO-diet could have also contributed to the trend of lower growth but to lower extent compared to feed intake because nutrients digestibility could be considered as high in both diets. In any case, this decrease cannot be associated with a decrease in feed efficiency, because the feed conversion ratio did not differ between the two diets.

Overall, using MO formulation to decrease environmental impacts of feed made it possible to significantly decrease the environmental footprint of the fish farming system studied per kg of body weight gain (Figure 3). The decrease in impacts was lower at the farm level than that at the feed level, especially for EU and, to a lesser extent, NRE and CC. In contrast, the feed and farm levels had similar decreases for NPPU, WD, LO, AC, and PD. This is not in agreement with what has been observed in pig and poultry where the formulation has been applied (de Quelen et al., 2021; Meda et al., 2021). The farm level included emissions due to biological processes of fish as well as emissions from the operation of the farm facility. NPPU and PD depended only on the feed, which explains why their decrease was the same for both levels. In the experimental system used, the fish were reared in raceways in which water was taken from a river, continually flowed through the system, and then returned to the river. Because the water could thus be reused, it was not included in water use in life cycle inventory, as recommended by Boissy et al. (2011). Consequently, the decrease in WD at the farm level was the same as that at the feed level. Finally, the experiment was performed in 60 L tanks, which contributed less to LO than the areas used to produce the crops that provided feed ingredients.

Conclusion:

MO formulation is a useful tool to reduce the environmental footprint of aquaculture production without compromising animal performances or necessarily increasing production cost. Nevertheless, some points deserve further investigation. For example, because growth performance could decrease over the long term, the rearing period should be extended to validate the performance of these diets in portion-size trout or to evaluate them when producing large trout intended for smoked fillets, which requires longer rearing periods.

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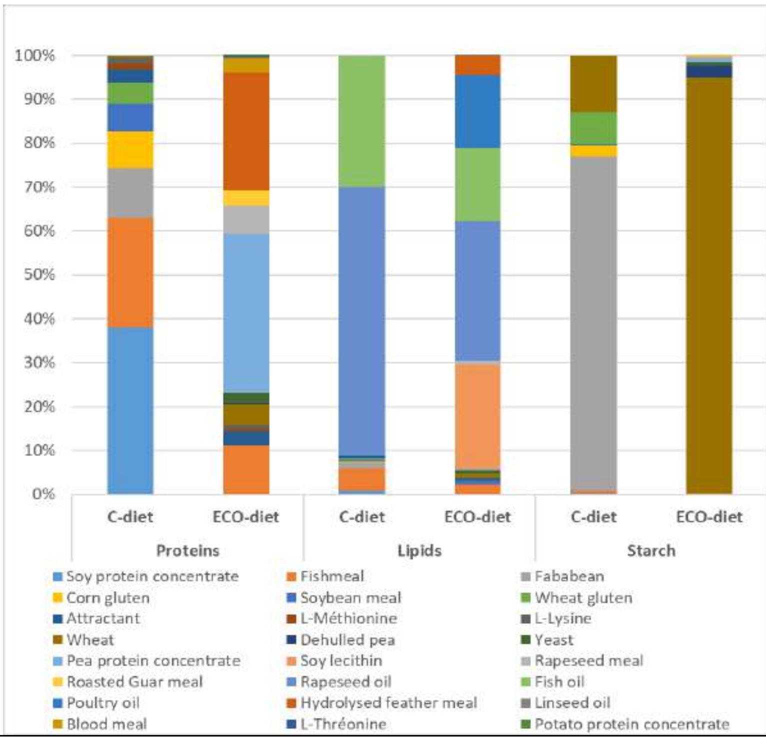

Figure 1: Feed ingredients contribution to (a) feed protein, (b) lipid, and (c) starch contents for the C-diet (left) and ECO-diet (right).

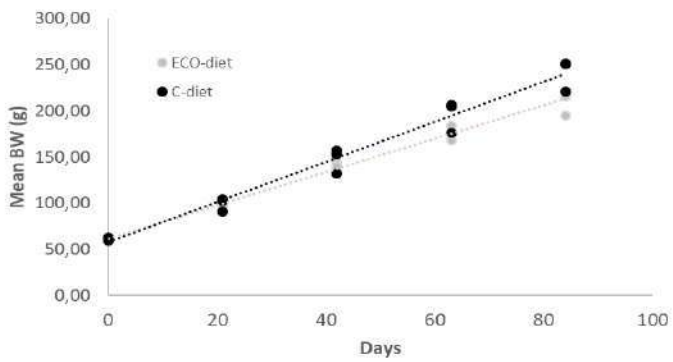

Figure 2. Mean body weight of fish fed the C-diet and ECO-diet during the 84-day experiment.

C-diet	ECO-diet
$y = 2.1634x + 58.173$	$y = 1.9095x + 61.531$
$R^2 = 0.97$	$R^2 = 0.98$

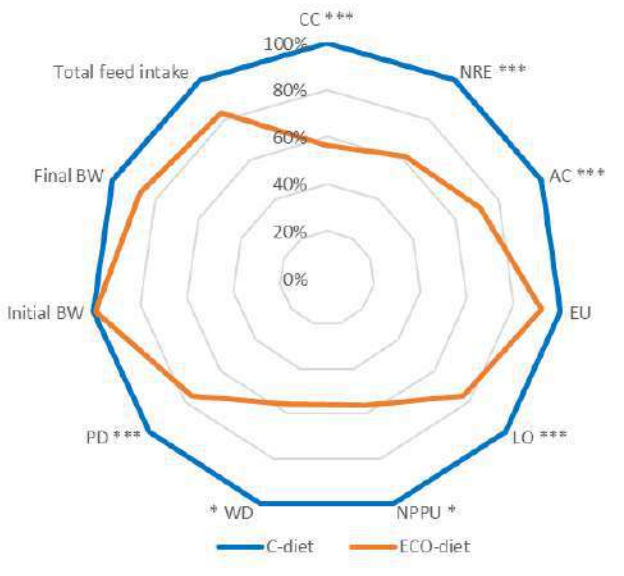

Figure 3: Relative environmental impacts at the experimental facility gate and total feed intake, final body weight (BW), and initial BW of the C-diet and ECO-diet treatments. Results are represented as a percentage of the largest impact in each category. CC = climate change; NRE = non-renewable and fossil energy demand; AC = acidification; EU = eutrophication; LO = land occupation; NPPU = net primary production use; WD = water dependence; PD = phosphorus demand

Towards a sustainable aquaculture in the Mediterranean Sea: case study of farmed seabass

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Keywords: *Product Environmental Footprint, sustainability, Aquaculture, improvement, ecological parameters*

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Rationale and objectives

Aquaculture is playing, and will continue to play, a significant role in boosting global fish production and in meeting rising demand for fishery products.
Carvalho & Guillen (2021) state that fish accounts 20% of the animal protein consumed by humans globally. Due to the relevant contribution of fish to the global food provision, the aquaculture sector has been subject to a production increase of 527% from 1990 to 2018 (FAO,2020). Moreover, this sector is projected to be the prime source of seafood by 2030, as demand grows from the global middle class and wild capture fisheries approach their maximum take. In the Mediterranean Sea aquaculture is a particularly fast-growing sector, expanding approximately 5 % annually (Massa *et al.,* 2017).

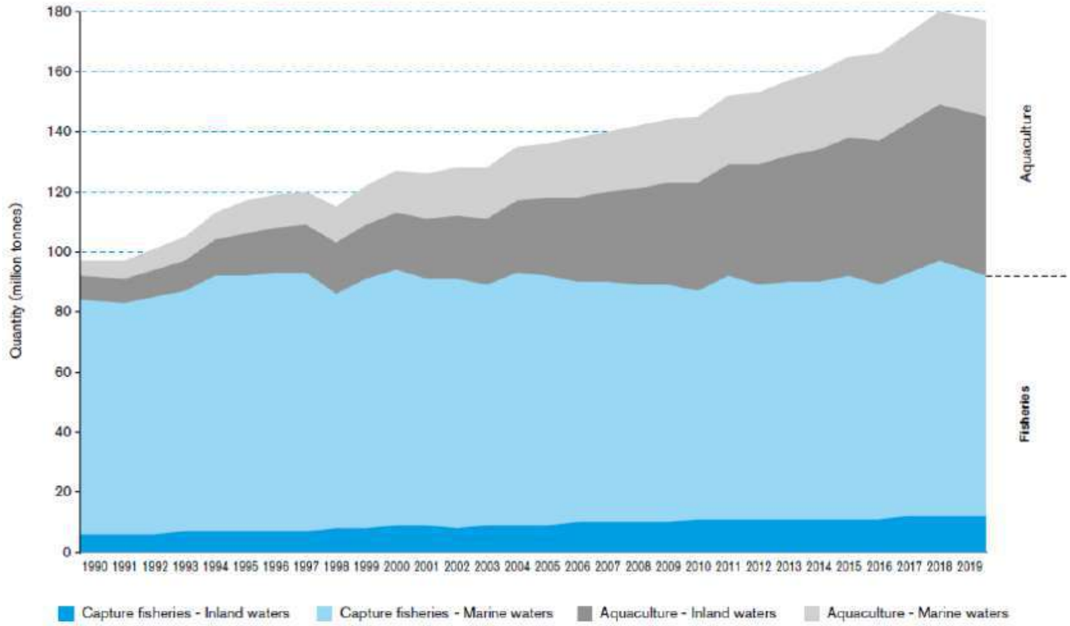

Figure 1: World capture fisheries and aquaculture production by environment 1990 – 2019 (FAO, 2020).

A further shift towards alternative diets, such as pescatarian diet, has the potential to reduce global agricultural greenhouse gas emissions and help prevent diet-related diseases (Tilman & Clark, 2014). Thus, aquaculture could contribute to the overall objective of filling the gap between EU consumption and production of seafood.

In 2019 there was a production of over 2 million fish tones in the Mediterranean from which 43% was aquaculture production. Among the main cultivated species in the Mediterranean aquaculture sector are: Gilthead seabream (Sparus aurata) and European seabass (Dicentrarchus labrax), with 28% and 25% of the total production in weight (34% and 30% in value) respectively (FAO, 2020).
However, in order to stay within planetary boundaries and considering the huge growth expected for aquaculture products, specific actions to be more sustainable and to mitigate the environmental impacts linked to this sector are required. Product Environmental Footprint (PEF) (COM2013/179/EU) appears as a suitable tool for assessing the sustainability of aquaculture products, although this methodology has also some gaps that needs to be faced, such as the inclusion of specific impact categories for assessing marine impacts.
Within this framework in 2018 the AQUAPEF project (LIFE17 ENV/ES/000193) was launched with the aim to validate the usefulness of the PEF methodology to assess the potential environmental benefits arisen from the implementation of different environmental improvement strategies in Mediterranean Marine Fish Farms, more specifically in Eastern Mediterranean (Aegean sea).
The Mediterranean Sea is subjected to the relevant European legislation that commits the European Union member states to secure a good qualitative and quantitative status for all their water bodies, following the Water Framework Directive (WDF; 200/60/ec). WFD constitutes of a set of descriptors that is used to cover the ecological, physical, chemical and anthropogenic components that define an ecosystem's status. Based on the WFD, various ecological parameters were measured in situ and the most relevant ones were suggested to complement LCA results to make the PEF more integrative and reliable.

Approach and methodology

A stepwise approach was used to measure the benefits in the Environmental Footprint resulted from the implementation of environmental strategies in two different aquaculture farming sites located in Eastern Mediterranean, specifically in the Aegean Sea, one site in the north and one in the south. Both sites are located near the coastline, the production system is Open Net-pen and the specie selected for the study was seabass.
First, the potential environmental impact related to the production of farmed seabass was measured according to the First Open Public Consultation version of Marine Fish Product Environmental Footprint Category Rules (Marine Fish PEFCR) (draft v1), released July 30th 2021. The fish value chain considered by Marine Fish PEFCR consist of the full Life Cycle (Cradle-to-Grave) of 1 kg of consumed packed edible unprocessed marine fish. The phases considered are feed production, juvenile production, fish growing stage (sea-cages), preparation (degutting, filleting and packaging), distribution, retailer storage, consumer and End of Life (EoL). For this study, the last three stages were not included because they are not within the aquaculture companies scope and the data used are default values.
Second, main causes and origins of the seabass environmental footprint were identified and the specific environmental improvements strategies were selected and implemented in two different aquaculture companies.
Third, the environmental impact calculation was performed considering the implemented improvements in seabass cages of Marine Fish Farms studied.
Finally, a comparison of the results for environmental impacts without and with environmental improvements was carried out to assess the success of those implementations in the seabass farms studied and consequently, in the Aquaculture of Mediterranean Sea.
Apart from that, since traditional LCA approaches do not consider ecological parameters in their estimation of marine environmental footprint, ecological parameters were proposed to obtain a better understanding of the Aquaculture sector environmental behavior. For this purpose, the ecological quality of the water and sediment adjacent to fish farms was assessed by sample analysis

(inorganic, organic and dissolved nutrients concentrations, dissolved oxygen concentration, CO_2 concentration, Chlorophyll-a and physiological parameters for the water column, nutrients and metals sinking capacity, redox potential and physiological parameters for sediments). Afterwards, the most suitable parameter to complement LCA results was identified between marine researchers and LCA practitioners.

Results and discussion

The environmental impacts of 1 kg of packed fresh edible Mediterranean aquaculture seabass, head on, delivered to retailer (cradle to gate) are presented in the Figure 2. For the assessment, primary data has been collected from two aquaculture companies located in the Aegean Sea (Eastern Mediterranean) and their suppliers for the operational years 2018 and 2021. And, Ecoinvent 3.5. and commercial databases are used for background datasets.

Main consumables and infrastructure for operation of every step of the life cycle are included. However, the vaccines which could have a negative impact in the environment are out of the scope due to lack of databases. The International reference Life Cycle Data system (ILCD) methodology, released by the Joint Research Centre in 2012, and the software SimaPro 9. are used for the study.

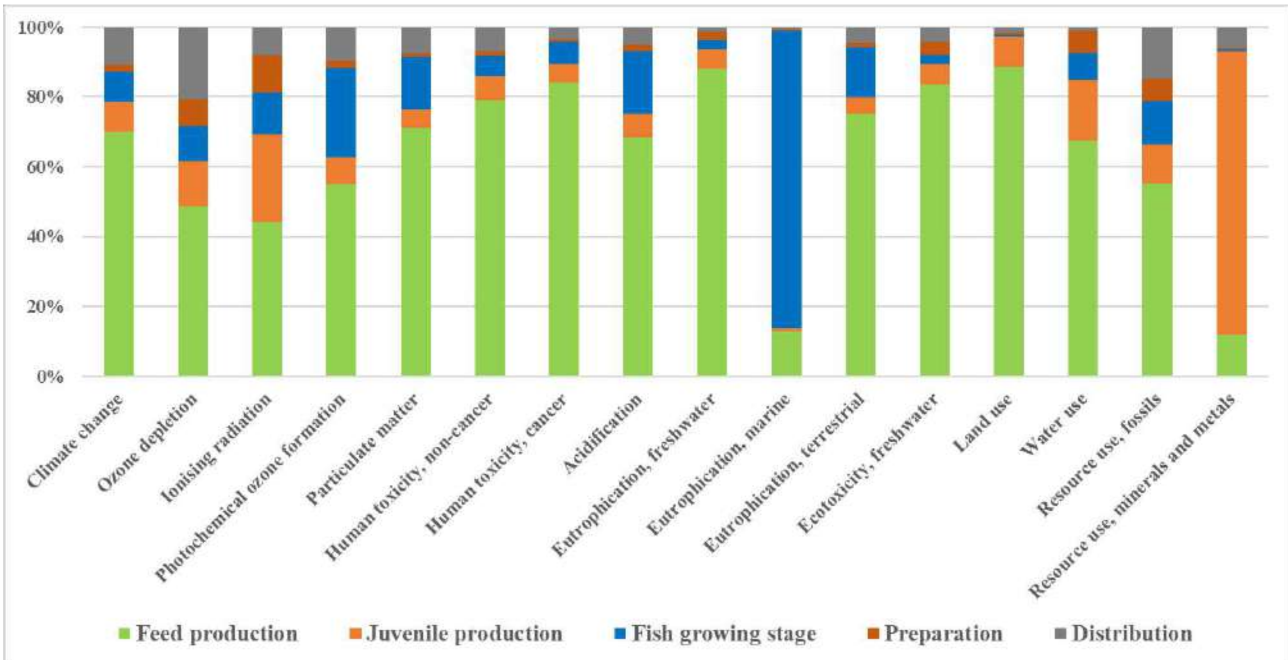

Figure 2. Potential environmental impacts related to the production of 1kg packed fresh edible seabass farmed in the Eastern Mediterranean Sea, head on and deliver to retailer.

Feed production phase is by far the major responsible for most of the impacts assessed for seabass farmed products in the Mediterranean Sea. However, fish growing stage must be highlighted due to marine eutrophication impacts, as non-ingested feed and the actual metabolism of fish (i.e. feed feces or egestion) lead to large organic and inorganic loading to the environment.

There are several environmental improvement strategies identified for impact reduction in the Mediterranean fish farms focused on these hot-spots: i) incorporate environmentally friendly feed ingredients in diets, ii) optimization of feed demand with automatic feeders, iii) optimization of feed demand with online-connected cameras and sensors and iv) reduction of fish load in cages, among others.

In this study, in order to further explore the impact of feeds in fish farming areas, improvements in

management practices are implemented in two Mediterranean aquaculture companies. Thus, the comparison of the environmental footprint of seabass production before and after the implementation of improvements in sea farms has shown positive results.
On the one hand, the implementation of automatic feeders for the optimization of feed demand shows a reduction of 9 % in Climate Change (kg CO_2 eq.), 2 % in Marine Eutrophication (kg N eq.) and 16 % in Land Use (Pt), among others. And on the other hand, the installation of online-connected cameras and sensors in sea-cages to optimize feed demand allows a decrease of 18 % in Climate Change (kg CO_2 eq.), 7 % in Marine Eutrophication (kg N eq.) and 40 % in Land Use (Pt), among others. Therefore, minimizing feed wastage and organic loads with these strategies could obtain a reduction in the environmental impact.
Apart from that, the environmental assessment of the marine ecosystem quality around two fish farms located in Eastearn Mediterranean sea, with and without improvements, has indicated potential water column parameters that could complement LCA approaches.
The differences between the Improvement, non-improvement and control stations were assessed by Analysis of Variance (ANOVA) and indicated that between them, the parameters that differed were the inorganic nutrient concentrations (particularly ammonium , MS=3.8,F=4.8, $P < 0.001$), the concentrations of dissolved phosphorus (df=5, MS=0.03, F= 2.8, $P < 0.05$) and dissolved nitrogen (df=5, MS=3.0, F= 2.3, $P < 0.05$) and the concentration of particulate organic phosphorus (df=5, MS=1.0,F=5, $P < 0.001$). Values of these abiotic parameters were higher in stations close to fish farms comparing to the control sites (post hoc Tukey test, $P < 0.05$) at both locations in the Mediterranean.
Consequently, these parametes seem to be the most relevant to evaluate fish farm ecological impact. These are included in formulas for the calculation of ecological eutrophication indicators such as trophic index TRIX (Vollemweider et al. 1998) and eutrophication index EI (Primpas et al. 2010) that show the highest potential of incorporation in the current LCA approaches. These parameters can complement the PEF calculation in relation to the impact in marine eutrophication and the contribution of implemented ecological improvements to its reduction.

Conclusions

- Focusing efforts on implementing improvements related to fish feeding is effective to reduce the environmental footprint of marine aquaculture production.
- Complementing the LCA study with water column ecological parameters could widen the scope of the environmental sustainability assessed.

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Potentials and challenges of novel feed inputs in salmonid diets

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Introduction

Global salmonid aquaculture has in the last 30 years grown from 0.5 to 3.8 million tons of annual production while capture fisheries which have been stable at around 1 million tons during the same period (FAO 2021). With the emergence of new producing countries and technological advances, the production volume is expected to continue to rise. As carnivorous species, salmonids have a high dietary requirement for proteins and high-quality amino acids. Further, to fully utilize the growth potential,most salmonids require an energy dense diet, with a high content of omega-3 fatty acids. The feed for salmonids is to a large extent composed of high-quality protein ingredients and lipids, traditionally of marine origin (Aas et al. 2019). The world's largest fishery, the Peruvian Anchovy (*Engraulis ringens*) is mainly destined to feed for terrestrial and aquatic animals. In 2017, ca. 507 thousand tonnes liveweight Peruvian anchovy were used in Atlantic salmon feed in Norway and Chile, the two leading producers of farmed salmon globally (Winther et al. 2020, FAO 2021, Pelletier et al. 2009). As most marine resources are already exploited at, or above, their maximum capacity, efforts have been made to decouple aquaculture from these limited resources and marine inputs have primarily been replaced by soy protein concentrate (Aas et al. 2019).

Recently, much attention has been given novel feed ingredients, as these are thought to enable the salmonid industry to grow more sustainably, while meeting the requirements of both fish and consumer. Insect larvae, algae, sea squirts, blue mussels and the utilization of side streams to produce microbial feed ingredients all represent interesting feed alternatives for salmonids.
Since blue mussels, sea squirts and seaweed can be farmed without any external inputs of feed or fertilizers, their cultivation has a relatively small environmental impact on a mass basis, and the nutritional composition could offer an interesting alternative source of protein. Their extractive nature can even help mitigate local eutrophication. However, there are knowledge gaps when it comes to their function as animal feeds.
Insects, or specifically insect larvae, are another source of protein which has gained increasing attention for their potential use in fish feeds. Insect rearing requires comparatively little space and energy, the requirements for feed quality are low (allowing the use of food industry side streams like e.g. potato peel) and the feed is very efficiently converted to biomass due to being ectothermic animals (Thevenot et al. 2018).

Here we present results from two different feed trials, a grow out trial of rainbow trout (*Onchorhyncus mykiss*) and a juvenile feed trial on Atlantic salmon (*Salmo salar*).

Methods

The rainbow trout feed trial investigated the possibility of growing trout based on a feed which utilizes predominately Swedish ingredients with the aim of producing 5 tonnes of fish to be sold to the consumer market. The fish were fed a diet consisting of proteins from insect larvae (mealworm (*Tenebrio molitor*) and black soldier fly (*Hermetia illucens*)) reared on food waste, marine inputs from Atlantic herring (*Clupea harengus*) and European sprat (*Sprattus sprattus*) fished in the Baltic Sea and meals from the sea squirt (*Ciona intestinalis*) and blue mussel (*Mytilus edulis*) farmed in the Nordic countries (Table 1). Compared with industry standard feed, the novel rainbow trout feed included a much lower share of plant-based ingredients (novel: 37% vs. conventional: 70%), and similar inclusion of marine feed inputs (32% vs 29%) (Winther et al., 2020). Insect meals were used to bridge the gap left by low plant-based ingredient inclusion. This experimental feed formulation was tested to compare its performance in fish health and growth to commercially available feeds in a grow out experiment.

Table 1: Experimental feed formulation for the rainbow trout feed trial

Ingredient	*% share*
Mealworm meal	16.5
Black soldier fly meal	12.5
Ciona meal	4.0
Blue mussel meal	3.0
Fish meal	12.0
Fish oil	12.9
Vegetable meals	23.2
Vegetable oil	13.5
Micro ingredients	2.5

In the second trial, the aim was to investigate the effects on fish health and growth of including low trophic species into Atlantic salmon feed as a replacement of fish meals. Locally farmed kelp (*Saccharina latissima*) and blue mussels were chosen as feed ingredients due to their low impact and potential for upscaled production.
In total seven different feed formulation were tested. Four feeds containing fermented kelp at a 1 – 4% inclusion rate and three feeds containing silage made from blue mussels (3, 7 and 11% inclusion) as a fishmeal replacement (Table 2). These novel feed formulations were tested in a feed trial with juvenile, smolt stage, Atlantic salmon and compared to a control group of fish reared on an industry standard feed.

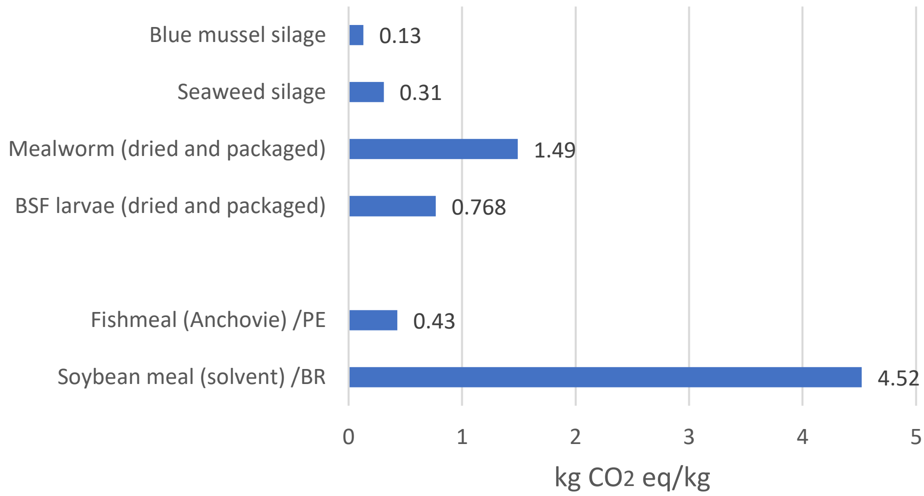
Table 2: Experimental feed formulation for the Atlantic salmon feed trial. Inclusion rates are stated in percent.

	Seaweed Feeds				*Blue Mussel Feeds*		
	SW1	SW2	SW3	SW4	BM3	BM7	BM11
Fish oil	10.3	10.4	10.5	10.6	10.3	10.4	10.4
Fishmeal	23.3	21.6	19.9	18.2	20.3	15.4	10.5
Vegetable meals	48.5	49.2	49.9	50.6	49.8	51.3	51.9
Vegetable oil	13.6	13.4	13.2	12.9	13.3	12.4	11.6
Micro ingredients	3.3	3.4	3.5	3.6	3.3	3.5	3.6
Seaweed silage	1.0	2.0	3.0	4.0	-	-	-
Blue mussel silage	-	-	-	-	3.0	7.0	11.0

All feed ingredients and complete feeds were modelled using mass allocation and characterization factors from the IPCC 2013 report (100 year time horizon) were used to calculate the global warming potential (GWP).

Results

We present LCA results for these two trials using new data for key novel feed ingredients (black soldier fly larvae, mealworms, mussel silage and fermented seaweed) complemented with existing data for conventional ingredients. We present differences in the environmental performance of the tested feeds themselves as well as of salmonids fed with the novel feeds compared to those fed with conventional feed.



Graph 1: Global warming potential of novel feed ingredients (top) compared to two common feed ingredients (bottom)

For both the seaweed silage and blue mussel silage the cultivation phase accounts for most of the carbon dioxide emissions. Producing ensilage does not require extensive processing steps after harvest making it a very efficient method.
Insect larvae have their global warming potential hotspots in the feed and electricity use during rearing and drying. Part of the feed used in farming the larvae analyzed in this study was industry side streams in the form of unsold vegetables (black soldier fly larvae) and potato peel (mealworms).

Applying this to the whole feed perspective we found that both feeds with novel feed ingredients had lower GWP than the commercial feed used in the studies. The Swedish experimental feed had 3.5 times lower carbon emissions per kg than the commercial rainbow trout feed. This large difference can be partly accredited to the use of bloodmeal in the control feed which had a large contribution using mass allocation. Both Atlantic salmon feeds showed decreasing carbon emissions with rising inclusion of blue mussel or seaweed silage. Compared to the control formulation the seaweed feed had <1% to 2.5% lower global warming potential and the blue mussel feed showed a decrease between 1% and 11.8%.

For rainbow trout, the experimental diet was efficient and led to equal outcomes in terms of growth and health compared to the conventional feed. Further testing of sensory quality of filets showed no difference between the two groups.
The feeding trial with salmon has shown that the replacement of fishmeal with seaweed- or mussel silage has a negative impact on the fish's growth performance. Thus, compared to conventional feeds, potential environmental benefits of the novel ingredients would need to be put in relation to the increased amount of feed needed to reach grow out stage as well as the prolonged use of farm infrastructure.

Discussion

The Swedish feed trial showed that farming rainbow trout based on local, Scandinavian ingredients is possible without negative impact on fish growth and nutrient profile. Additional benefits of the circular approach are the increased utilization of waste streams and the potential for closing nutrient loops in a geographic area. The Baltic Sea is facing increasing eutrophication problems so cycling nutrients within the same watershed can lower fish farming's contribution to this problem.

The novel Atlantic salmon feeds had a lower carbon footprint than the control feed formulations, but this advantage was offset by the lower growth rate of the fish. The seaweed was included at very low inclusion rates and still affected growth rates negatively. Despite containing high levels of many micro-nutrients, there are question marks regarding their bioavailability in seaweed. The same is true for undesirable substances like heavy metals in kelp, where low bioavailability would be desirable. Blue mussels have a nutrient composition that is more similar to fish meal which favors it in use as a replacement for fishmeal and/or other protein ingredients in feeds for salmonids. When replacing fishmeal or fish oil for alternative ingredients often a higher inclusion of so-called micro-ingredients (e.g. vitamins, minerals, amino acids, pigments) is needed. These are used to fulfill the nutrient requirements of the fish, supply health promoting substances and achieve adequate palatability of the feed to maintain a high feed intake. Some micro-ingredients carry a high environmental burden and can contribute to canceling out the environmental benefits of novel feed ingredients. A limitation of this study was only testing the juvenile life stage. To obtain results more applicable to realistic farming scenarios future research should focus on expending the trial period to cover the salmons whole lifecycle from hatching to slaughter.

A potential issue of all novel feed ingredients assessed in the two studies is scalability of production to reach the required volumes which would enable further growth of the salmonid aquaculture industry. Especially the Swedish novel feed ingredients are sourced from pilot scale production which makes a direct application of our results to upscale scenarios more insecure. Additionally, most novel feed ingredients require a higher degree of labor and material input than the very efficient forage fisheries. This means that prices are likely to be higher and there is currently no financial incentive for the feed producers to switch to novel feed ingredients.

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Applying multi-nutrient functional units

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Keywords: *nLCA; nutrient index; protein rich foods; nutritional functional unit,*

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When looking for solutions to reduce the environmental impact of food, the integration of nutritional and environmental aspects becomes especially important; sustainability should be achieved in a way that human nutrition would not suffer when environmental impacts are reduced. Due to several environmental and health impacts, a transition to more plant-based diets in the Western countries is desirable, one manifestation of which is the replacement of animal-source products to plant-based alternatives. It requires a product-specific information and understanding on the substitution impact that integrates both environmental and nutritional perspectives. At the end of last year, FAO published a report on the best practices for integrating nutrition in LCA of food items, providing general guidelines for nutritional LCA (nLCA) methodology (McLaren et al. 2021). However, the methodological approaches remain varying because, as in any LCA, the methodological choices are dependent on the goal and scope of the study, ie a context of the assessment and intended usage of the results. Still, the use of nutritional functional units (nFUs) is a key solution for integrating nutrition into the LCA as it seeks to incorporate food functionality into the FU. This method has been developed over the last years (Saarinen et al. 2017; McAuliffe et al. 2020; Green et al. 2021).

The practical implementation of nLCA through product group specific nFUs is studied in NEPGa project led by Natural Resources Institute Finland. The project develops scientifically valid methodologies for combining nutritional factors with environmental impacts of food products in various product groups. The project's development work takes place in a Finnish context, but the scientific procedures can be implemented also elsewhere. In the project the methodological integration of nutritional quality into environmental assessment is developed in the multidisciplinary project team including food, environment and nutrition scientists from leading Finnish research institutes and universities. The work has been carried out as iterative development process in close collaboration, through discussions and test assessments. Workshops and seminars with stakeholders have been organized to collect feedback on views on usability of the methodology and communication of nLCA results to consumers. Indeed, in addition to methodological development, the NEPGa project aim to building a basis for a product labelling that integrates nutrition aspects to life-cycle-based environmental information.

In this study, we present the methodological framework for **the product group specific nLCA with nFU**. First, we describe the procedure for selecting suitable nutrients to be included in the nFU for protein rich foods in a national context, considering the Finnish nutrition and food recommendations, as well as the population's dietary habits and nutrient intake. We highlight the unresolved concerns involving the shift in diets toward plant-based foods and the resulting change in nutrient intake, and the sensitivities and uncertainties associated with nFUs. Since the use of nFU affects the other choices made in LCA modeling (e.g., system boundaries, allocations), we also discuss the challenges associated with nFU implementation in LCA. The methodological framework with practical implementation and discussion is described in detail in Kyttä et al. (2022, unpublished).

For product group specific nFUs, the grouping of foods is an important step - it needs to be broad enough to cover variety of foods that are substitutable with each other but narrow enough to differentiate the foods with different functions. Therefore, in this study the grouping was based on the plate model presented in the national food recommendations of Finland (VRN, 2014). As a result, the foods that are consumed similarly, and thus are substitutable, are grouped together. For proper usage of nFU, it is crucial to identify the nutrients that are derived from the product group under study. First, the nutrients that are currently obtained from sources of protein were identified. This was done based on the National FinDiet Surveys (Kaartinen et al. 2020) that monitor the dietary habits and nutrient intake of the adult population in Finland. According to the survey, in current diets the main sources of protein are meat and dairy products. Because our approach is based on the substitution effect of products, we mapped out all the nutrients that meat and dairy products are significant sources of in current diets. These criteria resulted to the following beneficial nutrients being included to the nutrient index of protein rich foods; calcium (Ca), iron (Fe), selenium (Se), zinc (Zn), vitamin B6, vitamin B12, niacin, riboflavin, and thiamine. Because the index is based on relation of nutrient content of food and the national daily intake recommendation of nutrient, the index was calculated separately for all population groups with different nutrition recommendations. The index was used directly as a FU for protein rich foods by dividing the environmental impacts by the index score. The sensitivity of climate impacts to the choice of nutrients in the index and system boundaries in LCA were tested with further analyses.

The results show that using nutrient index instead of mass as FU decreases the difference between animal source foods and plant-based foods. Due to high climate impacts of beef per 100 grams, also the climate impact per index score was the highest, and consequently, the high index scores of fish foods lead to low climate impacts per index. The results are sensitive to the choice of nutrients in the index, the type of food assessed and the system boundaries of assessment. The more detailed results are presented at the conference and in the scientific publication with methodological focus.

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CHEF WOO HIGH-PROTEIN RAMEN NOODLE LIFE CYCLE ASSESSMENT: A detailed comparison with animal-based protein sources

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Keywords: *high protein ramen noodle; life cycle greenhouse gas emissions; fossil energy; land use; water use*

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Rationale and objective: This study was conducted by The Center for Sustainable Systems at University of Michigan to provide environmental performance of replacing meat consumption with consumption of the novel plant-based Chef Woo (CW) ramen noodle, a unique product that supplies 20g of plant-based complete protein per serving. Typical wheat-based ramen provides 5 g of protein and Borealis Foods, the producer of the Chef Woo ramen noodle, seeks to make this shelf stable, high protein ramen noodle more widely accessible and affordable, particularly to low-income and other economically vulnerable consumers. The goal of the study is to conduct a comparative assessment of CW and beef, pork, chicken and a plant-based burger and to highlight opportunities for improvement in the environmental performance across the supply chain.

Approach and methodology:
A peer reviewed LCA of the Chef Woo product was conducted and environmental impact results were compared with representative studies of beef, pork, chicken and a plant-based burger designed to cover an equivalent boundary condition (cradle to preparation/cooking, excluding retail). The declaring differences were reserved to those where impacts differ by more than 25% (based on expert judgement). The novelty of CW ramen noodle is its supply of a full serving of nutritionally complete protein (having all essential amino acids). Therefore, for this study, protein provision will be considered the primary function. The chosen functional unit of 20g of protein was supplied to the end consumer in one ready-to-rehydrate cup of Chef Woo and 116g, 111g, and 89g of beef, pork, or chicken, respectively. In addition, the high-protein ramen was compared with a meal of regular ramen supplemented with pork or chicken to provide 20g protein total as well as a Beyond Burger patty (plant-based beef analog).
System boundaries included upstream ingredient and raw material supply (including farm production of agricultural crops), processing and packaging operations, distribution to point of sale, storage and preparation for consumption, and disposal of packaging materials. Impacts at retail were excluded, as were contributions due to retail- or consumer-level food losses. This exclusion is considered conservative as CW is shelf stable and does not require refrigeration, and therefore its allocation of retail-level energy consumption should be lower than that of fresh meats. However, representation of retail stages in LCA introduces a great deal of uncertainty and modeling challenges that were deemed unnecessary for the goals of this study. The preparation stage was included in order to demonstrate differences arising from preparation of the "instant" ramen product compared to other protein sources that require cooking before consumption. Instant ramen is prepared simply by adding boiling

water. The preparation stage impacts are therefore associated with the energy required to bring 250 mL of water to boiling. Primary, secondary and tertiary packaging materials were inventoried and packaging end-of-life management impacts were modeled using the EPA's Waste Reduction Model (WARM) and assuming representative U.S. average practices. The environmental impact of meat production came from three studies designed to be representative of U.S. production methods (Putman et al. 2017; Putman et al. 2018; Rotz et al. 2019). These farm-gate studies were used as inputs into a cradle-to-grave life cycle model that also included representative harvesting/processing, packaging, distribution (equivalent distance to Chef Woo), at-home storage and cooking for consumption. Production and packaging of Beyond Burger came from (Heller and Keoleian 2018), with other downstream stages modeled the same as meats. Ramen Express, a regular (wheat-based) ramen noodle manufactured in the same facility as Chef Woo, was modeled similarly to Chef Woo, with necessary changes to ingredients.
The environmental impacts assessed were chosen here as greenhouse gas emissions, fossil energy use, land use and water use. For greenhouse gas emissions CO2e are based on global warming potentials from IPCC 2013, 100-year time horizon. Fossil energy use is evaluated by converting "fossil resource scarcity" reported by ReCiPe as "kg oil-eq and multiplying this value by 43.2 MJ/kg (higher heating value of crude oil). Water use is based on "water consumption" reported by ReCiPe which is the amount of water extraction from surface water bodies or ground water that is lost from the watershed of origin. This "loss" is commonly through evaporation, evapotranspiration, or incorporation into a product. Land use is reported in m^2yr annual crop equivalents, and characterization factors are the relative species loss caused by a specific land use type (annual crops, permanent crops, forestry, urban land, etc). For typical agricultural land occupation with annual crops, the characterization factor is 1; the characterization factor is 0.55 for grasslands (including pastures and grazing), 0.3 for occupation by forest (e.g., for paper products) and 0.73 for most industrial or urban land occupations.
Primary data on processing of pea protein isolate were available under confidentiality from a supplier. Other CW ingredients were based on secondary datasets, modified to better reflect anticipated country-of-origin market mixes and electricity grid mixes. Drying of dehydrated vegetables was based on information provided by suppliers. Primary data on utility requirements for the noodle manufacturing process were provided by Borealis Foods.
More details regarding the methods, data collection and inventory, study limitations and detailed results are available in this ISO peer review study report (Heller and Keoleian, 2021).

Main Results: The contribution from major stages/components in the CW life cycle to the four impact indicators is shown in Figure 1, followed by a comparison of the total impacts across protein sources presented in Tables 1 and 2. Noodle ingredients (which includes frying oil) is a significant contributor across all indicators. Distribution of energy demand across life cycle stages follows that of GHGE fairly well, with the exception that processing and packaging represent somewhat larger shares. Ingredients contribute more than half of the fossil energy use, with pea protein isolate being the single greatest contributor, at 24.3% of total fossil energy use. As may be expected, agricultural production of ingredients dominates land use (93%, including noodle, oil and dried vegetables) with packaging representing the remainder. Contributors include sunflower oil (32%), pea protein isolate (31%), wheat flour (19%), proprietary protein (proxied by pea isolate) (9%), and all vegetables (2%). Agricultural production of ingredients also dominates water use, with noodle ingredients and oil contributing 73% and dried vegetables 5%. Downstream stages of distribution and preparation contribute minimally across all indicators.

When comparing an equivalent provision of protein, Chef Woo greenhouse gas emissions are significantly less than beef or pork, and somewhat less than Beyond Burger. Chef Woo fossil energy use is significantly less than beef, and somewhat less than pork and Beyond Burger. Chef Woo land use is significantly less than beef, somewhat more than pork and significantly more than chicken or Beyond Burger. Chef Woo water use is significantly less than beef and pork, somewhat less than chicken, and significantly more than Beyond Burger. Differences in greenhouse gas emissions and fossil energy use between Chef Woo and chicken cannot be determined by this study, due to underlying uncertainties. Supplying 20 g of protein through Chef Woo rather than a traditional noodle meal (regular ramen supplemented with meat) leads to significantly less impacts across all categories when using beef, significantly less greenhouse gas emissions and water use when using pork, and somewhat less greenhouse gas emissions and water use when using chicken.

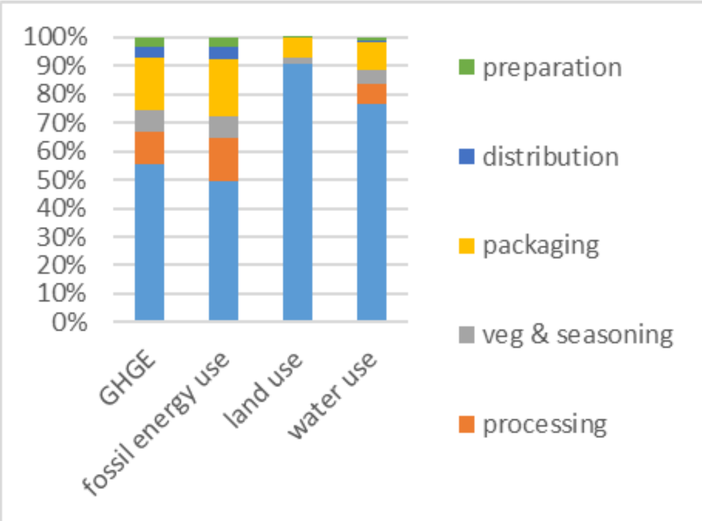

Figure 1. Distribution of impacts across life cycle stages for CW noodle cup.

Table 1. Comparison of total impacts for supplying 20g protein from various sources.

	GHGE	fossil energy use	land use	water use
	kg CO_2eq	MJ	m^2a	liter
Chef Woo	0.43	5.08	0.91	8.18
beef	3.32	10.33	3.13*	289.01
pork	0.88	7.55	0.72	35.67
chicken	0.39	4.22	0.40	15.15
Beyond Burger	0.59	8.36	0.45	4.29
Ramen Express + beef	2.85	10.81	2.69	220.52
Ramen Express + pork	1.02	8.71	0.88	30.14
Ramen Express + chicken	0.64	6.22	0.64	14.76

*land use value is from a different US beef production LCA than other beef indicators; used here as proxy

Table 2: Relative comparison between CW and other protein sources. Negative percentages mean Chef Woo has lower impact.

	GHGE	fossil energy	land use	water use
Beef	-87%	-51%	-71%	-97%
Pork	-52%	-33%	26%	-77%
Chicken	10%	20%	129%	-46%
Beyond Burger	-27%	-39%	101%	91%
Ramen Express + beef	-85%	-53%	-66%	-96%
Ramen Express + pork	-58%	-42%	3%	-73%
Ramen Express + chicken	-34%	-18%	43%	-45%

(green)	CW >50% reduction in impact; significantly reduced
(blue)	CW between 25% and 50% reduction in impact; somewhat reduced
(grey)	CW <25% different (+/-); unable to confidently determine difference
(yellow)	CW between 25% and 50% greater impact; somewhat greater
(orange)	CW >50% greater impact; significantly greater

Discussion and Conclusion: The range of environmental impacts from meat production seen in studies of other modeling frameworks, geographic locations and production practices suggest that the comparison made here, using studies designed to represent US production, is conservative, and that other contexts would likely further favor Chef Woo. Sensitivity analysis of the Chef Woo LCA suggests that modeling assumptions and processing efficiency-related parameters have minor influence (less than 10%) on the reported baseline, but that data quality for the upstream production of ingredients could have a notable effect on the reported Chef Woo environmental performance. We feel that all reasonable efforts were made to gather appropriate and supply-chain specific data on these ingredients. Based on the LCA findings presented here, CW outperforms beef as a source of protein in all impact categories, and performs as good or better than pork or chicken in all categories except land use. Combining regular (wheat-based) ramen with enough beef, pork or chicken to supply 20g of protein also has higher GHGE, energy use, and water use than CW. Beyond Burger, also a processed, plant-based protein source, results in 27% more GHGE and 39% more fossil energy use than CW but about 50% less land and water use.

This study confirmed expected findings regarding "hotspots" in the CW life cycle. The production of ingredients made notable contributions to GHGE, energy use, land use and water use. Supplying protein is often resource intensive, and the primary CW protein source, pea protein isolate, is the top contributor across all impact categories, with the interesting exception of land use, where sunflower oil makes a comparable contribution. Packaging, distribution and at-home preparation make minor contributions across all categories.

The poorer performance relative to meats of CW land use compared to GHGE appears to, at least in part, be due to contributions from sunflower oil. Whereas the contribution from sunflower oil to overall CW GHGE is 14%, its contribution to land use is 32%. Alternative oils suitable for frying (e.g., rapeseed, soybean) could lead to notable reductions in environmental impact. Environmental impact, of course, must be balanced with other criteria in the selection of frying oils. Still, this appears to be one area where CW environmental performance could be improved.

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Updating the Mediterranean diet towards sustainability: Beyond the nutritional benefits of superfoods

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Keywords: *Dietary pattern; food security; Food Supply Chain (FSC); Life Cycle Assessment (LCA); sustainability; quinoa*

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Introduction

Dealing with a global nutritional demand while trying to care and preserve the environment is one of the main challenges facing today and will continue to be trial in the coming years. Food systems are resource-, emission-, and energy-intensive, generating one third of the total anthropogenic greenhouse gas (GHG) emissions and consuming more than 70% of the water withdrawn (FAO, 2017). In addition, demands for water, energy, and food are estimated to increase by 40%, 50% and 35% respectively by 2030 (Endo et al., 2017), threating the sustainability of food supply chains (FSC) and undermining the world's capacity to meet its food needs. This problematic situation stands up the need to update and redesign dietary patterns, which constitute a crucial step towards ensure food security and guarantee a more sustainable future. In this context, superfoods could play a key role. Superfoods are known as food products with superior nutritional properties and great biological value, and they are supposed to improve the overall health and promote the smooth operation of organic systems (Magrach and Sanz, 2020). Their unique characteristics bring some questions into play: Can superfoods improve the diet not only from a nutritional point of view, but also from an environmental perspective? Can they be the solution to ensure access to healthy and sustainable food for all?
Attempting to answer these queries, Life Cycle Assessment (LCA) has proven to be an effective tool for assessing the potential environmental impacts of products, processes or services, allowing to propose sustainable solutions for global food challenges, as well as supporting the transition towards improved production and consumption patterns (Sala et al., 2017). In this framework, this study aims to apply LCA to evaluate the performance of two 'updated' diets, in which the introduction of quinoa was considered to replace the nutrient intake of two conventional products, rice and meat. The results will enable to assess the convenience of including superfoods in common diets from an environmental perspective as well as of reducing animal-proteins to improve the sustainability of dietary patterns.

Methods

Goal and scope

The goal of the study is to estimate the environmental impacts of two alternative diets in which the introduction of quinoa was considered by means of: i) the overall replacement of rice (scenario #1), and ii) the partial substitution of meat, namely, beef (20%), pork (30%) and chicken (30%) (scenario #2) (Figure 1). The comparison of the updated dietary patterns and the current Spanish diet will enable to understand the benefits associated with superfoods from an environmental perspective, allowing consumers, as well as all stakeholders involved in the FSCs, to make decisions that will lead to a

more sustainable sector.
In order to fulfill this goal, one of the most common functional units (FU) for diets comparison was applied, i.e., a food basket with all products consumed in home by an average Spanish citizen during a year (Heller et al., 2013). On the other side, a 'cradle to gate' approach was defined, which includes the cultivation and production of plant-based products (tillage, fertilization, harvesting, etc.), fishing and breeding of animals (feeding, cleaning, farms maintenance, etc.), as well as the packaging and industrial transformation of foods (manufacturing, processing, cooking, etc.).

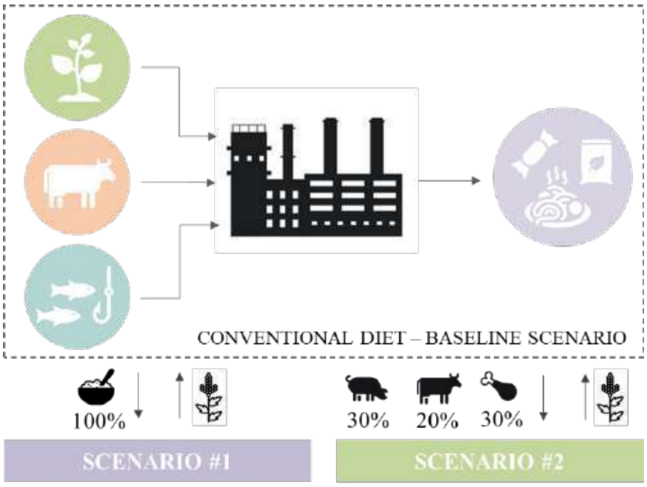

Figure 1: Overview of the scenarios and system boundaries.

Life cycle inventory (LCI) compilation
The food basket for an average Spaniard was based on the household consumption surveys carried out by the Spanish Ministry of Agriculture, Fishery and Food (MAPA). Data from 2020 were considered as it is the most recent data available (MAPA, 2020). A total of 267 different food products were included in the LCI, which were divided into 5 categories according to the following food classification: meat-based products (including meat, fish, eggs, milk and dairy products), plant-based foods (fruits, vegetables, mushrooms, cereals, legumes and nuts), sweets (confectionary, pastry, candies and sugar), beverages (water, juices and alcoholic beverages), and ready-to eat products (prepared meals, sauces and snacks). On the other hand, background processes, i.e., secondary data, were compiled from the Agribalyse v3.0.1 database (ADEME, 2022).

Life cycle impact assessment (LCIA)
Six different impact categories were assessed in this study: ozone depletion (ODP), photochemical ozone creation (POPC), freshwater eutrophication (EP, freshwater), marine eutrophication (EP, marine), global warming potential (GWP) and cumulative energy demand (CED). The selection of the indicators was based on a revision of LCA studies of diets, which compilated the most used categories for assessing their environmental impacts (Heller et al., 2013). The translation of inputs and outputs into environmental impact values was done by applying the IPCC 2021 and Environmental Footprint (EF) 3.0 methods, which provide the better degree of specificity and consistency, as well as being the recommended by the European Commission (Manfredi et al., 2015). On the other hand, the Cumulative Energy Demand (CED) method was used to estimate the energy requirements of the diets.

Results and discussion
Figure 2 depicts the impacts associated with an average diet of a Spanish citizen and the two 'updated' scenarios proposed in this study. The current consumption patterns generate annually $1.15 \cdot 10^{-4}$ kg CFC11 eq., 4.70 kg NMVOC eq., 0.15 kg P eq., 6.43 kg N eq., and 1.18 t CO_2 eq., and consume

around 19.7 GJ of energy per person. These figures are dominated by animal-based products, with percentages between 58% and 72%. Only in CED, plant-based foods presented the major contributions (87%). The rest of the impacts are divided into the remaining categories, ranging from 1% to 13%. These values and trends in the results are supported by other studies: In a Spanish context, Muñoz et al. (2010) reported a carbon footprint (CF) of 1.56 tons CO_2 eq./capita and year, whereas the energy consumption reached up to 12.5 GJ. Batlle-Bayer et al. (2019) estimated a cradle to consumer emissions of 1.6 t CO_2 eq./capita and year, with a contribution of 89% from food production and processing. Considering the WHO (World Health Organization) healthy diet guidelines, per capita GHG emissions get up to 1.19 t CO_2 eq., a quite similar value than that calculated in our study (Ritchie et al., 2018).
In view of the results, the need to focus efforts on improving diets involving especially animal- and plant- based products is evident. Based on this, scenario #1, which gives attention to the replacement of rice for quinoa, leads to slight environmental benefits in all categories except for EP freshwater. This is due to two reasons: (i) quinoa production and processing generally has, in terms of the impact categories selected, a better environmental performance than rice, and (ii) a lower intake of food to meet basic health requirements is needed as consequence of the nutritional profile of quinoa (4.16 kg of rice vs 2.11 kg of quinoa/capita and year). However, a more intensive use of phosphate fertilizers is made to ensure the growth and quality of the crop, which has a strong impact on freshwater eutrophication. Overall impacts reach $1.14{\cdot}10^{-4}$ kg CFC11 eq., 4.69 kg NMVOC eq., 0.15 kg P eq., 6.42 kg N eq., 1.18 tons CO_2 eq., and 19.7 GJ of energy/capita and year. Based on these figures, improvements range from 0.03% (CED) to 0.37% (GWP), which is translated into avoiding annually around $2{\cdot}10^5$ tons CO_2 eq. considering the Spanish population.
On the other hand, scenario #2, which focused on the partial substitution of meat for quinoa, seems to lead to more significant environmental benefits, reporting the following impacts: $1.12{\cdot}10^{-4}$ kg CFC11 eq., 4.63 kg NMVOC eq., 0.15 kg P eq., 6.32 kg N eq., 1.13 tons CO_2 eq., and 19.6 GJ of energy per capita and year. Given that meat is considered one of the major resource consumer and generator of pollutant emissions, its replacement by products of vegetable origin heads to enhancements up to 4.02% (GWP). This trend was already confirmed by other authors, who reported that the environmental impact of meat-based diets may be roughly a factor of 1.5-2 higher than the effect of vegetarian meals in which meat is replaced by plant proteins (Van Dooren et al., 2014). Likewise, Kustar and Patino-Echeverri (2021) evidenced that plant-based solutions have lower impacts on land use (average 51%), water use (27%), and GHG emissions (33%) than omnivorous diets. Contrary, as in scenario #1, the impact on EP freshwater is increased by 3.33% as a result of quinoa farming practices, so the implementation of more sustainable techniques and control of fertilizers use is strongly recommended to improve the sustainability of the system.

Based on the methodology applied and the results obtained, it is of interest to highlight the weaknesses and opportunities for improvement of the study, which will be the focus of future research. The use of nutrition-based FU is a key point to develop, since it allows visualizing the environmental performance of the diet considering priority aspects when dealing with nutritional quality. To this end, taking into consideration FU related to a specific nutrient, such as protein, or a complex index that encompasses several ingredients, such as Nutrient Rich Food 9.3 (NRF9.3) (Drewnowski, 2009), is an interesting aspect, especially for carrying out diet comparisons. On the other hand, the introduction of significant indicators to address food production, such as land or water use, would be an opportunity to broaden the study and gain a more comprehensive understanding of its environmental performance. Finally, as it has been proven that the introduction of quinoa brings environmental benefits, especially by partially replacing meat consumption, the study of the inclusion of other superfoods to complement diets, such as spirulina, or more novel foods like insects, is a focus of research to be taken into account.

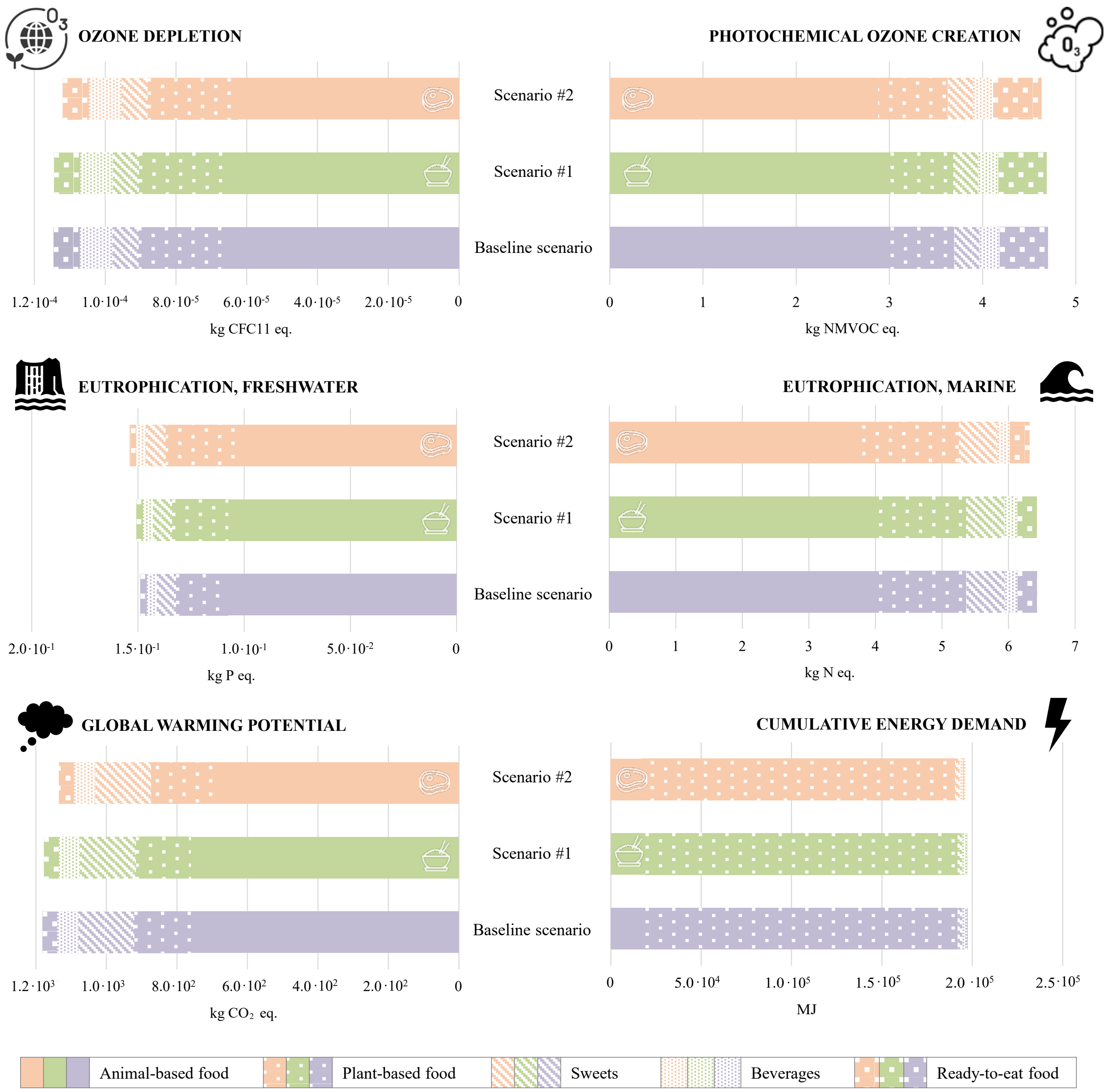

Figure 2: Results reported for the scenarios under study expressed per capita and year.

Conclusions

In a global scenario where food systems are in a critical position from an environmental perspective, this work shows how superfoods can play an important role in moving towards more sustainable diets. The main results show that the substitution of rice by quinoa is associated with slight environmental benefits, up to 0.34%, as both are products of plant origin. However, considering a partial replacement of beef, pork and chicken consumption by quinoa, environmental improvements significantly increase, reaching benefits of 4.02% in GWP, which translates into the avoidance of almost $3 \cdot 10^6$ tons of CO_2 equivalent per year considering the Spanish population. Therefore, the inevitable conclusion is that diets based on reduced animal protein clearly improve the sustainability of dietary patterns and consumption habits, especially if superfoods with complex nutritional profile such as quinoa are included. Based on this, future studies will focus on addressing nutritional aspects by considering nutrition-based FU, as well as addressing the inclusion of a wide range of superfoods in diets.

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The Chilean dietary pattern under the spotlight of environmental sustainability and nutritional quality

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Keywords: *Carbon footprint, water footprint, nutrient-derived metric, Latin America*

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1. Introduction

Depletion of natural resources, ecosystem degradation and water scarcity are affecting global food production. In addition, climate change is leading to a shift in precipitation patterns, global temperature and river runoffs on which the global agricultural system depends. Without decisive action to remedy the current situation, the world will not be on track to meet the United Nations Sustainable Development Goals by 2030 (Willett et al., 2019).
On the other hand, non-communicable diseases (NCDs), such as cardiovascular diseases, cancer and type II diabetes mellitus, are currently the leading cause of death and disability in the world, affecting the quality of life of citizens. In this context, the WHO Global Health Observatory identified malnutrition and unhealthy consumption habits and lifestyles the main risk factors for the development of NCDs (WHO, 2020).
In an effort to provide context-specific advice on healthy diets in Latin America, the Chilean government has recently published the study "Radiography of Food in Chile" (Govenment of Chile, 2021). This study analyses Chilean dietary patterns based on household expenditure. The findings of this study revealed a high consumption of sugary drinks, bread and sweets, who give preference to the economic cost of the products purchased over environmental and nutritional indicators, which they are often unaware of or question. Therefore, connecting nutrition with environmental sustainability provides opportunities to raise social awareness about Chilean eating habits. Therefore, the purpose of this research was to quantify the environmental impacts expressed as carbon and water footprints and the related nutritional quality of the Chilean dietary pattern.

2. Materials and methods

Life Cycle Assessment (LCA) and Water Footprint Assessment (WFA) methodologies were followed to estimate the most directly related indicators: Carbon Footprint (CF) and Water Footprint (WF) of the Chilean diet. The functional unit of reference that establishes the basis of calculation for consumption and emissions was the average daily dietary intake per capita.

2.1. Carbon footprint assessment

The scope of the carbon footprint study was broad, covering the following stages (see **Figure 1)**:

- Agriculture and industrial manufacturing: This stage comprises the production of the different foodstuffs that constitute the Chilean dietary pattern.
- Wholesale and retail distribution: This stage covers the distribution activities involved in the

logistics of the different food items from the factory or farm gate to wholesaler and retailer. In this stage, special attention was paid to the geographical origin of the food items.

- Transport to households: This stage considers the transportation of the food items from supermarkets to households. Due to the available data, cooking was not considered within the system boundaries as in other similar studies available in the literature (González-García et al., 2020; Van Dooren et al., 2014).

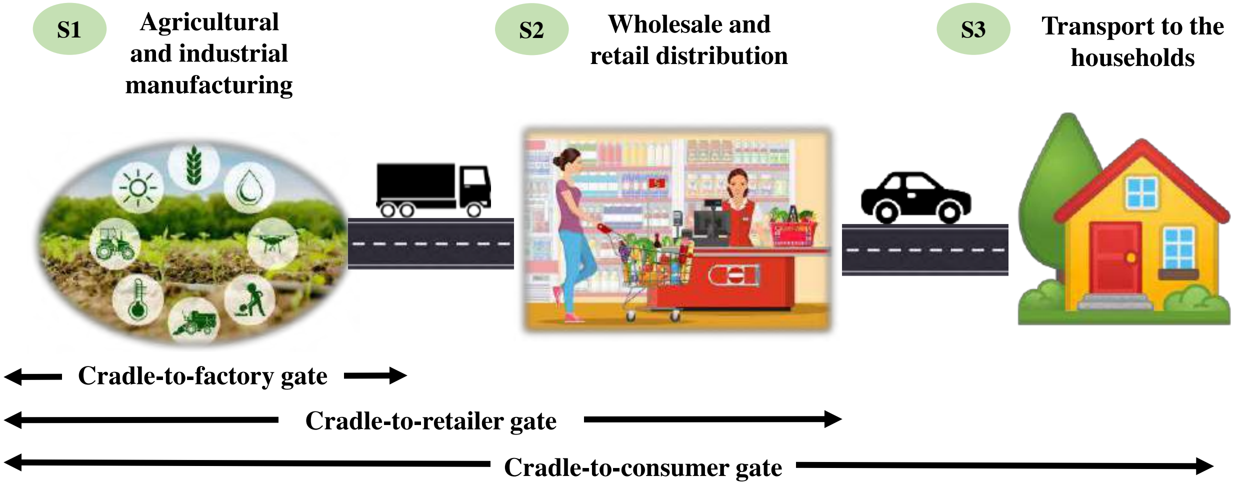

Figure 1. System boundaries considered in the carbon footprint assessment of the Chilean Dietary Pattern.

To assess the effect of primary agricultural production or industrial production of all foods on climate-warming greenhouse gas emissions, a systematic review of thirty-one food life cycle assessment studies was conducted from a "cradle-to-gate" approach. For international products, wholesale and retail distribution distances per food item were calculated considering production data, and exports and import statistics provided by the Observatory of Economic Complexity and the Food and the Agriculture Organization Corporate Statistical Database (FAOSTAT). For domestic food products, an average national distance of 50 km was considered (Dirven, 2005). Regarding transport from supermarkets to households, one shopping trip of 3.3 km per week was assumed (Batlle-Bayer et al., 2019).

2.2. Water footprint assessment

On the other hand, the dietary water footprint was calculated considering their three components, green WF_j (rainwater), blue WF_j (surface and groundwater) and grey WF_j (freshwater required to assimilate the pollutant load) and the daily intake per food item and person (M_j) (see **Eq. (1)**). The scientific articles by Mekonnen and Hoekstra (2010, 2011) were used as the basic database for the calculation of the water footprint.

$$WF_{diet} = \sum_{j=1}^{n} \left(Green\, WF_j + BlueWF_j + GreyWF_j\right) \cdot M_j \tag{1}$$

2.3. Nutritional quality assessment

A nutrient-derived metric (Van Dooren et al., 2014) based on ten components (fruits, vegetables, fish, saturated fats, free sugars, sodium, total fats, protein, fibre, carbohydrates and total energy) was used to assess the overall quality of the diet as can be seen in **Eq. (2)**. In addition, the nutrient targets reported by the World Health Organization and the World Cancer Research Fund International were considered.

$$Nutritional\ Index = \left(\frac{gveg}{200} + \frac{gfruits}{200} + \frac{gfish}{37} + \frac{gfiber}{30} + \frac{5}{gsodium} + \frac{30}{E\%\ total\ fat} + \frac{10}{E\% free\ sugar} + \frac{10}{E\%\ sat\ fat} + \frac{52}{E\%\ carbohydrates} + \frac{2000}{kcal\ energy}\right) \cdot \frac{100}{10} \quad (2)$$

3. Results and discussion

According to the results, the average CF of the Chilean diet was 4.25 $kgCO_2 \cdot person^{-1} \cdot day^{-1}$. Agriculture and industrial manufacturing were associated with 96% of total greenhouse gases (GHG) emissions. The other stages of the supply chain, wholesale and retail, and household distribution, were responsible for the remaining 4% of total GHG emissions. The largest overall contribution to the CF came from meat (42%), followed by beverages (29%) and starch-based products (9%) as can be seen in **Figure 2a**.

An analogous trend was found in the research literature for other Latin American countries. For instance, Vázquez-Rowe et al. (2017) estimated the GHG emissions linked to the average Peruvian diet. Their reported score did not include beverages and only considered the production stage. Considering this more restrictive approach, the estimated CF associated for the Chilean diet (2.91 $kgCO_2 \cdot person^{-1} \cdot day^{-1}$), would be close to that reported in their study (2.62 $kgCO_2 \cdot person^{-1} \cdot day^{-1}$).

On the other hand, the CF results for other well-positioned dietary recommendations in Europe such as the Mediterranean diet (2.21 $kgCO_2 \cdot person^{-1} \cdot day^{-1}$) or the New Nordic Diet (2.29 $kgCO_2 \cdot person^{-1} \cdot day^{-1}$) were lower than that identified for the Chilean dietary pattern (2.91 $kgCO_2 \cdot person^{-1} \cdot day^{-1}$), because they are dietary recommendations with a higher plant-based content. Otherwise, there are no large differences in the GHG emissions between Dietary Guidelines for Americans (2.98 $kgCO_2 \cdot person^{-1} \cdot day^{-1}$) and the Chilean dietary pattern (2.91 $kgCO_2 \cdot person^{-1} \cdot day^{-1}$). Note that the comparison between the Chilean dietary pattern and the American and European dietary patterns was made with attention to the production stage. Moreover, the CF score reported by Cambeses-Franco et al. (2021) included food losses and food waste along the supply chain, which have not been considered in our assessment of the Chilean diet.

Regarding the WF of the Chilean diet, it was calculated at 4519 $L \cdot person^{-1} \cdot day^{-1}$. Beverages (55%) were found to be the main environmental contributor to WF. Meat (19%) and starch-based products (10%) were also the main contributors (see **Figure 2b**). Although different data source were used, our consumptive WF for the average Chilean diet (3799 $L \cdot person^{-1} \cdot day^{-1}$) was in line with the range of values reported by Harris et al. (2020) for the combined green and blue WFs for South America.

In terms of the diet quality index, the Chilean diet achieved a score below the recommended (100). The reason behind this result is the lower consumption of healthy food groups (vegetables, fruits and fish) and qualifying nutrients (fibre) by the Chilean population, as well as the higher intake of disqualifying nutrients such as free sugars and saturated fatty acids. In comparison, other European and American Dietary Guidelines clearly showed higher diet quality indexes (above the recommended). This is the case of the Mediterranean Diet (178), the New Nordic Diet (119) or the Dietary Guidelines for Americans (116).

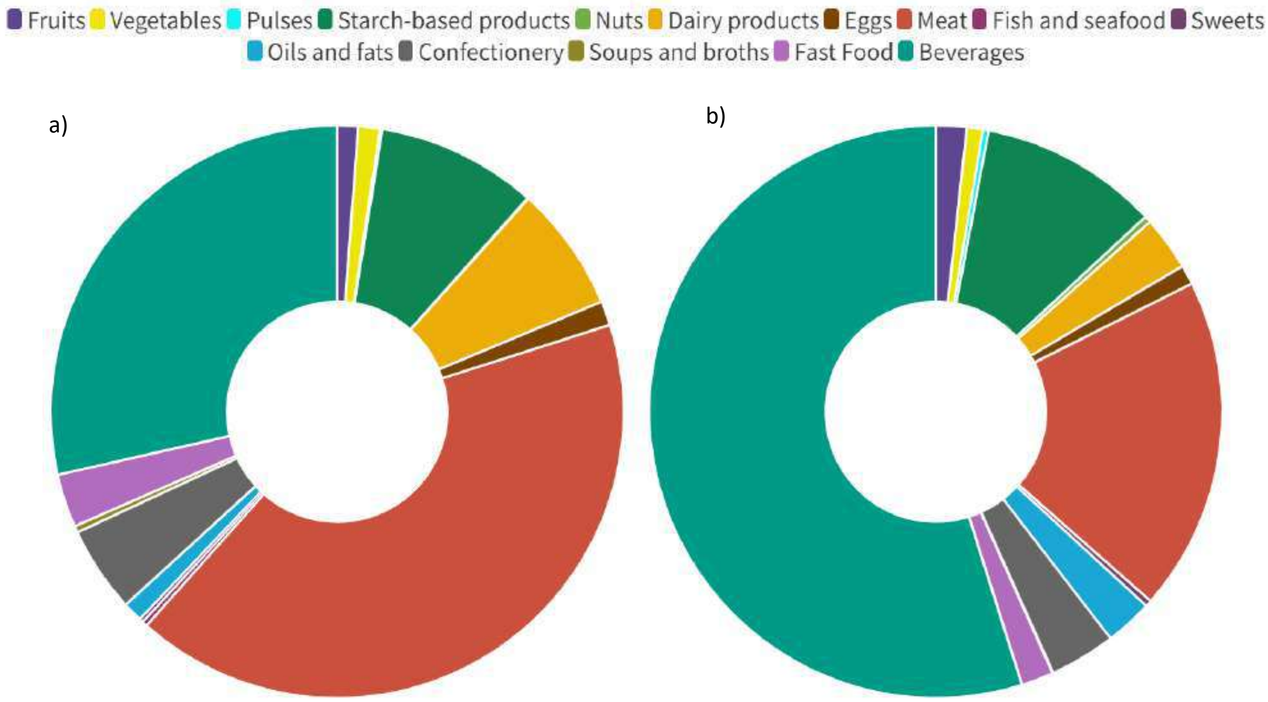

Figure 2. Distribution of carbon footprint ($kgCO_2 \cdot person^{-1} \cdot day^{-1}$) and water footprint ($L \cdot person^{-1} \cdot day^{-1}$) among food categories.

4. Conclusions

The results show that malnutrition and unhealthy dietary patterns are issues of concern in Chile. The current average Chilean dietary pattern is neither healthy nor sustainable. The rationale behind these results is that Chilean diet is high in sugary drinks and animal-based products, mainly meat, and low in healthy foods such as vegetables, fruits and fish.

The findings of this study establish a diagnosis of the Chilean dietary pattern and provide information for decision-making for the planning and implementation of national dietary guidelines in Chile. The formulation of public nutrition policies that promote vegetables and fruits and reduce their dependence on animal products, fatty foods and sugars is likely to improve nutritional quality and environmental sustainability in the country, reaffirming the national commitment to the SDGs.

Acknowledgements

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Using nutrient profiling algorithms to compare nutritionally-invested environmental impacts of cow's milk and plant-based beverages

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Keywords: *plant-based beverages; nutrient profiling; life cycle assessment; sustainability; milk*

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Rational and objective

Consumers are beginning to adopt more plant-based diets; consequently, establishing key tradeoffs between environmental and nutritional sustainability domains of plant-based beverages (PBB) versus cow's milk is a pertinent question. Accordingly, we quantify nutrient densities, fatty acid profiles, disqualifying nutrient scores, and environmental impacts of these drinks. For the nutrient densities, we developed a novel profiling algorithm to rank food items within a food group based on their ability to address nutrient deficiencies in certain dietary patterns. For environmental impacts, we included deforestation, global warming potential (GWP), stress-weighted water use, non-renewable energy, land competition, eutrophication, acidification, freshwater ecotoxicity organics, and freshwater ecotoxicity inorganics.

We assessed cashew, soy, almond, hemp, oat, spelt, rice, and coconut PBB, as well as cow's milk produced from arable-land based, pasture-raised, and grass-fed systems— the predominant difference between these systems was the percentage of feed concentrates; additionally, we compared soy produced in France versus soy from Brazil. Lastly, in addition to estimating environmental impacts per serving size of beverage (200ml) we used the nutrient metrics as the functional unit to estimate environmental impacts on a nutrient basis.

Approach and methodology

For this study, a nutritional group measured the nutrient contents of all drinks. We further combined literature and database data to estimate environmental impacts for which we included farm, transport, processing, and packaging impacts. We used the Swiss Agriculture Life Cycle Assessment (SALCA) impact assessment method (Roesch et al., 2017) for all impact categories expect water, for which we used the AWARE method (Boulay et al., 2018).

Following the 'points of differentiation' framework (Green, 2022), we developed a novel nutrient profiling algorithm termed the Food Substitute Index (FSI20) to rank the nutrient density of substitute products within a food group. The 'points of differentiation' framework provides guidelines on how to develop and apply nutrient metrics in the context of LCA. The FSI20 metric is reflective of national nutrient deficiencies across various dietary patterns (in this case, omnivore, vegetarian, and vegan diets). This particular index was applied to Switzerland for ranking PBB versus cow's milk; however, the algorithm is applicable for all countries. We also used a previously developed nutrient metric, the Nutrient Rich protein-substitution index ($NR_{prot\text{-}sub}$), which was developed to rank protein-rich food items (Green et al., 2021). Using these metrics as the functional unit, we were able to estimate nutritionally-invested environmental impacts.

Results and discussion

Preliminary findings show that coconut and cashew PBB, on average, have a lower combined sustainability compared to other drinks. This is due to the high environmental impacts of cashew and low nutrient density of coconut drink. Cow's milk, in general, performs much better with a nutrient-based functional unit compared to a volumetric one because while it has high environmental impacts it is also very nutrient dense. Of the PBB, soy milk was the most nutrient dense and has low environmental impacts when produced in France; however, it has relatively higher impacts (e.g., deforestation, GWP) when produced in Brazil. PBB were only nutritionally competitive with cow's milk when fortification was accounted for. Spelt and hemp, which are more novel beverages, show promise; for example, hemp has a favorable fatty acid profile.

We also provide commentary on the role of these beverage in the context of lower-income nations and emerging economies. For example, vitamin A is not a nutrient of concern for Switzerland but it is important in lower-income nations particularly amongst children and pregnant women. Thus, in such a context, cow's milk is the best option as the other beverages do not contain vitamin A. Zinc, which we measure based on differences in levels of dietary phytate which inhibits absorption of zinc, is also a nutrient of concern in lower-income nations. Cow's milk provides around 9% of daily recommended intakes (based on average needs for a 19-50 yr old female in Switzerland) for this nutrient, while soy ranges from 6-11%, cashew 5-11%, and almond provides 1-7%. In general, foods are considered inadequate sources of nutrients if they provide less than 5% of daily recommended intakes.

Conclusion

The nutrient density of beverages varied greatly even within a single beverage type; environmental impacts can also be wide-ranging (albeit to a lesser extent), and this is predominately due to differences in the percent of raw material used in the beverage. This high variation means that recommended optimal beverages for particularly populations to cover nutritional deficiencies in an environmentally-friendly manner is not straightforward.

We developed a novel index (i.e., FSI20) reflective of micronutrient deficiencies across varies dietary patterns. Such a context-specific index will be useful in lower-income economies as most indices (e.g., NRF9.3) are based on data from higher-income contexts. The main barrier here is a lack of dietary studies in lower-income nations that provide nutrient deficiency data for most essential nutrients.

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HESTIA: An open-access platform for sharing harmonised agri-environmental data

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Keywords: *open access, online, repository, inventory data, calculation engine*

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Introduction

Over the last decades, large volumes of life cycle inventory (LCI) and life cycle impact assessment (LCIA) data for agricultural practices have been assembled by different authors and institutes. These are available in the literature, but come in many different formats and with different levels of transparency. This often obstructs reuse of these data and hampers the collective knowledge of the LCA community. Methodological and assumptions by individual LCA practitioners also render comparisons of LCIA results inaccurate. In response, we have developed HESTIA (hestia.earth), an online open-access data platform that allows LCA practitioners and other users to upload their agricultural LCI and LCIA data using a standardised schema and glossary of terms. The LCI data can, in turn, be exported for integration in LCA software or be recalculated into LCIA results using our online calculation engine. This allows users to compare results across LCA studies using a harmonized set of terms, methodological choices, and assumptions.

HESTIA was initiated in 2019 and is already operational. The platform is continuously being updated to make the platform more user-friendly and meet diverse requests from users. To date, 3,000 agricultural cycles are available on the platform, derived from published LCA articles and datasets from related sciences. The data uploaded build on previous work by Poore and Nemecek (2018), Gephart et al. (2021), and other related initiatives, but we strive towards increasing individual contributions from the scientific community. In return, users who upload data will ensure archiving and more correct interpretation of their data, promote their work to a wider set of users, and be assigned unique DOIs.

By limiting HESTIA to agricultural processes, we have been able to streamline the upload format to make it intuitive to researchers from all fields of agricultural research, with an ambition to also allow for uploads by individual farmers. Biotic and abiotic factors can to a large extent be gap-filled using remote sensing data, while environmental emissions from fields, animals, and ponds are provided through HESTIA's calculation engine. Our API also allows for results to be integrated for additional uses, such as procurement processes, certification schemes, or data explorers.

The HESTIA session at LCAFood 2022 seeks to introduce the LCA community to the HESTIA platform and walk participants through the uploading process. The session will guide participants through the structure of HESTIA's schema, glossary of terms, and calculation engine. An agricultural case study will also be used to walk participants through the uploading process and explore the different outputs from the HESTIA calculation engine. In more detail, we will discuss the following during this interactive session:

- Introduction to the HESTIA online interface
- Introduction to the HESTIA Schema
- Introduction to the HESTIA Glossary of terms
- Exploring how data are gap-filled using geospatial data and lookup tables
- Example of an LCI upload
- Exploring emission models and LCIA results
- Examples of different uses for HESTIA data
- Questions and discussion

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GHG emissions and carbon sequestrations in the apple orchards

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Keywords: *Apple production, LCA, Net Zero, carbon sequestration*

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Objective:

The Paris Agreement requires that all human activities reach net zero GHG emissions by mid-century. This paper reviews LCA and wider literature on apple production globally to identify ranges of emissions and carbon sequestration in orchards, to inform pathways of transitioning apple production systems to net zero.

Methods:

A combination of LCA and other literature were reviewed, including GHG accounting for farming systems and carbon balances in apple orchards. We conducted this research in three steps. Firstly, we reviewed and synthesized a total of 84 published literature investigating the contribution of apple production to environmental impacts globally. 38 published papers were selected for further investigation based on availability of transparent data. Secondly, to enable the comparison on the same terms from different apple production practices in different geographic and climatic conditions, we harmonised the inventory data across available 31 datasets from reviewed LCA studies. Thirdly, a focused review of orchard carbon sequestration has been performed to provide ranges of carbon sequestration in apple orchards across the 6 published studies. Finally, we combine the above steps together and discuss pathways to net zero GHG emission of apple production.

Results and discussions:

This review reveals a large range of GHG emissions from apple production reported by different studies, ranging between 1 and 67 tCO_2-eq/ha/yr. These differences are due to methodological choices, different cultivation practices and local conditions for cultivating apples. We note that the inventory of apple production was usually collected for one year, which is not representative of the whole apple production cycle. This contributes to an important bias, due to the variability in farming practices and environmental conditions over the orchard lifespan.

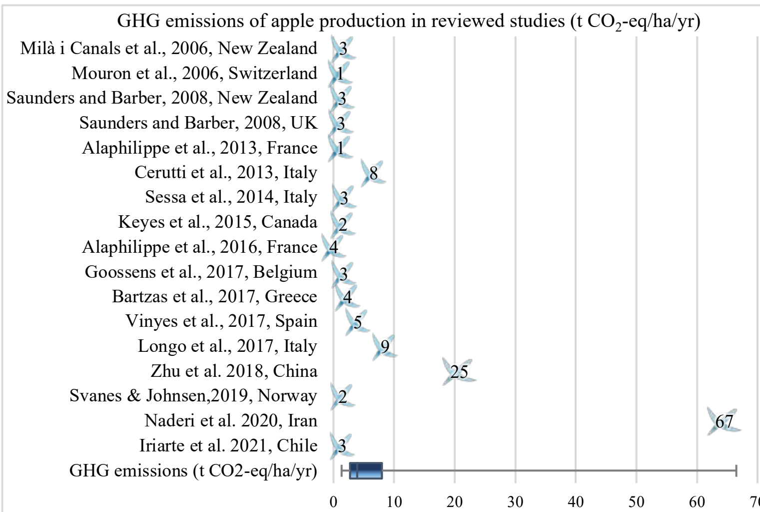

Figure 1 GHG emissions of farming stage of apple production reported in the reviewed literature. Grey dot pattern filled bars showed the range of different inputs of global apple production after statistical analysis. Grey solid filled bar showed the range of calculated individual inputs specifically demonstrated in studies.

Zooming further into the inventories supporting these GHG emission profiles (see Figure 2), it is possible to note a high variability of inputs to apple production, in particular in terms of energy consumption (diesel in agricultural machinery, electricity for irrigation) and fertiliser application. These results are very useful for informing transition to net zero, as they point to key measures needed for reducing emissions from apple production. Understanding where and how the use of these inputs can be reduced, and whether they could be substituted with their low carbon equivalent, is a key next step.

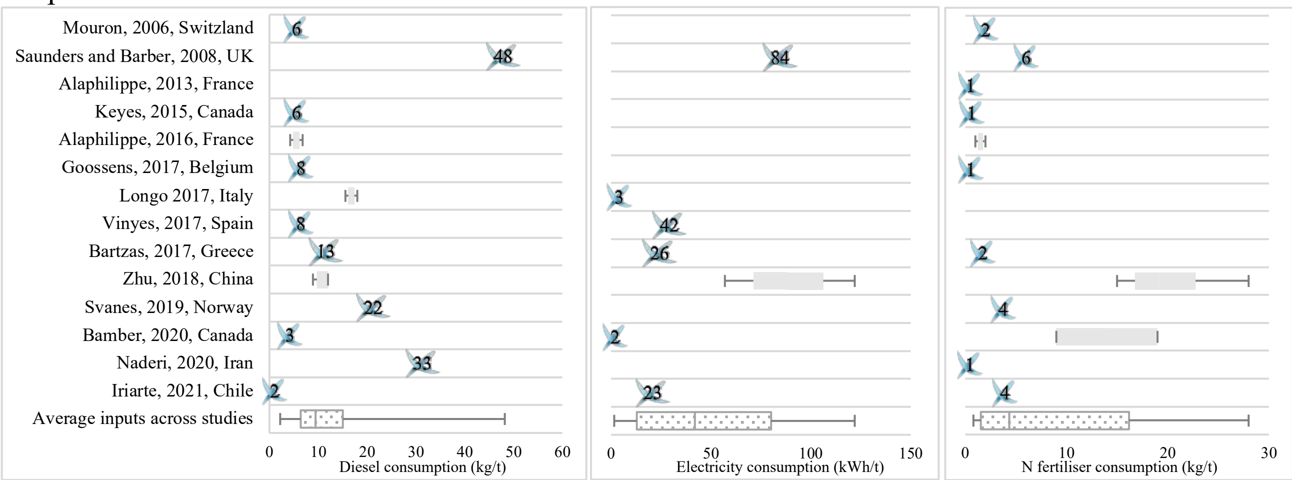

Figure 2 Comparison of key inputs to apple production from reviewed studies. Grey dot pattern filled bars showed the range of different inputs of global apple production after statistical analysis. Grey solid filled bar show the full range of individual inputs reported in the reviewed studies.

Besides reducing emissions, another important lever is the management of carbon sequestration in the apple orchard. Only one paper from reviewed 32 LCA studies investigated the effects of carbon sequestration in the orchard. A limited number of studies from other disciplines showed that sequestration by above ground vegetation (green bars in Figure 3) in apple orchards is in the range 29 to 79 t CO_2/ha/year. (Lakso, 2010; Robertson et al., 2012) While the soil is the biggest carbon sink, storing in the range 21 to 272 t CO_2/ha/year, only two out of the reviewed studies reported it. Grey bars in Figure 3 show the estimated carbon balance in apple orchards combining available data from reviewed studies. It shows that in selected locations, the operation of apple orchards could be an overall net negative, i.e., more sequestration than emissions. However, more investigation is needed to validate these findings.

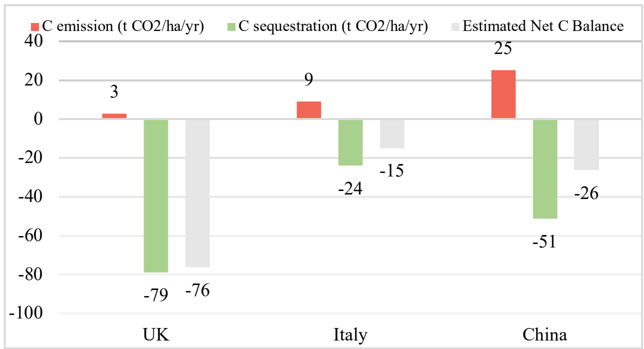

Figure 3 Estimated carbon balance in the UK, Italian and Chinese apple orchards combining available data from studies evaluating carbon emissions and sequestrations in the same country but not in the same farming systems.

Conclusion:

Achieving global net zero GHG emissions requires both enhancing sinks and reducing emissions. This study provides a harmonised comparison of global apple production to highlight environmental impact hotspots and supplies insights on which production processes could be improved in order to reduce GHG emissions. Enhancing carbon sequestration in orchards, there is a great potential for delivering potentially net sequestration from apple production, which can compensate emissions hard to abate elsewhere in the economy. Examples of ways to enhance sequestration include processing pruned branches, leaves and old trees into biochar which can be reapplied to soil in the orchard (e.g., Payen et al., 2021).

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The applicability of LCA standards to model the effects of feed additives on the environmental footprint of animal production

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Keywords: *Feed additives, LEAP, Animal Production Systems, LCA.*

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Abstract

Purpose. Animal production systems are an important part of the current global food system, and it is associated with high environmental impacts and resource use. Various standards and guidelines such as the PEFCR for Dairy (The European Dairy Association, 2018), FCR red meat (Technical Secretariat for the Red Meat Pilot, 2019) and the LEAP guidelines provide guidance on the modeling of environmental footprint of animal production. The FAO LEAP Partnership elaborated specific guidelines applicable to feed additives (FAO, 2020), to account for both their production and their value upon use. The main purpose of the study is to explore the applicability of those authoritative sector LCA guidelines (FAO LEAP and/or EC PEF) to nutritional interventions resorting to feed additives.

Methods. We conducted a road testing LCA of nutritional interventions, based on feed additives supplementation, to explore if the current LCA methodology and available background data are sufficiently developed to conclude on the magnitude and certainty of lifecycle impact of the use of feed additives. The guidelines were tested by studying diverse nutritional interventions (n=14) based on feed additives supplementation in different target species (n=3, broilers, fattening pigs and dairy cows), starting from one reference system for each species.

Results and discussion. The study shows that the use of feed additives can have a positive environmental impact over the entire lifecycle.

The study shows that available sector LCA guidelines provide adequate guidance, to evaluate interventions improving productivity, animal health, lifetime performance or emissions. However, it also identified areas where the existing guidelines need to be more specific to confer more robustness to the LCA outcome.

Conclusion. The study confirms the important role that additives can play at farm level in conducting sustainability improvement plans. The multiple LCA case studies (multi-species, multi-interventions) were an opportunity to detect and discuss path for improvements for livestock sectorial guidelines, while verifying the actionability of systematic foot-printing approach, including when applied to nutritional interventions.

Introduction

Animal production systems are an important part of the current global food system, providing approximately 18% of the global dietary energy intake and a third of global protein consumption (Mottet et al., 2017; Rojas-Downing, Nejadhashemi, Harrigan, & Woznicki, 2017). On the other hand, the animal production sector is associated with high environmental impacts and resource use. At global level, animal production is estimated to be responsible for 14.5% of global anthropogenic GHG emissions (Gerber et al., 2013), occupies an estimated 40% of arable land for grazing and feed production (Mottet et al., 2017), represents 42% of freshwater consumption for agriculture (Heinke et al., 2020). Moreover, agriculture as a whole also significantly affects nutrient flows (Conijn, Bindraban, Schröder, & Jongschaap, 2017). Life Cycle Assessment (LCA) captures the above-mentioned environmental effects and pressures in the impact categories global warming; land use and agricultural land transformation; water use/scarcity; terrestrial, freshwater, and marine eutrophication; and terrestrial acidification. Feed additives provide a potential strategy to mitigate environmental impact of animal production (Grainger & Beauchemin, 2011; Knapp, Laur, Vadas, Weiss, & Tricarico, 2014).

Various standards and guidelines such as the PEFCR for Dairy (The European Dairy Association, 2018), FCR red meat (Technical Secretariat for the Red Meat Pilot, 2019) and the LEAP guidelines for poultry (FAO, 2016) provide guidance on the modeling and environmental footprinting of animal production. The FAO LEAP Partnership elaborated specific guidelines applicable to feed additives, as feed additives have been identified to carry environmental benefits, in their use phase, via support on productivity, animal health, lifetime performance or even direct environmental benefit, by abating emissions from the digestion process. These guidelines dense and up to date set of resources to conduct rigorous Life Cycle Assessment, when focusing on nutritional interventions in farm systems.

The main purpose of the study is to explore the applicability of those authoritative sector LCA guidelines (FAO LEAP and/or EC PEF) to nutritional interventions with feed additives. To this end, a diverse set of nutritional interventions (n=14 in total) based on the application of enzymes, vitamins, carotenoids, eubiotics, has been documented with an extensive bibliography (along the FAO LEAP Guidelines principles for feed additives) and further translated into effects observable at farm level. Three terrestrial target species were studied: broiler chickens, dairy cows, and fattening pigs, while the reference systems were designed from Dutch and Belgium references. The full methodological exploration is reviewed by external experts along ISO 1400/44 requirements for LCA (Blonk, Bosch, Braconi, Cauwenberghe, & Kok, 2021).

Methods

We conducted a road testing LCA of nutritional interventions, based on feed additives supplementation, to explore if the current LCA methodology and available background data are sufficiently developed to conclude on the magnitude and certainty of lifecycle impact of the use of feed additives. Additionally, we also explored how LCA studies can deal with the use of multiple feed additives as one intervention, the so-called combined effects. The primary aim of this study is to draw conclusions on adequacy of current LCA guidelines and standards that would support the LCA practitioner in conducting LCAs of nutritional interventions based on feed additives use. The secondary aim of the study is to explore the likely impact of the use of feed additives (multiple type of additives, applied to different target species) and how this impact could be further substantiated depending on the goal of the LCA study. We do not aim to assert the impact of use of feed additives for specific farm systems regions or points in time.

The guidelines were tested by studying a high number of diverse nutritional interventions (n=14) based on feed additives supplementation and in different three target species (n=3, broilers, fattening pigs and dairy cows) starting from one characterized reference system for each species. The dietary interventions were only applied to the selected life stages, although the effects can also be relevant for the level of replacement and thus the extent of the replacement herd, in case of dairy farming.

The environmental impact of feed additives was provided by industry partners, and modelled according to WBCSD (2014) guidelines. Environmental impact of feed ingredients and other inputs at animal farms was based on Agri-Footprint 5.0 database (Van Paassen, Braconi, Kuling, Durlinger, & Gual, 2019a, 2019b). Emissions at animal production systems was calculated using the APS-footprint tool (Blonk Consultants, 2020d, 2020b, 2020a, 2020c).

Results and discussion

The study demonstrates that the use of feed additives can have a positive environmental impact over the entire lifecycle. Except in one case (for a product with a high inclusion rate), the environmental impact of the production of feed additives is confirmed negligible compared to the positive impacts delivered, which can amount up to 10% (cumulative effect for some impacts and some species). Cumulative results for the three target species, broilers, fattening pigs and dairy cows are shown in figures 1, 2, and 3 respectively. For pigs, dairy cows and broilers, the cumulative change in various impact categories ranges from 0% to -12%, from -9% to -11% and from -3% to -7%, respectively. Lack of uncertainty and sensitivity analysis does not allow to conclude on the robustness and significance of the estimated numerical results.

Improvement in productivity and specific reduction of emission confirm their concrete prospects with regards to the reduction of livestock footprint and were relatively easy to model. Environmental benefit provided by enzymes upon feed formulation requires extended information on feed recipes to be properly generalized. Our study evidences the need to integrate the footprint of ingredients as optimization criteria, rather than as a calculated outcome, to fully capture the potential of enzymes to minimize resources use. It also confirms the significance of the contribution of phytase to abate phosphorus and nitrogen related impact on farm. Finally, solutions supporting the lifetime performance of the animals (longevity, fertility, health status) also indicate a potential for impact mitigation, although requiring sophisticated modelling of herd/flock dynamics.

The study shows that available sector LCA guidelines provide adequate guidance, to evaluate interventions improving productivity, animal health, lifetime performance or emissions. However, the study also identified areas where the existing guidelines have to be more specific to confer more robustness to the LCA outcome. This is the case, in particular, for the accounting of the variability and certainty when translating complex zootechnical dynamics in an LCA model; for accounting for changes in production and composition of manure leaving the farm and for modelling of nutritional interventions that act on product quality and subsequent stages in the value chain. The study also highlights the pivotal role of feed formulations to derive robust conclusions. The way these dilemmas are managed by LCA experts may affect the outcome to a large extent, hence the need for clearer guidance.

Conclusion

The study confirms the important role that additives can play at farm level in conducting sustainability improvement plans. The multiple LCA case studies (multi-species, multi-interventions) were an opportunity to detect and discuss path for improvements for livestock sectorial guidelines, while verifying the actionability of systematic foot-printing approach, including when applied to nutritional interventions.

Figure 1: Effect of all intervention combined for fattening pigs.

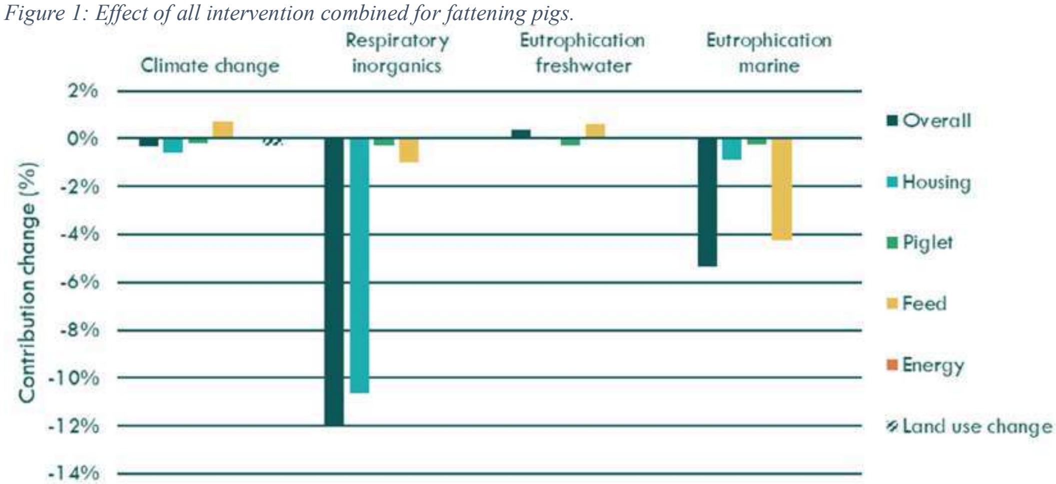


Figure 2: Effect of all intervention combined for dairy cows.

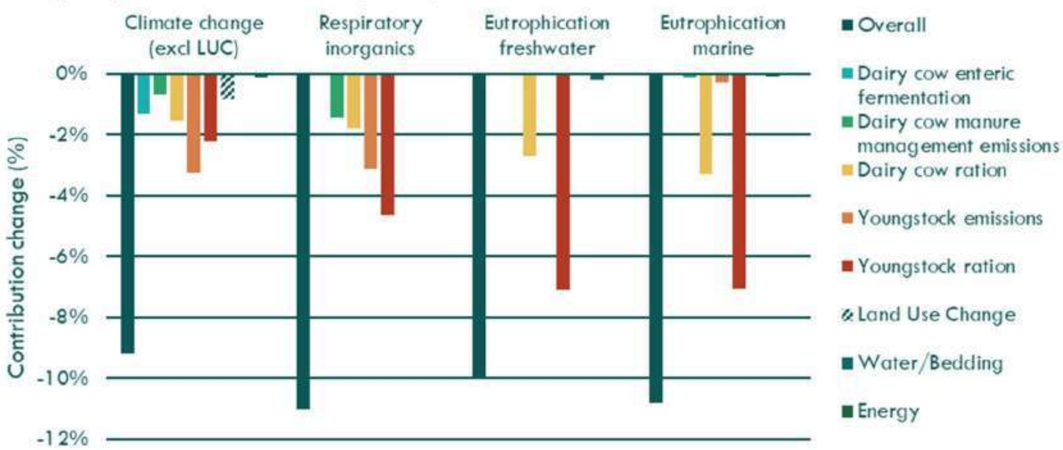
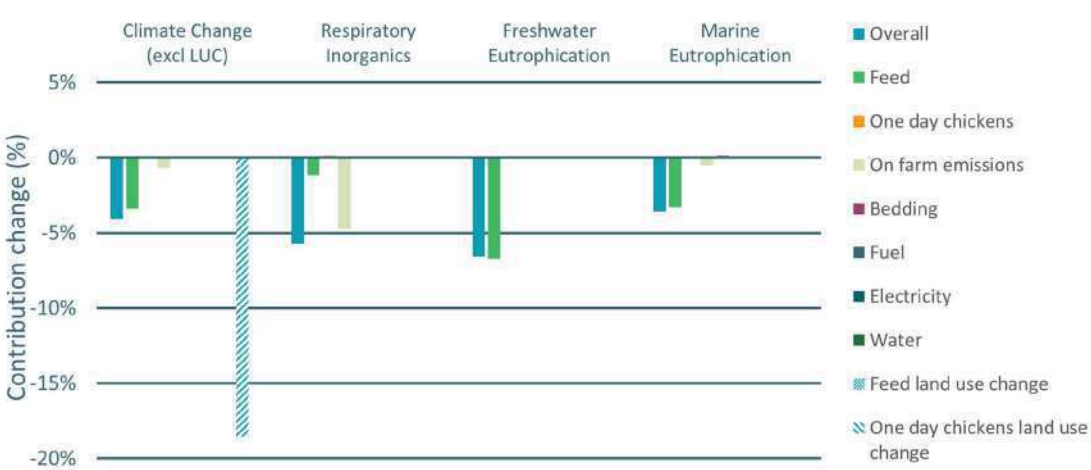


Figure 3: Effect of all intervention combined for broilers.



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LCA and cost calculation tool for SUstainable INsect CHAINs

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Keywords: Life cycle assessment, Modular design, Web-based tool, Life cycle inventory

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Abstract

Purpose
Introducing insect protein into the food system has been recommended as a promising solution for securing future food security while reducing adverse environmental effects associated with food production. However, the market for edible insects in Europe is still small, and a generalized tool is needed to ensure the sector's sustainable scaling. Applying heuristic algorithms with life cycle assessment (LCA) is a promising approach to efficiently optimize the insect production chain and minimize the environmental impact in a very large design space. Developing a web-based tool integrating a heuristic digital approach can contribute to overcoming barriers to insect production's economic and sustainable viability by performing scenario analyses and optimization along the insect production chain that leads to many alternative life cycles. Applying the modular approach to the multi-objective decision-making process through a simplified web-based tool can provide not only means for the estimation of environmental impacts of insect production for food and feed but also introduce basic principles of sustainable trade-offs to the industrial stakeholders. Such an approach can contribute to a sustainable scaling of the insect production sector.

Approach
The research relied on a modular LCA approach (Steubing et al. 2016) and scenario life cycle inventory (LCI) databases combined into a single superstructure database (Steubing and de Koning 2021) to analyze the production of multiple insect species (*Acheta domesticus, Musca domestica, Hermentia illucens, Tenebrio molitor*). The production system for each insect species was divided into 29 module variants that could be combined into 4608 distinct product scenarios for each species (Spykman et al. 2021), which allowed us to compare 18432 scenarios with different feeds, processing and utilities, type of end product, packaging and scaling options. These options were used to aggregate module results into production scenario results. The modular parametric optimization tool combining modular LCA cost, environment, and social impacts and multi-objective optimization further extended to simultaneous analyses of multiple insect types and production scenarios to test the sensitivity of results. Country-specific optimal scenarios and hotspots supporting industrial-scale production of insects were also explored.

Results and Discussion
Different species environmental impacts and cost values are shown in Table 1; all insects reared on plant residues subject to blanching and microwave drying processing were packaged in polyethylene foil (LDPE). *Tenebrio molitor* has the lowest carbon emissions despite the high non-renewable energy use as compared to *Hermentia illucens*. The most eco-efficient scenario of insects

in Europe was for production of house cricket (*Acheta domesticus*) because its production was both environment, energy, and cost-efficient.

Table 1: Some environmental impacts and cost of per ton raw insects' production

Species	GWP, $kgCO_2$ eq	Non-renewable energy, MJ	Land use, m^2	Water use, m^3	Cost, Euro
Acheta domesticus	429.17	929.01	48.51	205.66	270.78
Musca domestica	445.90	5190.03	54.03	301.07	276.93
Hermentia illucens	445.90	929.01	0.97	0.03	51.28
Tenebrio molitor	209.01	7333.00	8.34	272.28	276.93

The online tool as shown in Fig 1, based on modular scenarios, allowed for quick estimation of the most promising production scenarios for every of the four insect species, relying on limited available options for each stage (module) of production. Moreover, it allowed us to define the recommendations for the improvements associated with the type of feed and processing (the main processes responsible for high environmental impact and cost).

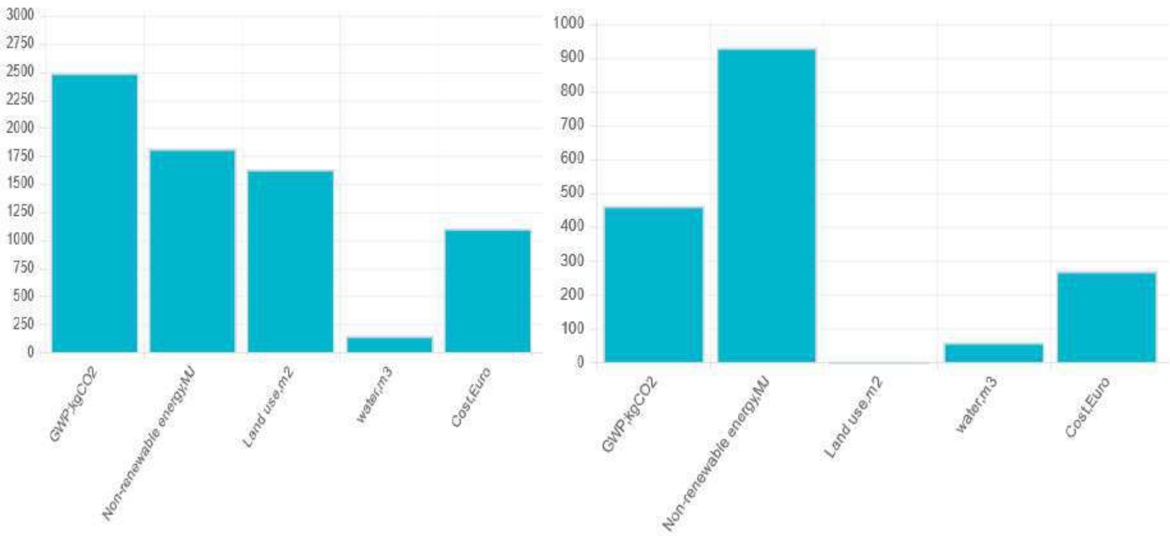

Figure 1: Left- Poultry feed as feed, Right- Plant residues as feed; Environment impacts and cost

If poultry feed is applied, it should be replaced by milling by-products, brewery grains, or plant residues, as poultry feed is more expensive and has higher environmental impacts than residues and by-products. Using electricity instead of natural gas considerably reduced the environmental impacts of production. The combination of scenarios can potentially provide the eco-efficient production life cycle for each species considered.

Conclusion

The developed web-based modular assessment tool assesses multiple potential sustainable scenarios of insect production. It also shows process-type recommendation options that can possibly reduce environmental impact and production cost. Using a superstructure database removes the limitation of redundant storage of LCI database information and simplifies the complex scenario analysis process. The results are sensitive to methodology selection, so they need careful consideration and communication during the design of the modular assessment system.

Acknowledgments

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Environmental impact of *Tenebrio molitor* rearing. A case study in Spain

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Keywords: *Life cycle assessment; edible insects; entomophagy; Tenebrio molitor; Spain.*

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Introduction

Around 2,385 species of edible insects are consumed worldwide, together with 15 species of arachnids (Jongema, 2017). Approximately 2 billion people consumes insects in traditional diets, where México stands out as the country with the greatest consumption (around 549 different species) followed by China, Thailand, and India (Jongema, 2017; Baiano 2020; FAO 2013). Wild harvesting is the most common way to obtain edible insects, in fact, 92% of the know edible insects are collected in this way, the remaining 6% correspond to semi-domestication systems, and only 2% of the consumed edible insects are reared (Yen, 2015).

The production of quality protein is one of the challenges to be faced in the next future. Among the alternative protein sources, different authors agree that insect consumption by humans should be promoted as they provide a high protein content per kilogram, also supplying other nutrients such as fats, calcium, iron, and zinc (Govorushko, 2019; van Huis, 2013). According to Govorushko (2019), insect farming has some advantages compared to other protein sources, among them, farm management is relatively easy, with lower space and water requirements than conventional animal farms and greater food conversion efficiency in a short time, which translates into a fast return of investment. Along these lines, the production of insects for human food purposes can allow the Sustainable Development Goals (SDG) to be met, specifically SDG 2, zero hunger, and SDG 12, responsible consumption, and production.

Nowadays, insect farming is increasing, with more companies taking a chance on this commodity. Considering that edible insects are claimed to be more environmentally friendly than conventional protein sources, assessing their environmental impacts is crucial to detect potential hot spots and improve the environmental profile of the product. Therefore, the aim of this study is to assess the environmental impacts of *T. molitor* rearing process in a medium scale farm located in Spain by using Life Cycle Assessment (LCA).

Methods

An LCA was carried out in accordance with ISO 14040 and 14044 standards (ISO, 2006 a, b). The farm has produces 1000 kg of fresh larvae per week, and the cycle of the insects takes 5 weeks. The percentage of protein in the fresh larvae is 18.9%, with a conversion ratio of 3.5 kg of feed per kg of fresh larvae. The system inputs are the insects' feed, namely carrot by-products and wheat, and the electricity for heating; as a result, the desired product, fresh larvae, is obtained together with the frass, composed of excretions, dead insects and feed remain, which is given away to be used as fertilizer.

The functional unit used for this LCA was 1 kg protein and cradle to farm gate system boundaries were set. As concerns the frass, the avoided loads of producing conventional N, P_2O_5 and K_2O fertilizer were accounted for, by considering its N content (3.29% wet basis), P_2O_5 (3.88% wet basis) and K_2O (2.95% wet basis). As the carrots used are a by-product from agricultural activity, an economic allocation was considered by considering the price and mass percentage of both, the commercial grade carrots, and the by-products. The price of the carrot by-product was retrieved from the insect producer whereas that of commercial grade carrot from the Spanish Department of Agriculture (MAPA, 2022). The mass percentage of both types of carrots was obtained from Ríos (2001).

To carry out the inventory analysis, primary data on the farming process (feed and electricity inputs, and frass and fresh larvae outputs) were obtained directly from the company. For the background processes (production of Spanish electricity mix, carrots, and wheat), secondary data were retrieved from Ecoinvent database v3.7 (Wernet et. al., 2016). Eighteen impact categories were assessed by using ReCiPe 2016 v1.1 Midpoint (H) method (Huijbregts, et. al., 2017).

Results and discussion

The environmental impacts of *T. molitor* rearing are shown in Table 1. As expected, when considering the avoided loads associated with the use of frass as organic fertilizer, the impacts decrease in most of the impact categories. For example, for climate change, a 31.75% decrease in the total impact with respect to that without considering the avoided loads is observed, while the decrease observed in the total terrestrial ecotoxicity value is 70.57%.

Table 1. Environmental impacts of *T. molitor* from cradle to farm gate. Avoided loads correspond to the use of frass as organic fertilizer.

Impact category	Unit	Impacts	Avoided	Total impact
Climate change, default, excl biogenic carbon	kg CO_2 eq. · kg protein^{-1}	7.1	-2.2	4.8
Fine Particulate Matter Formation	kg PM2.5 eq. · kg protein^{-1}	$9.7 \cdot 10^{-3}$	$-2.7 \cdot 10^{-3}$	$6.9 \cdot 10^{-3}$
Fossil depletion	kg oil eq. · kg protein^{-1}	1.9	$-8.8 \cdot 10^{-1}$	1.1
Freshwater Consumption	m^3 · kg protein^{-1}	4.3	$-4.5 \cdot 10^{-2}$	4.3
Freshwater ecotoxicity	kg 1,4 DB eq. · kg protein^{-1}	$3.2 \cdot 10^{-1}$	$-1.1 \cdot 10^{-1}$	$2.1 \cdot 10^{-1}$
Freshwater Eutrophication	kg P eq. · kg protein^{-1}	$1.7 \cdot 10^{-3}$	$-5.6 \cdot 10^{-4}$	$1.1 \cdot 10^{-3}$
Human toxicity, cancer	kg 1,4-DB eq. · kg protein^{-1}	$3.6 \cdot 10^{-1}$	$-1.8 \cdot 10^{-1}$	$1.8 \cdot 10^{-1}$
Human toxicity, non-cancer	kg 1,4-DB eq. · kg protein^{-1}	9.8	-2.2	7.63
Ionizing Radiation	kBq Co-60 eq. to air · kg protein^{-1}	$3.1 \cdot 10^{-1}$	$-1.4 \cdot 10^{-1}$	$1.7 \cdot 10^{-1}$
Land use	Annual crop eq.·year · kg protein^{-1}	$2.4 \cdot 10^{+1}$	$-9.6 \cdot 10^{-2}$	$2.4 \cdot 10^{+1}$
Marine ecotoxicity	kg 1,4-DB eq. · kg protein^{-1}	$3.8 \cdot 10^{-1}$	$-1.4 \cdot 10^{-1}$	$2.4 \cdot 10^{-1}$
Marine Eutrophication	kg N eq. · kg protein^{-1}	$2.8 \cdot 10^{-2}$	$-3.3 \cdot 10^{-4}$	$2.7 \cdot 10^{-2}$
Metal depletion	kg Cu eq. · kg protein^{-1}	$4.1 \cdot 10^{-2}$	$-5.0 \cdot 10^{-2}$	$-9.9 \cdot 10^{-3}$
Photochemical Ozone Formation, Ecosystems	kg NO_x eq. · kg protein^{-1}	$2.3 \cdot 10^{-2}$	$-4.3 \cdot 10^{-3}$	$1.9 \cdot 10^{-2}$
Photochemical Ozone Formation, Human Health	kg NO_x eq. · kg protein^{-1}	$2.3 \cdot 10^{-2}$	$-4.1 \cdot 10^{-3}$	$1.9 \cdot 10^{-2}$
Stratospheric Ozone Depletion	kg CFC-11 eq. · kg protein^{-1}	$7.3 \cdot 10^{-5}$	$-4.0 \cdot 10^{-6}$	$6.9 \cdot 10^{-5}$
Terrestrial Acidification	kg SO_2 eq. · kg protein^{-1}	$3.4 \cdot 10^{-2}$	$-9.9 \cdot 10^{-3}$	$2.4 \cdot 10^{-2}$
Terrestrial ecotoxicity	kg 1,4-DB eq. · kg protein^{-1}	$1.2 \cdot 10^{+1}$	-8.5	3.5

Feed production is the stage that contributes the most to all the impact categories (Figure 1). In particular, the share of wheat production ranges from 64.77% of the total fossil depletion impact, to 96.96% of the total freshwater consumption. The production of carrots has a lower impact than wheat production because, as commented in the methods section, the carrots used are a by-product. The production of electricity has also a remarkable contribution across the assessed impact categories, ranging from 0.06% of total marine eutrophication to 30.53% of fossil depletion.

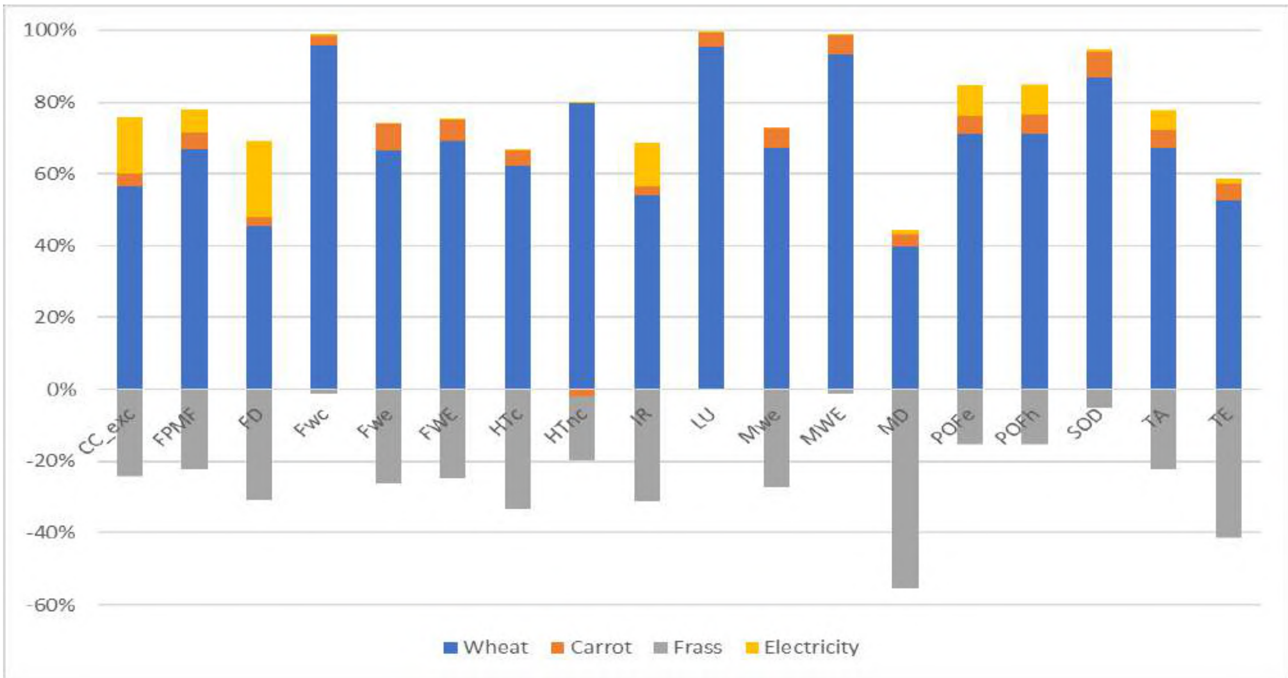

Figure 1. Impact contribution analysis of 1 kg protein of *T. molitor*, larvae. Climate change, default excl biogenic carbon (CC_exc), fine particulate matter formation (FPMF), fossil depletion (FD), freshwater consumption (Fwc), freshwater ecotoxicity (Few), freshwater eutrophication (FWE), human toxicity cancer (HTc), human toxicity non-cancer (HTnc), ionizing radiation (IR), land use (LU), marine ecotoxicity (Mwe), marine eutrophication (MWE), metal depletion (MD), photochemical ozone formation ecosystems (POFe), photochemical ozone formation human health (POFh), stratospheric ozone depletion (SOD), terrestrial acidification (TA), and terrestrial ecotoxicity (TE).

The climate change value obtained in this study has been compared with those for other protein sources from literature, inasmuch as, it is the most commonly assessed impact category due to its great concern worldwide. In particular, the score of *T. molitor* obtained in this study is 1.35 kg CO_2 eq / kg protein, while that for *Acheta domesticus* (crickets) is 2.57 kg CO_2 eq / kg protein (Halloran et al., 2017) and 374.72 kg CO_2 eq / kg protein for pig (Lamnatou et. al., 2016).

Conclusions

The environmental impacts of *T. molitor* rearing of a medium-scale farm located in Spain have been assessed. Feed production is the stage that contributes the most to the all the environmental impacts. In particular, the production of wheat shows the greatest contribution, as the carrots used are a by-product from agriculture and an economic allocation is applied to estimate their environmental impact. The use of frass as fertilizer shows to be an interesting management strategy from the environmental point of view, otherwise the greater impacts would be obtained. To reduce the environmental impacts, a good design of feed composition is required. Along these lines, the use of by-products from agriculture or food processing is recommended, contributing in this way to foster circular economy. However, shifts in the feed composition can imply potential shifts in the insect yield and in its protein content, which in turn would affect the impact results. In addition, frass composition could also change, influencing the total impacts too. Strategies such as self-production of energy with renewable methods would also decrease the environmental impacts of the process, as the electricity production is the second largest contributor to environmental impacts after the production of wheat. Comparisons with other animal commodities show that *T. molitor* is a low impact protein source. Assessing the whole supply chain of Tenebrio, including further processing, could give a better insight on the impacts of this insect. In addition, the inclusion of alternative functional units (e.g. € earned, or protein bioavailability) is recommended in future studies.

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Allocation of pre-crop effect in LCA of crops in cultivation sequences

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Rationale Field crops are commonly grown in sequences or rotations where different species are placed at specific times in order to capture benefits from changes in such factors as chemical and mechanical inputs, and breaking the disease cycles of the major crops. Legumes offer an additional benefit of biological nitrogen (N) fixation, so they not only need minimal input of N fertilizer but also, they leave N-rich residues that may reduce the need for nitrogen input on the following crop. According to Costa et al. (2020), in Life Cycle Assessment (LCA) the pre-crop effect is typically either overlooked or counted as a benefit for the following crop. Black box assessment, multiple product- or area-based functional units have been proposed for the assessment of crop rotations (Knudsen et al. 2014, Naudin et al. 2008, Nemecek et al. 2008). Yet, when the environmental information is to be used in communicating single product sustainability, results for separate products are needed. ***Objective*** In this study, the objective was to assess the climate change impact as carbon footprint (CF) of selected crop sequences and to analyze the impact of different allocations of the pre-crop to pre-crop effect. The aim was to identify a reasonable method for allocation when assessing CF for single crops cultivated in sequences containing legumes. ***Approach and methods*** An LCA model was constructed to assess the CF from crop sequences by utilizing IPCC methods for quantifying direct and indirect N_2O emissions from fertilization, N_2O from peat decomposition and CO_2 from liming (IPCC 2006, 2013, 2019). Emissions from input production and use were included. Assessment was conducted for a set of crop sequences that were considered as typical for a livestock farm. The aim was to assess all crops in the sequence separately, to provide a CF per crop with a functional unit (FU) of 1 kg of produced crop (as fed). Two approaches were compared: typical and allocation approach. The system boundary was set from cradle to farm gate. Crop cultivation characteristics were included as described in Hietala et al. (2022) and were considered to represent typical Finnish feed crop cultivation. For this study, the shares of different soil types were set as constant according to average soil types in faba bean cultivation in Finland. The studied crop sequences were four to six years long and designed around typical Finnish rotations together with one of the Leg4Life project field experiment sequences: Typical: continuous cereal (CC, barley-barley-wheat-barley-barley-oat), Typical: single break bean (SBB, barley-barley-faba bean-wheat) and Experimental: high bean content (HBC, faba bean-wheat-faba bean-turnip rape-faba bean-wheat). The amount of N left in soil after faba bean was estimated to be 20-70 kg ha^{-1} and the level for this analysis was set at 35 kg ha^{-1}. It was assumed that the input fertilization level of the following crop would be reduced by the amount of the residual N. Three approaches were used: 1) without allocation, 2) with allocation to pre-crop and residual N together with 3) black box assessment for pre-crop and benefiting crop, utilizing allocation to crops as co-products. The allocation was conducted in parallel by utilizing physical mass, economic and biophysical allocation based on N yield or fertilization rate (kg N/kg FU). For the mass allocation, the basis was the mass of the yield of the crop and the mass of the N residue.

For the economic allocation, the allocation basis was the 5-year market price of the crop and the residue value was assumed the same as price of mineral fertilizer. Nitrogen yield based allocation was determined based on nitrogen content of the harvested crop and the residue.

Results and discussion The assessment result for CC presents a typical situation without any pre-crop effect related to N residue (Table 1). This CF level was defined as the upper limit for cereal CF when different allocations were investigated. SBB and HBC without allocation illustrated the typical assessment of singular production years when the pre-crop effect is accounted as a benefit for the following crop. In both cases, the wheat CF per FU was lowered. With a co-product approach, the N residue amount was treated as a product, to which emissions were allocated. All allocation approaches resulted in lowered emissions for faba bean and increased emissions for the following crop, in comparison to the no-allocation approach. Allocation based on N yield resulted in higher CF per FU for wheat than the upper limit based on CC. In HBC for turnip rape, the CF per FU remained below the reference value (1.06 kgCO_2-eq / FU, without pre-crop), resulting in the lowest CF with mass allocation and the highest with allocation based on N yield.

Table 1. Assessment results of CF as kgCO_2-eq / FU for three different crop sequences with different allocation approach. (CC=Continuous cereal, SBB=Single break bean, HBC=high bean content).

	CC	**SBB**	**HBC**	**SBB and HBC**		
	No allocation			*Co-product approach*		
				Mass	**Economic**	**N yield**
Barley	0.47	0.47	-	0.47	0.47	0.47
Wheat	0.55	0.50	0.50	0.51	0.52	0.56
Oat	0.45					
Faba bean		0.42	0.42	0.41	0.40	0.32
Turnip rape			0.86	0.87	0.90	1.01

It was also investigated whether assessment could be conducted without information on residual N amount. The pre-crop and benefiting crop were observed as a black box, yet the N fertilization of the following crop was still lowered by the assumed 35 kg / ha. To achieve separate results for each crop in the system, the result per ha was allocated to co-products based on their mass, value, nitrogen yield and fertilization rate. The mass, economic and N yield allocation resulted in elevated CF for faba bean, whereas the fertilization rate-based approach yielded lowered CF for the legume and increased CF for the following crop. Nevertheless, the upper limits for the cereal or turnip rape CF were exceeded, so the approach was found to be unreasonable.

Conclusions It is evident that the legumes in crop sequences benefit the following crops, which should be considered in LCA. Here, three different crop sequences were analyzed with typical and allocation methods (co-product and black box). Allocation based on economic and mass bases had little impact on the results, and that based on the N yield of the pre-crop and residue yielded clearer differences. With the black box approach, no satisfying method could be identified. Thus, in the further analyses, more detailed data collected from specific crop sequence experiments is to be utilized to rerun the comparison of approaches.

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Comparative LCA of low crude protein strategy in broiler and swine production systems in Germany and England.

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Livestock production is facing numerous sustainability challenges such as how to reduce climate change, eutrophication and acidification. In this context, improving the nitrogen (N) efficiency of animal production systems allow to improve their overall environmental performance. More specifically, this study analysis, through the Life Cycle Assessment (LCA) methodology, the impact of reducing crude protein (CP) content in pig and broiler diets, formulated using new amino acid solutions. Two conventional production systems were selected: a broiler system in South England and a pig production system in North of Germany. These livestock systems and countries were selected because they are highly specialized, representative of the local context and located in areas highly subjected to environmental and social pressure. The goal of this study was to conduct an LCA to calculate and analyze the cradle-to-gate environmental performance of the mentioned production systems, while comparing control and low CP diets. Comparison of different animal systems and regions was not intended and in scope. The present study is, to our knowledge, the first study evaluating the full benefits of a reduction of dietary CP using LCA results of all types and origins of feed-grade amino acids (AA) in the broiler and swine life cycle inventory (LCI).

This LCA study was reviewed according to ISO 14040/44 and aligned, where possible, with the UECBV Red Meat FCR, the LEAP poultry, the LEAP additive, and the LEAP nutrient guidelines. The LCA reference unit for the broiler and pig systems was 1 kg of live weight (LW) at farm gate. Pig and broiler systems were modelized based on current practices in North of Germany and South England, respectively. Agri-Footprint 5.0 dataset was used for secondary data for breeding animal farm, feed ingredients (except AA) and utilities for production. Piglets were reared to an average weight of 28 kg and then were grown to an average weight of 123 kg. Multiple compound feeds were used depending on the growth phase: pre-starter, starter, grower 1, grower 2 and finisher. For broiler, one-day old chicks were purchased and grown for 41 days to an average target weight of 2.5 kg, with a 3-phase feeding scheme: starter, grower and finisher. The baseline diets were formulated based on digestible AA ratios to Lysine (Lys) for all indispensable AA (Threonine (Thr), Methionine + Cysteine (M+C), Tryptophan (Trp), Valine (Val), Isoleucine (Ile), Arginine (Arg), Leucine (Leu) for broilers and Thr, M+C, Trp, Val, Ile, Leu and Histidine (His) for pigs) according to the requirement values used in the respective areas. The baseline diets, together with nutritional constraints, consider specific raw ingredients prices and availability based on May 2021. Final feeds were formulated with least cost formulation with Allix3. In this study, soybean was incorporated into the diet through two types of ingredients: soybean meal and soybean oil. In Agri-footprint database, the origin of ingredients was modelled through market mixes. The market mix was based on publicly available data FAOstat (FAO, 2018, 2019). The results were assumed to be representative of the actual origin of agricultural commodities in a given country. Out of the 19 impact categories calculated according to Environmental Footprint 2.0 method, some were analyzed in detail: climate change and climate change excluding land use change (LUC), acidification terrestrial and freshwater and eutrophication terrestrial. Monte Carlo analyses were performed with uncertainty analyses on crops cultivation yield, LUC emissions at soybean cultivation and feed conversion ratio at animal farms. It was carried out as implemented in SimaPro 9.1.1.1, by performing 1000 runs, with a fixed seed of 0.

The main change to the systems when optimizing fee-grade amino acids was a reduction in the dietary CP content (LCP scenario) of 1%pt. Dietary CP was reduced from the baseline level by setting a maximum on the dietary CP constraint before running a least-cost optimization. As all indispensable AA were constrained in ratio to Lys (AA/Lys) and the feedstuffs were freely optimized, the soybean meal was partially replaced by wheat and feed-grade AA. In the low CP diets, newly available feed-grade AA were needed to maintain adequate levels of the next limiting dietary AA: L-Val, L-Arg and L-Ile for broiler formulation and L-Ile, L-Leu and L-His pig and piglet formulations. Broiler and pig average diets are illustrated in table 1 below:

Table 1: Broiler and pig average diets for control and low crude protein scenario.

Broiler average diet (kg/ton)	Control	LCP		Pig average diet (kg/ton)	Control	LCP
Wheat	568	611		Grains (wheat, barley, maize, rye, wheat bran, wheat distillers' grain)	832	871
Soybean meal	257	219		Soybean meal	77	54
Protein meal (rapeseed, fish)	79	79		Rapeseed meal	35	22
Soybean oil	44	35		Soybean oil	22	13
Premix and minerals ($CaHPO_4$, $CaCO_3$, $NaHCO_3$, NaCl)	47	46		Premix and minerals ($CaHPO_4$, $CaCO_3$, $NaHCO_3$, NaCl)	26	28
Free AA (Met, Lys, Thr, Val, Ile, Arg)	6	10		Free AA (Met, Lys, Thr, Val, Ile, Trp, Leu, His)	9	11
Crude Protein (%)	20.2	19.3		Crude Protein (%)	14.6	13.7
Digestible Lys (%)	1.11	1.11		Digestible Lys (%)	0.86	0.86
AMEn (kcal/kg)	3017	2987		Net Energy (kcal/kg)	2379	2379

As part of a sensitivity analysis, AA origin was switched from Europe (Baseline EU) to China (CN). LCI data on the production of the AA were provided by METEX NØØVISTAGO, and previously validated in an ISO-conform LCA peer-reviewed study CN AA used in the sensitivity analysis were modelled using the inventory to produce feed grade amino acid by fermentation: carbohydrates, ammonia, chemicals, electricity, and steam adapting the background data to China. These results indicated strong differences between AA impact categories depending on area of production as illustrated in table 2 for the most important amino acids. For climate change impact, the main explaining factor of the differences between the two origins is the low carbon footprint of the EU source of sugar (sugar beet) and of the energy mix.

Table 2: Amino acid impact factors depending on location of production for climate change, eutrophication terrestrial and acidification.

Impact factor per ton of amino acid		Climate change	Eutrophication, terrestrial	Acidification
RAW MATERIAL	ORIGIN	kg CO2 eq	mol N eq	mol H+ eq
L-LYSINE HCL	EUROPE	1 859	32	12
	CHINA	9 147	182	79
L-THREONINE	CHINA	10 949	210	99
L-TRYPTOPHAN	EUROPE	4 228	81	37
	CHINA	23 444	467	202
L-VALINE	EUROPE	4 934	63	23
	CHINA	25 062	381	203
L-ARGININE	EUROPE	4 709	68	31
	CHINA	20 115	380	168
L-ISOLEUCINE	EUROPE	12 329	157	53
	CHINA	63 316	945	513

For the broiler fed with control diet a 2.92 and 1.20 kg CO2eq/kg LW for climate change and climate change excluding LUC, 0.038 mol H+/kg LW for acidification and 0.163 mol Neq/kg LW was calculated. Reducing CP reduced strongly climate change by 9.2% (SD ± 1.3%), had no effect on climate change excluding LUC (SD ± 0.1%), reduced acidification and eutrophication by 7.7% (SD ± 0.2%) and 8.0% (SD ± 0.2%) respectively. In case of CN AA, broiler resulted in 2.95 and 1.23 kg

CO_2eq/kg LW for climate change and climate change excluding LUC and minor changes for acidification and eutrophication in comparison to the baseline scenario. Reducing CP in broiler with CN AA reduced climate change by 6.8%, increased climate change excluding LUC by 6.5%, reduced acidification and eutrophication by 5.8% and 7.3% respectively in comparison to the control with AA CN.

The pig baseline resulted 3.71 and 2.64 kg CO_2eq/kg LW for climate change and climate change excluding LUC, 0.068 mol H+/kg LW for acidification and 0.30 mol Neq/kg LW. Reducing CP strongly reduced climate change by 8.1% (SD ± 1.7%), reduced climate change excluding LUC by 0.4% (SD ± 0.0 %), reduced acidification and eutrophication by 9.0% (SD ± 0.2 %), and 9.0% (SD ± 0.2 %), respectively. In case of CN AA, pig resulted in 3.85 and 2.78 kg CO_2eq/kg LW for climate change and climate change excluding LUC, slight increase for acidification and eutrophication in comparison to the baseline scenario. Reducing CP in pig with CN AA reduced climate change by 5.7%, increasing climate change excluding LUC by 2.5%, reduced acidification and eutrophication by 7.6% and 8.3% respectively in comparison to the control with AA CN. Detailed results are in the table 3 and 4 below.

Table 3: LCA results for the broiler system with different AA origin

Broiler - England (per kg live weight)		Baseline - AA EU			AA China			Δ	
Impact	Unit	Control	LCP	Δ LCP vs. control	Control	LCP	Δ LCP vs. control	AA CN vs. AA EU in Control	AA CN vs. AA EU in LCP
Climate change	kg CO2 eq	2.920	2.650	-9.2%	2.950	2.750	-6.8%	1.0%	3.8%
Climate change - excluding LUC	kg CO2 eq	1.200	1.200	0.0%	1.230	1.310	6.5%	2.5%	9.2%
Acidification terrestrial and freshwater	mol H+ eq	0.038	0.035	-7.7%	0.038	0.036	-5.8%	0.8%	2.9%
Eutrophication terrestrial	mol N eq	0.163	0.150	-8.0%	0.164	0.152	-7.3%	0.6%	1.3%

Table 4: LCA results for the pig system with different AA origin

Pig - North germany (per kg live weight)		Baseline - AA EU			AA China			Δ	
Impact	Unit	Control	LCP	Δ LCP vs. control	Control	LCP	Δ LCP vs. control	AA CN vs. AA EU in Control	AA CN vs. AA EU in LCP
Climate change	kg CO2 eq	3.710	3.410	-8.1%	3.850	3.630	-5.7%	3.8%	6.5%
Climate change - excluding LUC	kg CO2 eq	2.640	2.630	-0.4%	2.780	2.850	2.5%	5.3%	8.4%
Acidification terrestrial and freshwater	mol H+ eq	0.068	0.062	-9.0%	0.069	0.064	-7.6%	1.9%	3.4%
Eutrophication terrestrial	mol N eq	0.300	0.273	-9.0%	0.303	0.278	-8.3%	1.0%	1.8%

In both systems the largest contribution to climate change including LUC was feed production: 86% in broiler and 61% in swine, emission at the farm and manure expansion was minor for broiler 2%, but significant in swine with 23%. In broiler, acidification terrestrial and freshwater were mainly driven by ammonia (NH_3) emission at fertilization for feed raw materials: wheat grain, soybean, and rapeseed products. However, for swine it was mostly generated by NH_3 emissions by manure generated at pig and piglet farms.

Reducing dietary CP by 1%pt positively reduced climate change, eutrophication and eutrophication of pig and broiler in their respective system. For climate change, the reduction was connected to the reduction in LUC associated to the vegetal proteins and the oils used in animal feeds. Reduction of soybean meal and oil use, as largely sourced from South America, were contributing mostly to the reduction in climate change. When excluding LUC, the impact related to climate change did not show sensible changes.
For eutrophication and eutrophication, differences were mainly explained by lower excretion of

nitrogen related compounds like NH_3 and nitrous oxide (N_2O) and better N efficiency in the animal systems when reducing CP as illustrated in table 5. These effects are explained by the maintained growth of animals fed with low nitrogen content feeds. These results are in line with Cappelaere et al. (2021) data and valid as long as the nutritional constraints are maintained.

Table 4: Nitrogen (N), ammonia (NH_3) and nitrous oxide (N_2O) excretion by broiler, pig and piglet in function of scenario: control and LCP using EU AA

Animal	Scenario	kg NH_3/kg LW	kg N_2O/kg LW	kg N excretion/kg LW
Broiler	Control	7.12	0.14	16.64
	LCP	6.13	0.13	14.63
	% Change	-14%	-12%	-12%
Pig	Control	11.36	0.4	20.88
	LCP	9.54	0.35	18.09
	% Change	-16%	-13%	-13%
Piglet	Control	8.11	0.33	17.69
	LCP	6.82	0.29	15.58
	% Change	-16%	-11%	-12%

Interestingly, using different origin of AA have an effect on the final LCA results of pig and broiler, especially on climate change: stronger reductions are noticed using EU AA in comparison to CN AA. These differences were explained by the higher climate change (excluding LUC) contribution of CN AA. Differences were as well higher in the LCP scenario when comparing EU AA and EU CN utilizations. These differences were explained by the higher inclusion of AA in the LCP diets in comparison to the control diets. Results of Monte Carlo analyses did not overturned LCA results as all the SD calculated were lower than the means. The robustness of the results was thus confirmed, and we would suggest to further increase such robustness by expanding the number of parameters tested in the Monte Carlo analysis.

In conclusion, this study highlighted that LCP is an interesting strategy to mitigate climate change, acidification and eutrophication impacts of broiler and swine in their respective context of production. The reduction in the climate change impact category calculated in this study was mainly connected to a reduction in soybean-related feed ingredients in the LCP diet as it was substituted with cereals and AA. Amino acid origin of production has an impact of climate change, especially in the LCP scenario. Still, robustness of these conclusions might be increased further to better assess the LUC emissions methodology uncertainty and to better test variability connected to ingredient availabilities, ingredient sourcing and LUC-free certification. The reduction in acidification and eutrophication observed in the LCP scenario were mostly explained by a reduction in N-emissions at animal farm. For acidification and eutrophication, the AA origin has as well an impact that could be interesting to consider in further studies. These reductions hold for the sensitivity and as well as the uncertainty analyses performed. The main limitations affecting the robustness of the acidification and eutrophication results were identified in the variability connected to manure management system and eventual abatement technology in place at farm.

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Pig Farming Under a Life Cycle Thinking Lens: The First Combined Environmental, Economic and Social Life Cycle Analysis

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1. Introduction

The pig production sector has a significant socio-economic weight in the European Union. The EU-27 host a yearly average population of 150 million pigs, which alone accounts for nearly half of total EU meat production. Pork is the most consumed meat in the EU in general and in many member states individually, including Italy, where the supply chain specializes in the breeding of the so-called heavy pig, intended to produce dry-cured hams.
Increasing attention is being paid to the sustainability of food systems both by national and EU policies and by consumers themselves. Animal production chains are particularly under observation due to the environmental problems associated with them. Many environmental studies focused on pig production chains, extensively with the life cycle assessment approach (McAuliffe et al., 2016), in some cases also combined with economic considerations (Pexas et al., 2020). On the other hand, studies that have considered social aspects of the supply chain have been more limited (e.g. Zira et al., 2020).
The aim of this study was to approach the sustainability of the pig farming production system from all three points of view for the first time. This has the dual objective of testing the methodological combination of the three sustainability analyses and highlighting any similarities, shared hotspots or even trade-offs of the different layers and having a more complete view of the supply chain impact. A case study was conducted in Northern Italy (Lombardy region), which concentrates a high share of the country's intensive pig farming, by means of primary data collected from closed-cycle pig rearing farms.
Starting from the results, an alternative scenario was explored in which the introduction of an emerging mitigation technique was tested in order to explore its possible influence on the three layers of sustainability. This is represented by an end-of-pipe air treating technology, currently not widespread in the sector in Italy, which concerns air scrubbing to reduce particularly ammonia (NH_3), and even particulate emissions, from the housing phase (Santonja et al., 2017). The environmental, economic and social consequences associated with NH_3 emissions are, in fact, currently one of the main issues related to pig farming, especially if intensive and located in populous areas such as the Po Valley.
The construction and maintenance of air scrubbers involves the consumption of acid, energy, and materials such as stainless steel, in addition to an increase in the workload for its management and that of a liquid nitrogen-rich effluent that is co-produced by its operation; but at the same time it achieves very high NH_3 emission reduction efficiencies (up to 99%, but in operating conditions it is reasonable to consider efficiencies around 70%), and if it is used with air that recirculates inside the stables it also improves the environment and therefore in theory of the welfare of animals and operators. This study therefore also aims to evaluate, thanks to the alternative scenario, all the pros and cons of this mitigation strategy with a view of its impact as complete as possible.

2. Methods

Questionnaires were set up relating to production, technical, economic performance and social and environmental conditions that could best characterize the farms involved; and compiled by means of field surveys and meetings especially with farmers, and with other actors in the supply chain (e.g., agricultural technicians, agricultural services provider companies, veterinarians). As for the alternative scenario, the primary data collected by the farmers were integrated with data deriving from various experimental campaigns held during the Life-MEGA Project, supported by the EU, aimed precisely at measuring environmental, economic and social consequences from implementation of air scrubber prototypes in Italian pig farms.
The environmental impact was analyzed with the life cycle assessment in a cradle-to-farm gate approach with 1 kg of live weight (LW) produced, ready to be sold to the slaughterhouse, as functional unit. This is in line with similar studies carried out in the literature, as well as consistent with the adopted system boundaries. The inventory data collected directly in the farms were integrated with secondary data related to estimates of emissions from animals (enteric and manure management), while background data were retrieved from the established Ecoinvent® database (Wernet et al., 2016). The final inventory was characterized with a midpoint perspective impact assessment. For more details, refer to Conti et al. (2021) where the LCA study of one of the farms is described in detail.
For the economic side, a cash flow analysis was used taking into consideration all the costs and revenues of the farms involved during a year. Therefore, both the consumables and raw materials used, the cost of labor and services, the depreciation of capital goods, and company production and sales were considered.
The social analysis was performed using with the social-LCA method. To this end, the UNEP guidelines (UNEP / SETAC, 2020) were followed and adapted to the present case study, selecting a series of indicators for the sector, related to four stakeholders' categories (society, local communities, workers and animals), thanks to an in-depth literature review. The reference scale approach was then used for analyzing the social inventory. The Reference Scale impact assessment provides a qualitative assessment of the social performance by attributing scores to each indicator considering performance reference points (PRP). PRP are thresholds, targets, or objectives that set different levels of social performance or social risk. In this study, context specific PRP are defined for each indicator, taking in consideration the geographic context and the economic sector. Compared with the respective reference scales, the indicators can be assigned the score: "Committed"; "Proactive"; "Compliant"; "Risky".

3. Results

The achieved results for the environmental side are in line with other LCA studies focused on pig rearing, with a GWP varying between 3.5 and 4.0 kg CO_2 eq/kg LW. Feed consumption is the main environmental hotspot for many impact categories, reaching contributions of 50-70% of the total impact for terrestrial acidification, eutrophication and particulate matter formation, and even greater than 80% for categories related to human and ecosystem toxicity (freshwater). For the GWP the contribution of the feed is lower because also the methane emitted by manure management plays an important role (30-50%).
The feed is also by far the main cost item, varying between 60 and 75% of the total, followed by the costs for work, depreciation capital goods, energy and other factors of production. Given the total production costs which are around 1.1-1.3 €/kg LW, the profit margin is quite low compared to market selling prices. A first consideration that emerges from this result is that farmers cannot easily afford investments to improve environmental and social conditions.
As for the social LCA, the farms involved appeared well aligned with the average social data of the sector, which means that most of the indicators appeared as 'compliant', therefore without a positive or negative impact. Only in a few indicators the analyzed farms demonstrated some social risks (e.g.

hours of on-the-job training), or social commitment (especially as regards the indicators linked to the *Local communities* stakeholder, demonstrating a good integration of the farms in the territory).

3.1 Alternative scenario

From an environmental point of view, on the other hand, trade-offs between different impact categories emerged. For example, as regards the GWP, the alternative scenario slightly increases its impact (although always < 5%) due to the consumption of raw materials for scrubber operation and despite the slight reduction of indirect N_2O emissions (thanks to the avoidance of part of the volatilization and soil re-deposition and denitrification of NH_3). However, impact categories linked to NH_3 emissions such as acidification and PM formation potential noticeably reduce their impact in the order of 10%. The way of modeling the co-production of ammonium solution effluent has an influence on the results. If we consider that this could replace synthetic nitrogen fertilizer otherwise bought externally by the farms, this generates a significant environmental credit. From the economic side, the installation of the air scrubber was estimated with a total cost varying between 3.4 and 17.2 €/pig place/year depending on the operation and removal efficiency. The results from the social analysis scored better for the alternative scenario, which is linked to improved values especially on the animal welfare indicators.

4. Discussion and conclusions

Methodological considerations that emerged with this study concern the fact that social analysis is certainly the one with the greater room for improvement, being the most recent methodology, and not perfectly standardized. It should also be emphasized that the inventory for environmental analysis and that for economic analysis are largely overlapped, reducing the effort of doing a combined analysis. Instead, as far as social analysis inventory is concerned, this is completely different, and it is very time consuming to set up due to the need of categories, sub-categories and indicators selection that are sector specific, and subsequently to the need of defining the social risk or commitment thresholds. Moreover, there is some sensitive information that is not always easily shared by farmers (e.g., regularity in payments, relations with local communities, etc.), which makes data collection slow and difficult. Finally, further development of the methodology is needed because the results from the S-LCA are complex to compare with those of other studies, which somewhat hinders their interpretation.

This study has shown how the pig sector, as well as, more broadly, many others within agriculture, has innumerable facets that determine different trade-offs in terms of sustainable production. Such extensive results, expressed in such a different way and not easily and directly comparable, certainly enrich the understanding of the complexity of a supply chain and highlight its strengths and critical points at different layers. Of course, on the other hand, this does not have to mean that all the results must be put at the same level of importance. It is always necessary to keep in mind the productive and socio-economic-political context within which a supply chain operates, since even this factors influence the choice the right impact mitigation actions to be undertaken.

As for the conclusions with respect to the alternative scenario, from an economic point of view the alternative mitigation scenario does not appear advantageous due to the costs of the tested technology, particularly operation costs, while not returning direct earnings to the farm. On the other hand, this triple layer analysis highlights that if the reduced environmental and social externalities were taken into account, even the "society" economic balance would improve. Future challenges will concern the analysis of how farmers can best exploit these findings economically, with an integrated vision of the three sustainability layers, favoring economic support of public institutions and / or consumers in view of their commitment to the environment.

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Differences in LCA impact between meat types are reduced when ecosystem services related to their production are accounted for

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Rationale and objective of the work

The negative environmental impacts of meat production assessed from LCA (further LCA impacts), is highly dependent on the concerned livestock species. To produce one kilo of meat, LCA assessments indicate that energy consumption and greenhouse gas emissions (GHG) increase from chicken to pork, and from pork to beef (de Vries and de Boer, 2010; Flachowsky et al., 2017).

However, LCA has been criticized for its inability to account for the positive aspects of certain forms of extensive farming, such as organic and agro-ecological farming (van der Werf et al., 2020). This is a limit as this type of farming, such as grass-based beef production, can deliver multiple benefits and ecosystem services (ES) (Dumont et al., 2018; Ryschawy et al., 2019). The permanent grasslands involved in such system can indeed provide, for example, ES of pollination, carbon storage, erosion prevention or recreation (Schils et al., 2022). The LCA impacts of meat of chicken, pork and cattle may therefore differ, or be nuanced, if positive impacts were accounted.

To solve this issue, a new method has been proposed to allocate LCA impacts to the strictly productive services and to other types of services (Boone et al., 2019). For a given production system, productive aspects are assessed according to their relative level of provisioning ES (PES), e.g. ES producing physical goods like grain, wood or meat, and other services are assessed based on their level of regulating ES (RES), e.g. ES contributing to stabilize biophysical processes like climate. This method proposes allocation factors based on the capacity of systems to supply the two types of ES and it has been applied to compare LCA impacts of organic and conventional crop productions. Here we apply the method to the production of chicken, pork and beef.

Approach and Methodology

The allocation factors $f_{prov,s}$ and $f_{reg,s}$ of the production system of livestock species s, are calculated based on the capacity of this system to deliver PES and RES. This capacity is itself quantified according to scores we calculated, and denoted $PES_{sys,s}^{score}$ and $RES_{sys,s}^{score}$, respectively (Eq. (1)-(2)). These scores are normalized and take values ranging from 0 to 5, referring to no capacity to very high capacity of the system to supply a particular ES. This scoring approach is based on the ES score matrix framework proposed by Burkhard et al. (2012).

$$f_{prov,s} = PES_{sys,s}^{score} / (PES_{sys,s}^{score} + RES_{sys,s}^{score}) \qquad \text{Eq. 1}$$

$$f_{reg,s} = RES_{sys,s}^{score} / (PES_{sys,s}^{score} + RES_{sys,s}^{score}) \qquad \text{Eq. 2}$$

The factors initially concern arable land only (Boone et al. 2019), but livestock production systems involves feeding systems with specific land use profiles. We therefore expressed PES_{sys}^{score} and RES_{sys}^{score} based on the scores of each land use (grasslands and croplands). The score of the whole feeding system is then assessed through a weighted average, calculated by weighing grassland and cropland scores by the areas used to produce one kilo of meat (Eq. (3)-(4)).

$$PES_{sys,s}^{score} = (a_{crop,s} \cdot PES_{crop,s}^{score} + a_{grass,s} \cdot PES_{grass,s}^{score})/(a_{crop,s} + a_{grass,s}) \quad \text{Eq. 3}$$

$$RES_{sys,s}^{score} = (a_{crop,s} \cdot RES_{crop,s}^{score} + a_{grass,s} \cdot RES_{grass,s}^{score})/(a_{crop,s} + a_{grass,s}) \quad \text{Eq. 4}$$

Where, for livestock species s, $a_{crop,s}$ and $a_{grass,s}$ are the area of croplands and grasslands, respectively. $PES_{crop,s}^{score}$ and $PES_{grass,s}^{score}$ are PES score of croplands and grasslands, respectively; and $RES_{crop,s}^{score}$ and $RES_{grass,s}^{score}$ are RES score of croplands and grasslands, respectively.

To assess PES scores we used the areas of grasslands and croplands used to produce one kg of chicken, pork and beef (based on Fischer et al. (2014)). We used in this aim an intermediate variable OP, quantifying the overall productive performances. We quantified it considering that the system requiring the less surfaces would be the most efficient, from a productive viewpoint. We derived from cropland and grassland areas an overall productive score to the feeding system OP, by attributing an overall score of 5 (maximum) to chicken systems, as a reference, as they are the most efficient (less area used). We normalized this way our score on a scale of 0 to 5. The scores of our three studied species are expressed by Eq. (5)-(7).

$$OP_{chicken} = 5 \quad \text{Eq. 5}$$

$$OP_{pork} = 5 \cdot (a_{crop,chicken} + a_{grass,chicken})/(a_{crop,pork} + a_{grass,pork}) \quad \text{Eq. 6}$$

$$OP_{cattle} = 5 \cdot (a_{crop,chicken} + a_{grass,chicken})/(a_{crop,cattle} + a_{grass,cattle}) \quad \text{Eq. 7}$$

We finally calculated $PES_{crop,s}^{score}$ and $PES_{grass,s}^{score}$ by breaking down OP_s according to the area of crops and grassland in the feeding system of the concerned species s (Eq. (8)-(9)).

$$PES_{crop,s}^{score} = OP_s \cdot a_{crop,s}/(a_{crop,s} + a_{grass,s}) \quad \text{Eq. 8}$$

$$PES_{grass,s}^{score} = OP_s \cdot a_{grass,s}/(a_{crop,s} + a_{grass,s}) \quad \text{Eq. 9}$$

The values of $a_{crop,s}$ and $a_{grass,s}$ were derived from Flachowsky et al. (2017), who give reference values for systems of different levels of productivity. We chose systems of intermediate productivity for the three species, as our purpose was to account for the differences of species only, without biases that could be induced by management intensity. We then obtained $RES_{crop,s}^{score}$ and $RES_{grass,s}^{score}$ from the matrix of score of Stoll et al. (2015), and considered the scores independent of the livestock species, as we focused on systems of similar management intensity. We finally collected the LCA impacts from de Vries and de Boer (2010), and broke them down according to the allocation factors we calculated.

Main results and discussion

Our calculations of PES scores in croplands returned important differences according to species, with PES score being lower for beef, followed by pork and then chicken (Tab. 1). This gradient is consistent with the feed efficiency of these animals. PES score for grassland is higher for beef than pork and chicken, which is consistent as well, as pork and chicken are not able to digest the forage cellulose (access to grassland is often more justified by animal welfare than productive purposes for these two species). The RES scores are identical according to species, as we chose, and are logically higher for grassland than crops, as they are less transformed habitats.

The overall scores $PES_{av,s}^{score}$ and $RES_{av,s}^{score}$ of the feeding systems, calculated from weighed averages accounting for the relative areas of cropland and grassland (Eq. 3 and 4.), follow opposite gradients. PES increases from chicken to pork, and pork to cattle, whereas RES increases inversely. As a result allocation factors follow gradients where $f_{prov,s}$ increases from chicken to pork, and pork to cattle.

$f_{prov,chicken}$ is 0.84, indicating that the bundle of ES that can be provided by the chicken livestock system considered is mostly of PES type. In other terms, $f_{prov,chicken}$ indicates that this system mostly contributes to the human well-being through meat production. Oppositely $f_{prov,cattle}$ is 0.26, i.e. below 0.5, indicating that the bundle of ES that can be provided by the cattle livestock system considered is mostly of RES type. In other terms, $f_{prov,cattle}$ indicates that this system mostly contributes to the human well-being through its regulating ecosystem services. $f_{prov,pork}$ is also above 0.5 (0.66) indicating that its contribution to human well-being is mostly made through the PES provision. It is however less skewed towards PES that the chicken system.

Table 1: Areas used to produce 1 kg of meat and scores of provisioning ecosystem services (PES) and regulating ecosystem services (RES) related to production system of different livestock species

	Areas used for 1 kg of meat (m^2)			Overall productive score	PES score		RES score		Overall score	
	grassland	cropland	Total		grassland	cropland	grassland	cropland	PES	RES
Beef	25.81	2.98	28.78	0.99	0.89	0.10	2.27	0.73	0.81	2.11
Pork	1.48	11.99	13.47	2.12	0.23	1.89	2.27	0.73	1.71	0.90
Chicken	0.42	5.30	5.72	5.00	0.37	4.63	2.27	0.73	4.31	0.84

The differences of LCA impact along the chicken-beef gradient is two and a half higher for chicken than beef for energy, and six times higher for CO_2-eq. When these differences are reallocated according to the f_{prov} factor, the LCA energy impact gradient is modified with beef having the lower impact, and pork the highest. The LCA CO_2-eq gradient is not modified but the differences of impact that was six fold between chicken and beef, is now reduced to twofold.

Table 2: Allocation factors and LCA impacts allocated and not allocated

Livestock system	Allocation factors		LCA impacts per kg - not allocated		LCA impacts per kg - allocated according to f_{prov}	
	f_{prov}	f_{reg}	MJ	CO_2-eq	MJ	CO_2-eq
Beef	0.28	0.72	50.00	30.00	13.86	8.31
Pork	0.66	0.34	30.00	10.00	19.68	6.56
Chicken	0.84	0.16	20.00	5.00	16.73	4.18

These calculations indicate that depending on the species bred, the production of one kilo of meat induces different bundles of ecosystem services. They show in particular that an important share of the LCA impacts of beef benefits to the delivery of RES. That does not mean that the impact energy or CO_2-eq of kilo of beef should be considered lower than currently assessed, but that this production system also contributes to the delivery of other ES than just PES, such as meat production services.

Integrating LCA and ES frameworks has received significant interest for almost a decade (Brandão and i Canals, 2013; de Baan et al., 2013), and it is still considered incomplete (De Luca Peña et al., 2022; VanderWilde and Newell, 2021). To complete LCA assessments, some authors proposed an additional type of assessment to the usual list of LCA variables (emissions of CO_2-eq, energy consumption, eutrophication, etc…). This proposed additional assessment aims at expressing the damage to ecosystem quality over specific durations and areas, through dedicated equations (Koellner et al., 2013). We used another approach aiming at allocating existing usual LCA impacts according to the contribution of livestock systems to distinct ES. To do this we used allocating factors that describes how balanced are the bundles of ES, between PES and RES.

Our approach contributes to the debate about the impacts of livestock farming in the global food system, which is criticized for its impact on ecosystems, climate and biodiversity. Monogastric animals (chicken and pork) have low CO_2-eq emissions compared to cattle, which is highly penalized by its methane emissions, due grass digestion processes (rumination). Oppositely, cattle and other ruminants can use a significant share of grasslands that are semi-natural habitats that provide interesting levels of RES. These habitats can also be used as refuges of biodiversity. Depending on where society is going to put the priority in addressing climate change or biodiversity crisis, the source of protein and other animal products may differ. As both issues must be addressed simultaneously, a trade-off approach is required, and we think that methods such as the one we present here can help quantifying these trade-offs.

Conclusion

By applying an allocation method, we allocated the usual LCA impacts between those contributing to productive activities of meat, and those contributing to the delivery of other ES of interest. Our approach thus shows how some positive impacts of meat production could be integrated in LCA methods. This approach can describe how balanced are the bundles of ES provided by livestock farming and assess their negative or positive impacts on climate change and ES. We think that such method able to give nuanced assessments and a trade-off vision is important to address the immense sustainability challenges that society and decision-makers are facing.

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Application of market-based feed formulation and LCA to capture actual displacements when integrating new ingredients in compound pig feed

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Abstract

Purpose. In many cases, environmental impact assessment of new ingredients (NI) only considers the ingredient level with assumptions to replace conventional ingredient with closest nutrient composition. For example, replacing soybean meal (SBM) with NI is widely studied. However, the reality is if one feed ingredient is replaced with another ingredient, the whole feed composition will adjust according to the optimization factors that consider nutrient requirement of the animal. This study compares impact assessment results from two approaches of using NI in animal compound feed: 1) using the Scandinavian feed unit (SFU) method which only considers the feed unit factor and 2) the market-based (MB) feed formulation method which considers several factors influencing animal compound feed composition which are the type of animal, its nutrient requirements and the price and nutrient composition of the feed ingredient.

Methodology. This study used market based (MB) method feed formulation to account for the changes in the composition of animal feed when NI is introduced. Three NI were considered in this study: 1) Black soldier fly larvae meal (BSFLM) from food waste, 2) Single-cell protein from methane-oxidizing bacteria (SCP-MOB) fed methane from biogas from anaerobic digestion of manure and 3) Green protein concentrate (GPC) from vegetable leaf and top fractions. In this study, the case of grower-finisher pig (P-GF) pig feed is used as an example. Changes in the P-GF feed upon incorporation of NI were translated to environmental impacts. Feed unit values from SFU method is also translated into environmental impacts based on the corresponding avoided conventional feed ingredients.

Results and discussions. Incorporation rate of NI in the P-GF feed was only until 5% for BSFLM, 4% for GPC and 3% for SCP-MOB. The MB method shows that inclusion of NI reduced wheat and induced additional requirement for other cereals maize and barley. Additional oilseed meals are also induced whenever SBM is reduced. In the entire P-GF feed level, 3% inclusion of SCP-MOB resulted to 16% GWP_{100} reduction in grower feed and 9% reduction in finishing feed. However, both BSFLM and GPC at incorporation rates of 5% and 4% respectively increase GWP_{100} to 13% and 34% in grower feed and 11% and 45% in finisher pig feed. On the contrary when impact assessment is done only up to the NI level using feed unit value from SFU method reduced GWP_{100} of BSFLM, SCP-MOB and GPC by 51, 82 and 20% respectively. This provides optimistic assumptions that NI has potential to reduce impacts of animal compound feed production.

Conclusion. The MB method showed that BSLFM and GPC increased the impacts of the P-GF feed. SFU and MB methods provide contrasting results when NI is used for animal feed wherein impact assessment results have different presentations. The approach of SFU method is on the feed ingredient level while the MB method is on the whole compound feed level.

Introduction

Novel processing technologies converting residual biomass to novel feed ingredients for animal feed provide promising solutions for the increasing demand for alternative feed resources (Santamaría-Fernández and Lübeck, 2020; Javourez et al., 2021). This support circular and bioeconomy ambitions to prioritize residual biomass streams from food waste, agricultural and forestry residues as feedstock for conversion to value added products or energy recovery (Teigiserova et al., 2020; Albizzati et al., 2021). In environmental impact assessment of emerging new ingredients (NI) for animal feed through Life Cycle Assessment (ISO 14044 and 14040, 2006), only few account for digestible energy values of feed ingredients derived from the nutrient functions of digestible values of protein, lipids and carbohydrates as considered by Tonini et al., 2016 using the Scandinavian feed unit (SFU) system developed by Moeller (1980). However, SFU only considers one factor which is the feed unit equivalent therefore, the environmental impact assessment is limited until the ingredient level. To capture actual displacements when integrating NI in animal feed, the evaluation should be applied up to the compound feed level to consider that if an ingredient is removed or added, the whole feed composition will change to meet the nutritional requirements of the animal. A more precise market-based (MB) approach for conducting LCA on animal compound feed production is using feed formulation to account for the changes in the feed composition (Garcia-Launay et al., 2018; Saxe et al., 2018; van Zanten et al., 2018). Feed formulation in this context optimizes feed composition based on ingredient nutrient composition and prices according to the nutritional requirement of the animal and its efficiency to utilize nutrients in the feed.

Although the end goal should be to capture cradle-to-grave environmental consequences associated with the integration of new ingredients, this study only focuses on the cradle-to-gate effect of the compound feed gate by using the case of growing-finishing pig (P-GF) feed as a starting point. Along with the comparison and quantification of environmental performance of P-GF feed with and without NI, another objective is to also show how impact assessment results could vary depending on the approach to account for displacements when using NI for animal feed and which conventional ingredients it could displace, hence this study also presents result comparison of the SFU method and the proposed MB approach.

Methodology

A feed optimization tool developed by Garcia-Launay et al., 2018 with Python 3.7 (Python Core Team, 2015) using the same linear programming principle applied by feed companies was used to compare difference in feed composition upon introduction of new ingredients. The tool provides optimized least-cost feed formulation under constraints of minimum net energy, maximum crude protein and minimum standardized ileal digestible (SID) amino acids with respect to the ideal protein profile. As a primary assessment, the study chose three new feed ingredients: 1) larvae meal (BSFLM) from black soldier fly larvae fed on food waste, 2) single-cell protein from methane oxidizing bacteria (SCP-MOB) utilizing methane in biogas from anaerobic digestion of manure and 3) green protein concentrate from grass or top leafy fractions of vegetables tops or grass. These ingredients represent "waste-to-nutrition" families presented by Javourez et al., (2021). The main selection criteria for NI were based on the following conditions: 1) NI must come from the conversion of residual biomass and 2) NI can be incorporated in animal compound feed. The feed formulation used 2021 prices (euro/ton) of conventional feed ingredients obtained from IFIP-Institut du porc in France. In the case for new NI, the prices of soybean meal (SBM) were used as proxy and a perturbation analysis was carried out to capture the sensitivity of the inclusion of NI to a range of prices. Nutrient and mineral composition, including SID amino acid and net energy values of feed ingredients for growing pigs were based on the French nutritional table INRAE-CIRAD-AFZ but were only limited to conventional feed ingredients. To provide nutrient values for new ingredients the study obtained information from published literatures. Differences observed in the whole pig feed composition upon incorporation of new ingredients were translated to environmental impacts through life cycle inventories (LCI) from Ecoinvent v3.6, Agribalyse v3.0, and own inventories for NI using the Environmental Footprint (EF3.0, 2019) Life Cycle Impact Assessment method.

Results and discussion

Integration of new ingredients in pig feed. The reference 1 tonne P-GF feed is composed of up to of 80% cereals mainly wheat, maize, and barley, at least 7% soybean meal, 10% oilseed meals rape and sunflower and the rest are the oil, premixes, amino acids and additives. Incorporation rate of NI was only until 5% for BSFLM, 4% for GPC and 3% for SCP-MOB. The incorporation of NI reached maximum when given prices as low as 30% of the SBM price (Figure 1). Low incorporation of NI resulted to more to reduction of wheat than SBM. Upon the reduction of wheat in the P-GF feed, other cereals maize and barley reacted to the change in wheat inclusion while oilseed meals reacts to the change in SBM inclusion. On the contrary, using the SFU method, using NI for animal feed allow for reductions of marginal feed ingredients assumed to be maize, SBM and palm oil. 1 kg of BSFLM avoids usage of 0.6 kg of SBM and 0.2 kg maize and palm oil while 1kg of SCP-MOB avoids usage of 0.9 kg SBM, 0.2 kg maize and 0.1 kg palm oil and 1 kg of GPC avoids usage of 0.6 kg of SBM, 0.3 kg of maize and 0.1 kg of palm oil. Figure 2 shows that in MB method, inclusion of NI changes the entire compound feed composition whereas the feed unit values of NI obtained from the SFU method focus only on feed unit equivalent that can estimate which conventional feed ingredient can be avoided.

Impact assessment of integrating new ingredients in pig feed. Table 1 shows selected impact category values for 1 tonne P-GF feed with and without NI for the MB method and impact values of NI for the SFU method. Incorporation rate of 3% SCP-MOB in a tonne of P-GF feed resulted to reduction on environmental impacts compared to the reference P-GF feed. SCP-MOB inclusion resulted to 16% GWP_{100} reduction in grower feed and 9% reduction in finishing feed. However, both BSFLM and GPC at incorporation rates of 5% and 4% respectively induced 13% and 34% increase in GWP_{100} in grower feed and 11% and 45% in finisher pig feed. BSFLM and GPC already had higher environmental impacts compared to other conventional ingredients which is mainly contributed to the electricity used along the production (Smetana et al., 2019; Skunca et al., 2021). Contrary to capturing impacts of 1 tonne P-GF feed, the SFU method has a different approach in assessing environmental performance of NI. The feed unit values of NI obtained from the SFU method focus only on the feed unit equivalent to emphasize its use for animal feed. It estimates which conventional feed ingredient can be avoided. Within the impact assessment, avoided production of marginal feed ingredients maize, SBM and palm oil where considered (Tonini et al., 2016) which resulted to GWP_{100} reduction of BSFLM, SCP-MOB and GPC by 51, 82 and 20% respectively providing optimistic assumptions that NI has potential to reduce impacts for animal feed production.

Conclusion

With increasing interest to find alternative for conventional feed ingredients, it is important that impact assessments for NI be done at the compound feed level to capture changes in the whole feed composition when incorporating NI to animal feeds. Considering feed unit only, the SFU method provides a more optimistic results for NI to reduce impacts on animal feed production. This is in contrary to the MB method wherein BSLFM and GPC increase impacts of the P-GF feed. The study only presented impact assessment until the compound feel level but on-going work is done to capture other consequences caused by the use of NI in animal feed. These include counterfactual use of the biomass before being converted into NI and the possibility of use of NI for other livestock species aside from the pig feed. Further parametric analysis should also be done to support robustness of findings.

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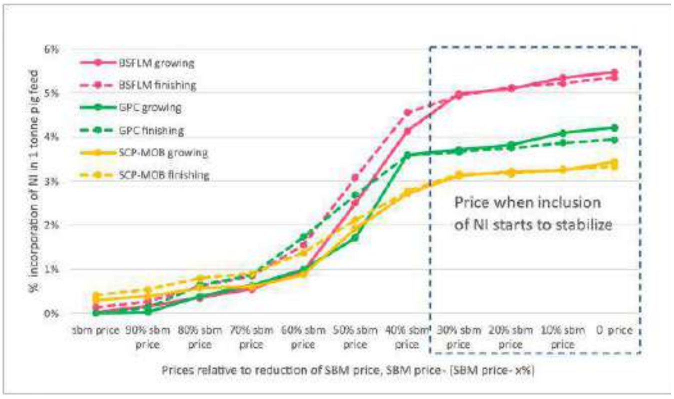

Figure 1. Inclusion of NI with decreasing price (euro/ton) to assess maximum incorporation rate in P-GF feed. Basis of price was the price of SBM in year 2021 that was gradually reduced.

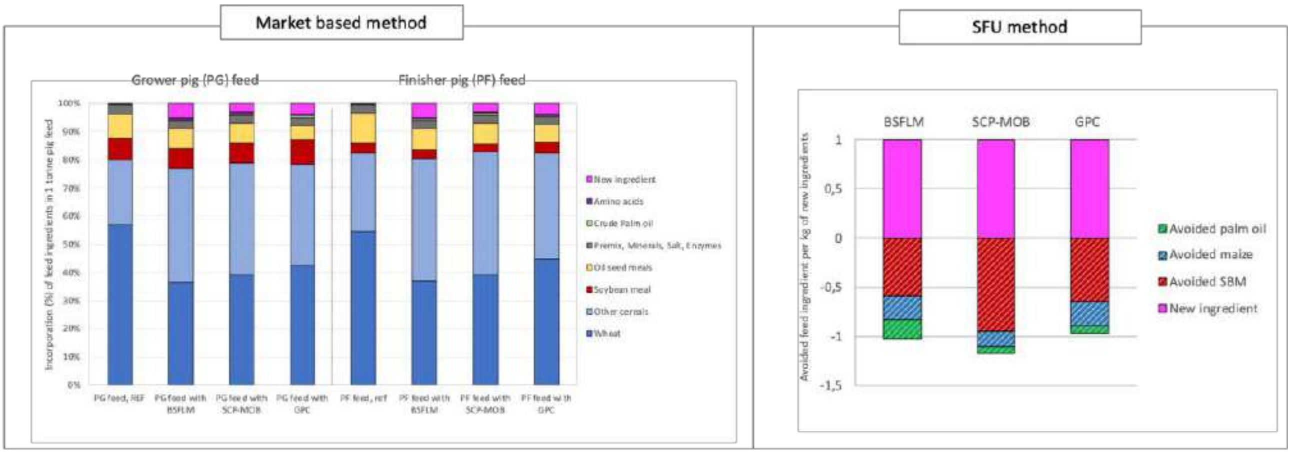

Figure 2. Comparison of MB method vs SFU method. MB captures changes caused by incorporation NI in the compound feed level. SFU method assigned feed unit factors for each NI which allows to estimate conventional feed ingredients that can be avoided wherein 1 kg of NI assumes avoidance of maize, SBM and palm oil.

Table 1. LCA impacts of (a) 1 tonne of grower-finisher pig feed with NI using MB method and impacts of (b) 1 kg NI ingredients only and NI, SFU considering feed unit equivalent and the corresponding avoided conventional feed ingredient. To provide reference for the comparison of impacts of 1kg of NI, impacts of (c) 1 kg conventional ingredient is also presented.

	GWP_{100}, kg CO2 eq	Eutrophication, kg N eq	Acidification,mol H+ eq	Resource use, MJ
	a. Impacts per tonne of grower-finisher pig feed with and without NI			
Grower, ref	1093	6.81	7.95	6079
Grower with BSFLM	1241	7.62	10.48	7901
Grower with SCP-MOB	920	6.80	8.08	5510
Grower with GPC	1469	8.95	16.97	10508
Finisher, ref	1013	6.82	7.98	5923
Finisher with BSFLM	1126	7.70	10.55	7656
Finisher with SCP-MOB	919	6.79	8.09	5504
Finisher with GPC	1469	8.95	16.97	10508
	b. Impact of 1 kg NI vs impacts of NI given feed unit value based on SFU method			
BSFLM	4.43	0.02	0.06	41
BSFLM, SFU	2.18	0.02	0.06	36
SCP-MOB	-0.04	-0.02	0.32	-9
SCP- MOB, SFU	-3.30	-0.03	0.32	-17
GPC	11.67	0.07	0.26	124
GPC, SFU	9.35	0.06	0.25	119
	c. Impacts of 1kg of conventional ingredients			
Soybean meal	3.28	0.006	0.004	6
Maize	0.58	0.004	0.007	5
Palm oil	0.90	0.005	0.003	-2

Analysis of the potential for reducing GHG emissions due to conversion of conventional agricultural systems into integrated farming systems in the state of Goiás-BR.

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Keywords: *Life Cycle Assessment; agroforestry; integrated farming systems; global warming; Goiás.*

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Rationale and objective:

Integrated farming systems are agricultural production systems that aim, primarily, to achieve greater productivity and reduce environmental impacts through the combination of an annual crop, livestock, and/or forestry activities in the same area, over different periods of time (Bieluczyk et al., 2020; Oliveira et al., 2018). It can be performed through intercropping, crop succession, or crop rotation, so that all the activities are mutually beneficial (Embrapa, 2018). In the 2015/2016 harvest, Brazil had approximately 11,47 million ha of integrated crop-livestock-forestry (ICLF) systems, which corresponded to 5.5% of the total area used for agriculture back then (Embrapa, 2016). For the 2020/2021 harvest, it was estimated that this number has increased to about 17.43 million ha, 8.35% of the total (Polidoro et al., 2020).

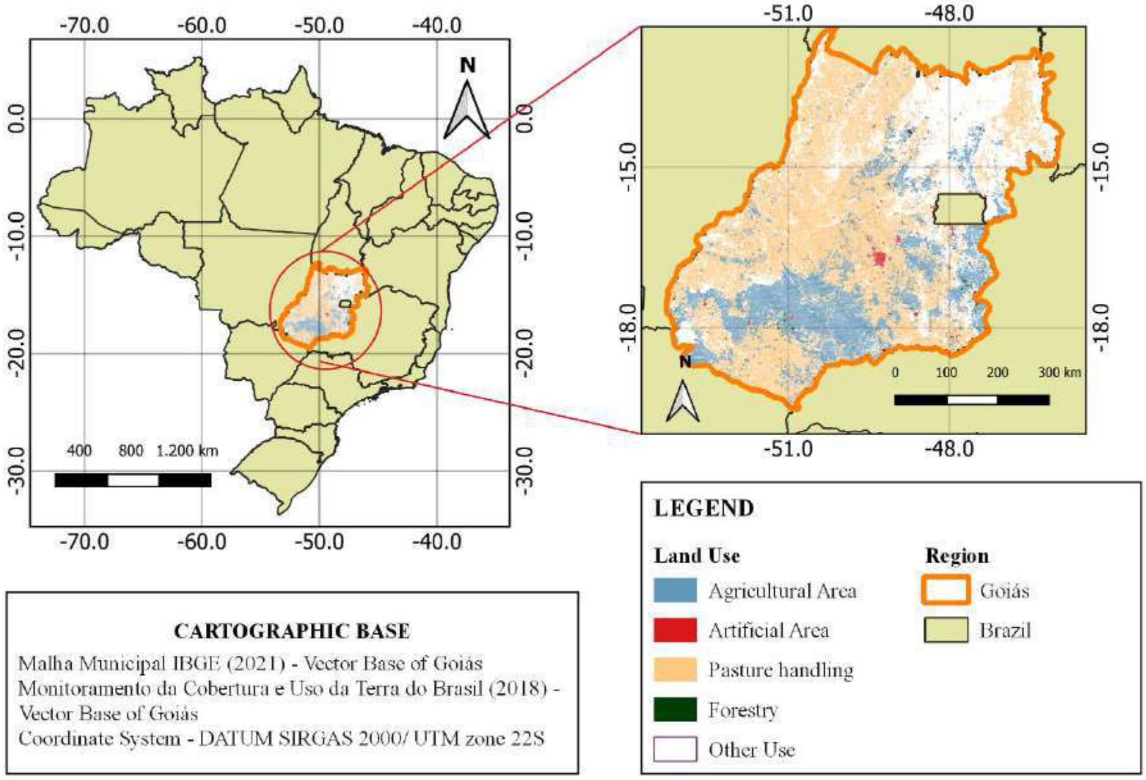
In Brazil, the adoption of ICLF systems was encouraged by the Low Carbon Agriculture Plan Emission (ABC Plan), which established the goal to increase the land area with ICLF by 4 million ha between 2010 and 2020 (Brasil, 2012). After reaching the target even before the deadline, a new phase of the ABC Plan, known as the ABC+ Plan, was launched in April 2021, providing for the expansion of ICLF systems by 10 million ha by 2030. The state of Goiás, one of the most important agricultural producers in the country, has, currently, about 20 million ha of conventional systems of soybean, maize, eucalyptus, and livestock, and 1.43 million ha of integrated farming systems (Rede ILPF, 2021).

This paper aimed to calculate the global warming potential (GWP) of the current agricultural configuration of the state of Goiás for the aforementioned crops and livestock, compared to a hypothetical scenario in which the current agricultural area of the state would be fully converted to an ICLF system, to verify, quantitatively, the reduction of Greenhouse Gases (GHG) emissions.

Approach and methodology:

The area of study is the state of Goiás, which is located in the center-west region of Brazil. A location map of the state of Goiás within Brazil, as well as a map showing the location of agricultural, pasture, forestry, and urban areas, were prepared with geographic data from the Brazilian Institute of Geography and Statistics (IBGE), for the year of 2018 (Figure 1).

Figure 1. Location map of agricultural, pasture, forestry, and urban areas in the state of Goiás - Brazil.



Source: The authors, 2022.

The crops selected for evaluation were soybean, maize, and eucalyptus, as well as livestock (considering only cattle), which together correspond to 63.2% of the total agricultural area used in Goiás. Other crops and livestock were not considered for this study due to the lack of ICLF information on LCA inventory databases (Costa et al., 2018).

Two production scenarios were considered for further comparison. The first scenario, here named "baseline scenario", was the current agricultural configuration for the state of Goiás, considering the production of soybean, maize, eucalyptus, and livestock, with a total area of 20.04 million ha of conventional systems, and 1.43 million ha of integrated farming systems, resulting in 21.48 million ha. Table 1 shows the information on the areas occupied by each production type, as well as the average productivity for each crop in conventional systems.

Table 1. Productivity values for each crop in conventional systems – baseline scenario.

Production type	Area (million ha)	Percentage area in relation to the total agricultural area of Goiás	Average productivity (t/ha.year)
Soybean	3.70	10.88 %	3.70
Maize	1.80	5.29%	6.60
Eucalyptus	0.15	0.46%	17.15
Livestock	14.40	42.35%	0.50
ICLF	1.43	4.22%	4.91
Other production types (not evaluated)	12.52	36.8	-
Total agricultural area for the state of Goiás[1]	34.00	100%	-

Source: Data retrieved from CONAB (2021); Ferreira, Miziara & Couto (2019); SEBRAE (2019); Costa et al. (2018); Rede ILPF (2021).

The second scenario, here named "full ICLF scenario", is hypothetical, in which the entire current agricultural area used in the state of Goiás for the production of soybean, maize, eucalyptus, and livestock, would be converted into ICLF. Table 2 presents productivity values for the full ICLF scenario, for each of the evaluated production types.

Table 2. Productivity values for each crop in an ICLF system – full ICLF scenario.

Production type	Area (million ha)	Average productivity (t/ha.year)
Soybean	21.48	0.27
Maize		0.79
Eucalyptus		3.49
Livestock		0.37

Source: Adapted from Costa et al., 2018.

The LCA method was used to model the global warming potential of the entire agricultural area of soybean, maize, eucalyptus, and livestock in the state of Goiás (baseline scenario). The life cycle inventory was based on secondary data from the ecoinvent® database (version 3.7.1). The life cycle impact assessment (LCIA) was performed with the software openLCA® (version 1.10.3), using the IPCC 2007 method (climate change – GWP 100a). Due to the lack of data on the integrated farming systems in the databases, results by Costa et al. (2018) were used to extrapolate the global warming potential of an existing ICLF system in Goiás (composed of soybean, maize, eucalyptus, and livestock) to the total analyzed area.

Results and discussion:

Table 3 presents a comparison between the total annual production values for the baseline scenario and the full ICLF scenario. Analyzing the values in Table 3, it is possible to observe that there is an increase in total production for all crops, except for soybean, in the full ICLF scenario. The most significant increase was in total eucalyptus production, which totaled 2701% more production than in the baseline scenario. Changes in productivity are directly influenced by specific factors in the distribution and management of crops and livestock over the integrated area and time, such as crop rotation and succession; interactions among the crops; the influence of shading caused by eucalyptus trees on other crops; spacing; climatic and management factors; availability of water and nutrients, among others (Magalhães et al., 2019). The total productivity of the 21.48 million hectares, when cultivated in the integrated arrangement, was higher than when cultivated in the conventional way, which shows that ICLF systems can potentially be more productive if appropriate agroforestry management techniques are applied.

Table 3. Comparison between total production values for the two scenarios.

Production type	Total production - baseline scenario (Mt/year)[1]	Total production – full ICLF scenario (Mt/year)[1]	Absolute increase/reduction (Mt/year)	Relative increase/reduction (%)
Soybean	13.7	5.8	-7.9	-58%
Maize	11.9	16.9	5.0	42%
Eucalyptus	2.7	74.9	72.2	2701%
Livestock	7.2	7.9	0.7	10%
Total production	35.5	105.5	70.0	198%

Source: The authors, 2022. [1]Total production values were calculated based on the data for the average productivity per year, and for the total area occupied by each production type, presented in Tables 1 and 2.

Table 4 shows the values of CO_2eq emitted for the baseline scenario compared to the full ICLF scenario, for each analyzed production, as well as the absolute and relative values of increase or reduction of emissions between the scenarios.

Table 4. Global warming potential contributions for the baseline and full ICLF scenarios.

Indicator	Unit	Eucalyptus	Livestock	Maize	Soybean	ICLF (Costa et al., 2018)	Total emissions
Baseline scenario	Mt CO_2 eq./yr.	0.31	157.00	4.02	29.40	6.04	196.77
[1]Full ICLF scenario	Mt CO_2 eq./yr.	4.88	83.60	11.00	5.49	-	104.97
Absolute reduction/increase	Mt CO_2 eq./yr.	4.57	-73.4	6.98	-23.91	-	-91.8
Relative reduction / increase	-	1466%	-47%	173%	-81%	-	-47%

Source: The authors (2022); [1]Costa et al. (2018).

Table 4 shows that there should be a large increase in CO_2 emissions for the cultivation of eucalyptus in the full ICLF system, at 4.57 Mt CO_2eq./yr., which may be related to the increase in its annual productivity by 2701% when compared to the current conventional production scenario. The increase in emissions also occurred in maize cultivation, at 6.98 Mt CO_2eq./yr. This crop also had its productivity increased when cultivated in an ICLF system.

The reduction of CO_2 emissions related to livestock was significant, at 73.4 Mt CO_2eq./yr., considering that the annual livestock is estimated to increase by 10% when carried out in an ICLF system, and that livestock is currently considered one of the main responsible for the GHG emissions. Soybean emissions were reduced by 23.91 Mt CO_2eq./yr., which corresponds to a reduction of 81%, representing the biggest relative reduction among all the production types. It should be noted that, for the ICLF system, annual soybean production is estimated to be reduced by 58%, which may have had some sort of influence on the results. These results show that the relationship between crop/livestock productivity and GHG emissions is not directly proportional, since while some production types that had their productivity increased in an ICLF system showed a reduction in emissions (*e.g.* livestock), for the others, the opposite occurred.

In the baseline scenario, when jointly producing 21.48 ha of soybean, maize, eucalyptus, and livestock (95.78% of this area in a conventional system and 4.22% in an ICLF system), the total CO_2eq. emissions to the atmosphere resulted in 197.77 Mt CO_2eq./yr. In the hypothetical scenario in which the entire area would be converted to ICLF, emissions totaled 104.97 Mt CO_2eq./yr., which represents a reduction of 91.8 Mt CO_2eq./yr. in total emissions. These results are aligned with one of the goals of the ABC+ Plan, which aims, by encouraging the implementation of ICLF systems, to mitigate greenhouse gas emissions from national agriculture.

Conclusion:

The projection of the implementation of the ICLF system composed of soybean, maize, eucalyptus, and livestock in the agricultural area of the state of Goiás, currently occupied mostly by conventional systems, proved to be environmentally more favorable concerning the impact category "climate change", because its global warming potential was 47% lower than the current agricultural configuration. The best results were found for livestock, since its productivity in an ICLF system was increased and its GWP reduced when compared to the conventional system.

It is important that economic feasibility studies are developed so that the systems are assembled and managed in a way that does not significantly reduce the production capacity of each integrated culture, in order to make the implementation of integrated farming systems increasingly viable. A gradual transition from a conventional system to an integrated system, respecting the climatic and geographic characteristics intrinsic to the production environment, and seeking technical and scientific assistance, is highly recommended so that national agriculture becomes increasingly sustainable and economically beneficial to farmers.

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Regionalized comparison of Canadian and European pulse production and transportation

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Keywords: *life cycle assessment, regionalization, transportation, peas, lentils*

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Rationale: Pulses are an increasingly popular source of plant-based protein among food manufacturers, food service providers, and retailers (Statistics Canada, 2015). They have high nutritional quality (i.e., high in protein and fibre, and low in fat) (Health Canada, 2021). Canada is one of the leading producers and exporters of pulses globally (Pulse Canada, 2022). Previous research has suggested that Canadian pulse production has relatively low environmental impacts (MacWilliam et al., 2014; Alberta Agriculture and Forestry, 2018; Bamber et al., 2020). A large proportion of Canadian pulses are exported to places such as Europe (Statistics Canada, 2015). It is therefore of interest to investigate the extent to which differences in the heterogeneous production conditions (e.g., soil types, climate, management practices, energy inputs and yields) in Europe compared to Canada determine differences in the sustainability profiles of Canadian and European pulses, as well as the role of transportation of pulses to Europe in this context.

Objectives: This study uses LCA to compare the impacts of peas and lentils produced in Canada and exported to Europe to those produced locally in Europe. We also investigate the differences between production regions within Canada (e.g., the provinces of Alberta, Saskatchewan, and Manitoba), and within Europe (e.g., France, Black Sea region).

Methods: LCIs for Canadian pea and lentil production, based on data collected from over 600 farms, were sourced from Bamber et al. (2020). These data are also now available in ecoinvent v.3.8 and on the Open Science Framework platform (osf.io/3y8r4/). These data include models for pea and lentil production at three different levels of spatial aggregation. There are models at the national level, the provincial level, and the ecozone level (regions defined based on soil and climate parameters, rather than provincial borders). For European pea and lentil production, LCI data from ecoinvent were given priority since they are methodologically consistent with the Canadian data. For additional LCI data, databases such as Agri-footprint and Agribalyse were consulted, as well as LCA studies from the literature (e.g., Koocheki et al., 2011; Elhami et al., 2017; Lienhardt et al., 2019; Bernas et al., 2021; Detzel et al., 2021; Tidåker et al., 2021).

All data not sourced from ecoinvent were re-modelled using methodologically consistent modelling practices (i.e., consistent with ecoinvent methodology) for maximum comparability. Emissions of heavy metals, carbon dioxide, phosphorus, nitrous oxide, nitrate, ammonia, and nitrogen oxides, as well as estimates of soil carbon sequestration, were also remodelled, if necessary, to align with the methods employed in the Canadian pea and lentil datasets in ecoinvent. Data for the transportation of Canadian peas and lentils to relevant regions in Europe were combined with the production data to create models for the import of Canadian peas and lentils into the European regions, to compare with peas and lentils produced locally in Europe. The Canadian average models were also compared with the provincial and ecozone models to assess the influence of regional differences in production on the LCA results.

Results and discussion: These LCA models were used to make comparisons of the relative sustainability of each scenario for pulse products available in the European market, as well as the relative contributions of transportation to the overall impacts. There are significant differences in the cradle-to-farm gate impacts of pulse production in Canada compared to Europe. One of the main contributors to these differences are the higher estimates of nitrous oxide emissions in Europe. Preliminary results show that the transportation of pulses from Canada to Europe contributes a large proportion of the cradle-to-market life cycle greenhouse gas emissions due to the long transportation distances and relatively low impacts of Canadian pulse growing. Despite these relatively significant transportation impacts, importing Canadian pulses to Europe may still have lower impacts than local European pulse production, depending on the types and distances of transportation.

Within Canada, there is also non-trivial variability in environmental impacts between the different pulse-growing regions. These differences were most pronounced between the different terrestrial ecozones of Canada, which are defined based on soil and climate factors, compared to the different provinces which have different crop growing guidelines and electricity grids. However, these differences in production are small compared to the overall impacts of production and transportation.

Conclusions: This study shows significant variability in the environmental impacts of pea and lentil production in different regions of Canada and Europe. Therefore, depending on the regions of production, the distances travelled, and the forms of transportation used, importing Canadian pulses into Europe may have lower impacts than would sourcing European pulses. The results of this research can be used to make suggestions to consumers and stakeholders around the sustainability of the different Canadian and European options for pea and lentil products, as well as potential hot-spots, or areas for improvement along the supply chain.

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Using life cycle assessment to support circular economy strategies in agricultural systems.

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The struggles to reduce humanity's environmental footprint revolve around a variety of human activities, one of them being food production, linked to agricultural exploitations. The intensification of food production systems to supply the ever-growing population's nutritional demand is causing major environmental impacts at both local and global levels (Foley et al., 2011). Cities are especially vulnerable because they host 55% of the world's population despite covering only 3% of the Earth's surface area (SEDAC, 2016; United Nations, 2014). In line with this global and asymmetric problem, scholars are exploring how to reduce the environmental impacts of crop and livestock farming while meeting food demand as well as ensuring other ethical standards such as farm animal welfare (Llonch et al., 2017).

Circular economy applied to agricultural systems can enhance their performance by improving flows' restoration and creating symbiotic relationships among the different producing systems (e.g., crop and livestock). The environmental benefit of closing the loop of materials and nutrients within and between agricultural systems must be accurately quantified and strictly monitored to avoid the implementation of contradictory strategies (Rufí-Salís et al., 2021). To ensure that circularity aligns with the principles of environmental sustainability, we first perform a life cycle assessment (LCA) of different agricultural production systems considering each one as an isolated and lineal system. Secondly, possible flow exchanges between and within the agricultural activities are identified and environmentally assessed.

In this study, we present the preliminary LCA results of several pig and dairy cattle farms across Europe (through the EU H2020 ClearFarm project, https://www.clearfarm.eu). The LCA methodology is applied as defined by ISO 14040 (ISO, 2006). The boundaries of the studied livestock systems are set from cradle to farm gate, meaning that we consider the extraction of raw materials but off-farm product transformation, final distribution of animal-derived products in retail and the disposal activities are excluded. The functional units used are 1kg of fat and protein corrected milk and 1kg of life weight meat for the dairy farms and 1kg of life weight meat for the pig farms. Primary data to create the life cycle inventories (LCI) were gathered from 5 pig farms located in Germany, The Netherlands and Spain and 6 dairy cattle farms located in Italy, Finland and Spain. For each farm assessed information was grouped by feeding, water use, installation needs, veterinary care, transport, and emissions from manure management and enteric fermentation. This latest division is also important to evaluate animal welfare as it may be affected by the health, comfort, nutrition or natural behaviour of farm animals. For each farm, specific data regarding feeding (including origin and production characteristics for main products), water usage, energy requirements, bedding systems, manure management techniques, transport, farm productivity, culling rates, as well as medical treatments were collected. When primary data were not available, for example for enteric fermentation, we estimated the values following the latest and most relevant literature approaches (IPCC, 2019; EEA, 2020). Infrastructure materials were excluded as most of the studies of this type do not consider it. Finally, in the dairy farms we used the biophysical allocation between milk and meat recommended by (IDF, 2015).

To perform the LCA we used Simapro 9.3 software from PRé Consultants and the databases Ecoinvent 3.8 and Agrifootprint 1.0. We included all materials, energy and emission flows gathered in the LCI but had to exclude medical treatments and some additives from the simulation due to voids in the databases for these products. The Life Cycle Impact Assessment was conducted through ReCiPe v2016 midpoint (hierarchist) method. It includes 18 impact categories of which we gave special attention to global warming, marine and freshwater eutrophication, terrestrial acidification, water use, mineral resources, fossil resources and land use. The use of ReCiPe adds complexity to the interpretation of the results, but it is relevant to identify potential trade-offs between impact categories. The results from the LCIA detected the environmental impact hotspots for each farm and helped to identify system strategies and improvements that could reduce those impacts. Briefly, results showed that feed is the top contributor to most of the impact categories followed by manure management emissions. Efforts to minimise the environmental impacts should mainly be oriented towards animal feed composition and production, and the manure management techniques. Finally, these processes need to be further analysed to identify potential synergies within the farm and between different agricultural systems to close flow loops while, at the same time, enhancing the environmental performance.

Finally, the ClearFarm project is developing an algorithm to achieve an animal welfare indicator through the integration of various domains (health, behaviour, feeding, housing, and emotional state). Here, the results from the LCA are discussed from an animal welfare perspective to understand how welfare practices, mainly linked to feeding and housing could affect LCA results, and, on the other hand, what role can LCA have on supporting decisions and providing information for the animal welfare algorithm. Thus, some initial hints on how different flows could affect the animal welfare algorithm are briefly discussed.

To conclude, this analysis identifies the most optimum combination of strategies in the pig and dairy cattle industry to move towards a more circular and sustainable food production. In terms of methodological contributions, the present work aims to highlight the use of LCA to assess agricultural systems when circular strategies are considered. Finally, it ends by discussing how the results of the LCA can contribute to advance further in the definition of quantitative indicators for animal welfare.

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Life cycle assessment of a novel method of producing bio-actives from fungal biomass

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Abstract

Rationale: Edible and medicinal mushrooms (e.g., *Hericium erinaceus*) are believed to be a sustainable source of unique bioactive metabolites, valued as promising for human health management. Mushrooms especially those rich in β-glucans and polysaccharides have health benefits and industrial applications. The anti-inflammatory and immunological properties make them a good candidate as feedstocks to make ingredients for food products with nutraceutical value (Boraston et al. 2007).

Objective: The purpose of this study was to explore the environmental impact of developing a novel submerged fermentation technology to produce mushrooms with high β-glucan concentration of pharmaceutical value.

Methodology: *Hericium erinaceus* was used as a substrate along with enzymes and sugars to grow fungal biomass in a laboratory scale aerobic, submerged fermentation system, and β-glucan was subsequently extracted. The life cycle assessment plan for this study was to use attributional LCA at the initial stage of development (TRL 1-3) followed by a consequential LCA during the later stages (TRL 4-6) (Brander et al. 2009). The attributional LCA was conducted to identify environmental impact hotspots so that informed decisions could be made for the design of scaling from TRL3 (laboratory proof of concept) to TRL6 (demonstration in industrially relevant environment). The system boundary included upstream production of inputs and laboratory processes to the preparation of pharmaceutical grade β-glucan. The functional unit was 100 g of β-glucans produced. The impacts considered were climate change and freshwater consumption (the policy driving commercial interest in the innovation), terrestrial acidification and freshwater eutrophication (two important impacts for the local mushroom industry, both regulated by European legislation).

Results: β-glucan production via solid substrate fermentation takes several months to produce fruiting bodies (Cui et al. 2010) when compared with submerged fermentation producing fruiting bodies in 10 days. The impact of producing 100 g of β-glucans was 167 kg CO2 eq (climate change), 0.52 m^3 (freshwater consumption), 0.109 kg SO2 eq (acidification) and 9.71×10^{-5} kg P eq (eutrophication). The results can be presented as foreground and background processes results. The results for foreground processes are divided into four sub processes i.e., media preparation (mixing and autoclaving), cultivation of biomass (homogenization and fermentation), freezing and drying (refrigeration and freeze drying) and extraction of β-glucans (rotatory evaporation). The driver of the climate impact was the energy consumption during cultivation of biomass. Within the bioreactor, 51% of the energy was consumed by a chiller to maintain a temperature of 25°C. It consumed 37.9 kWh per day to produce 67.5g of β-glucans, creating a hotspot of 86 kg CO_2/100g β-glucans. This was followed by energy consumption

during media preparation (30%) where a shaker was used, which was responsible for continuous mixing of media for 17days i.e., 52 kg CO_2/100g β-glucans. Freeze drying was also an important contributor. Freshwater consumption was also driven by cultivation of biomass, where 4L of water was used during fermentation. Once the fungal biomass was grown it was washed several times, making it a hotspot. Transportation of raw materials from Germany to Dublin was also a hotspot contributing 3.5 kg of CO2 eq/ 100g of β-glucan. Although transport was not a major contributor at laboratory scale, but it might potentially increase when advancing towards TRL 4-6 stage.

Discussions: The design used in the production of fungal biomass by submerged fermentation can achieve high production of the biomass compared to cultivating medicinal mushrooms using solid substrate such as composts or lignocellulosic wastes. Conventional production is complex and time consuming process, and usually takes several months to obtain fruiting bodies (Cui et al. 2010). The submerged production system is productively efficient, but in its current form it is highly energy intensive, relying on both a chiller and a shaker. Upscaling will require attention to the bioreactor design. The chiller that was used at laboratory scale was responsible for 51% of the energy used, but as the fungal biomass does not grow rapidly, it should be possible to operate at larger scale without such rigorous ambient temperature regulation. Understanding temperature regulation will be critical during upscaling design. Sourcing the raw material from Ireland should reduce the cost of international transportation and fuel combustion. During growth of the biomass, water was added continuously to the system for 240 hours and wastewater containing of Nitrogen, Phosphorous and other metabolites was discarded. Design for upscaling will have to ensure such large quantities of water will not be discarded, as these could become a significant the environmental burden of the production system.

Conclusions: The recommendation arising from this LCA study at laboratory scale was to continue research towards commercial development, with a specific focus on: (1) energy efficiency and minimization for the bioreactor; (2) further research on finding more efficient media preparation; (3) sourcing raw materials locally for commercial and environmental benefits; and (4) when upscaling, attention is required to introduce reutilization of wastewater to make the system circular in nature. A consequential LCA will be used to assess the different technology options during the design process from TRL3 and 6 to ensure the suggested interventions not only reduce the hotspots at an early stage but also to ensure there is a system-wide benefit from the technology innovation.

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Building environmentally sustainable supply chains

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Rationale and objective of the work

Food supply chains exist in a vast diversity all across the globe, in various degrees of efficiency and sustainability. In Europe, most supply chains have become tightly structured and organized with economic optimizations made at every step of the value chain. This has led to many long food supply chains, decoupling the region of production with the region of consumption [1]. However, a growing number of consumers wishes to buy regional goods [2]. This desire meets the urge of producers to sell their goods directly to consumers in order to be in a better market position of power and obtaining a large share of the margin [3]. In the food sector, farms have become more and more specialized on a few raw products. Consumers therefore need to buy from multiple farmers to fill their entire food basket, leading to inefficient transport ways. From an environmental perspective, the challenge becomes obvious: How can short food supply chains (SFSC) be organized in order to keep up with the efficiencies of long food supply chains?

Approach and methodology

The Smartchain project (2018-21) applied a multi-stakeholder approach to analyze SFSCs from a sustainability perspective and derive recommendations for policy and practice. Scientists with methodological expertise in sustainability assessment collaborated with practitioners and several stakeholders alongside the food supply chains in Europe. Important outcomes of the project are the environmental assessment of several case studies that represent different SFSC types and business models. These different types of SFSCs were categorized according to the guidelines of the European Commission: face-to-face (like e.g. farmers market), spatial proximity (e.g. local specialist retailers or hospitality industry) and spatially extended (e.g. AOP product sold in a foreign country). Of the first two categories, several representative case studies across Europe have been assessed by means of LCA. Recommendations that are adapted to the type of product, the rural or urban geography and the type of actor along the food chain were developed.

Main results and discussion

The study considered a variety of environmental impacts. Exemplary results are shown hereafter for GWP.

Figure 1 displays the carbon footprint of different sizes of food baskets distributed via a SFSCs of the type cooperative shop in comparison to two conventional supply chains in an urban and rural area respectively. The influence of both vehicle type and size of food basket are included. The transport distance of the consumer (from home to supermarket) is fixed at 14.6km (7.3 km one way) [4].

In all investigated case studies (different types of short chains, products and countries), the environmental assessment has shown two key hotspots: the primary production (assessed by secondary data) and the consumer transport (assessed by primary data).This is consistent with the findings of Malak-Rawlikowska et al. [2] who investigated food supply chains based on 208 food producers categorized in ten distribution channel types. In terms of GWP, impacts from primary crop production are mainly influenced by production and utilization of organic and mineral fertilizers, plant protection products and fuels [6].

In the study, the type of primary production is assumed to be independent of the type of distribution and is therefore not further discussed in the context of this article. However, the consumer transport depends on the way of distribution. More specifically, the individual car travel of the consumer (km driven per kg product) has been identified as a hotspot, making both the travel distance (and the type of transport/vehicle) and the basket weight key parameters that can be used as levers to lower the environmental impact. This finding is supported by a study of Majewski et al [3] which identified individual consumer transport by car to be the main driver of the environmental impact if small amounts of products are transported over long distances.
After the identification of the hotspot, the study aimed at defining the conditions under which the short food supply chains can perform better than long ones in rural and urban areas. The differentiation of the geographical context is relevant because of the different average distances driven in rural and urban areas.

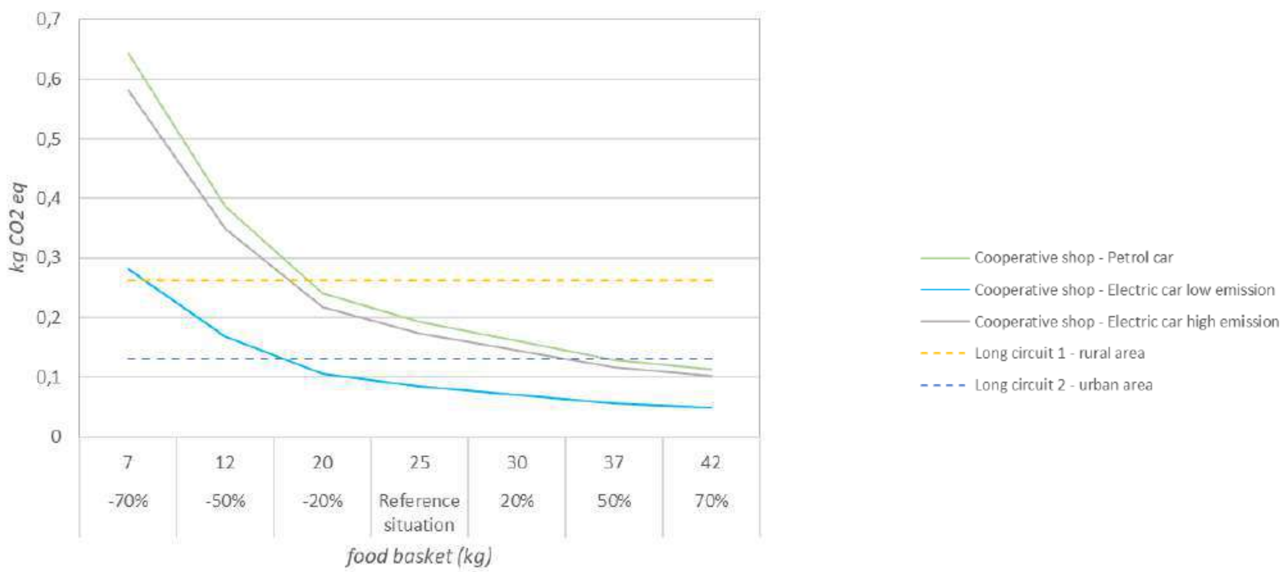

***Figure 1:** Global Warming Potential in kg CO2-eq. per kg of purchased product for a fixed consumer transport of 14.6km (7.3km one-way respectively) as a function of the food basket size (in kg) for 5 different transport scenarios [5]. LFSC key parameter average km/kg: urban (0.4 km/kg), rural (0.8 km/kg)*

These findings suggest a broader diversification of the goods offered per sales point, either by diversifying a single farm or by cooperation among farms. This has implications for the primary production and, additionally, a potential transformation stage is added to the raw products to cover a wider range of food items that can be offered.

Conclusion
While the primary production remains the main contributor to the overall products' environmental impact, a reduction of the environmental impacts of the short food supply chain can be obtained by

focusing efforts on the consumer transport, which is a current weakness of SFSC. Nevertheless, conditions under which SFSC can performs better than long chains from an environmental point of view exist. Indeed, consumer travel and basket size are key parameters to lower a SFSC's environmental footprint. Raising consumer awareness will lead to increase the size of the food basket or decrease the transport distance. Public authorities can foster the development of cooperative shops or farmers market, and other platforms with a large variety of goods available for consumers.

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Assessing the nutritional, health and environmental dimensions of foods and diets: comparison of nutritional metrics

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Introduction:

Recently, the link between environmental impact of diets and its relationship with health and nutrition has gained special interest. With the Agenda 2030 and the UN sustainable development goals (United Nations General Assembly, 2015), new food policies encompassed with changes on food production and consumption have raised worldwide to achieve environmental and nutritional goals. However, there are still some challenges developing a standardized method that include nutrition, health and environment calculations when assessing food products and diets. Dietary indicators are used to classify foods and diets depending on their nutrient content (Fulgoni et al., 2009), diversity (Green et al., 2020) or its compliance with dietary guidelines (Krebs-Smith et al., 2018). The assessment is more complex, if digestibility, absorption and bioavailability of some nutrients are considered (Sonesson et al., 2017) or when the health impacts of food products and diets are assessed (Stylianou et al., 2021). However, a holistic approach of the nutritional, health and environmental (NHE) dimensions is needed to ensure food products and dietary patterns are not only environmental friendly but also more nutritious and healthy for the present and future generations. In a literature review, five types of health/nutritional indicators were identified, and classified as follows: 1) Group A, includes metrics that consider a ratio between the nutrient food content and reference amount for qualifying and disqualifying nutrients and/or food groups; 2) Group B: includes indices based on the adherence to specific guidelines on healthy eating; 3) Group C: is based on nutrients and food group diversity; 4) Group D: considers metrics that evaluate nutrient quality characteristics specific to one or more nutrients (bioavailability, digestibility, etc.); and 5) Group E: accounts for metrics that consider health impact of foods and diets based on dietary risk factors. The aim of this research is to compare different nutritional and health metrics on food products and evaluate their differences.

Methodology:

This study evaluated the nutritional-health-environmental (NHE) dimensions of 445 foods from the Swiss EuroFIR database. The EuroFIR is a comprehensive nutritional food database that includes a wide range of raw and processed food items (Becker et al., 2008). For this analysis, only single, food products were considered (e.g. apple, chicken meat or milk), and complex or processed foods were not evaluated (e.g. pizza, cake, etc.). Consequently, the metrics selected to assess the nutritional and health dimensions were indicators of group A and E. The analysis consisted of three phases. First, the nutritional content of food products was calculated according to three different nutritional indicators: i) NutriScore (NS); ii) Nutrient Balance Concept (NBC); iii) Nutrient Rich Food 9.3 (NRF9.3). Each of the selected nutritional indicators considers a different set of nutrients and food groups, which allows for a comparative analysis. Second, the health impacts were evaluated through the newly developed HENI score (Stylianou et al., 2021) based on fifteen dietary risk factors from the Global Burden of Disease study (Murray et al., 2020). Third, the environmental impacts (EnvI) of the different foods were considered by LCA (Poore & Nemecek, 2018). Finally, a ranking of the different foods was performed as well as correlations between the different indicators.

Results:

When analyzing the 445 single food products considered, results show that NRF9.3 and NBC are the two indices with the highest correlation (r = 0.78; p < 0.001). Both indices consider only qualifying and disqualifying nutrients, while NutriScore and HENI consider also food groups (e.g. read meat). In addition, results show that correlations between the different indices change depending on how food group aggregations are considered (e.g. analyzing all meats vs specific meat types). Table 2 shows, that when analyzed by food groups (Table 1), the number of correlations between the different indices differ (Table 2). In addition, when assessing foods products individually, results show that the choice of indicators changes how foods are ranked. Table 3 shows the results for five commonly consumed foods by different environmental, nutritional and health metrics. For example, walnuts rank first for HENI and greenhouse gas emissions (GhGe) but rank in last position when considering water scarcity or the NBC. Therefore, metric usage should always be very well defined and its interpretation has to be done adequately.

Table 1: Food group aggregation for the correlation analysis (n=445)

Food group aggregation
Vegetables
Fruits
Meat
Grains
Pulses
Dairy
Oils and fats
Fish and seafood
Nuts and seeds
Sugars and sugar products
Eggs
Miscellaneous

Table 2: Number (n) of significant correlations between the different indices when analyzed by food groups

	NRF9.3	HENI	NBC	NS
NRF9.3		5	6	7
HENI			1	8
NBC				4
NS				

*Note: The metrics represented in the table are: **HENI:** Health Nutritional Index; **NBC:** Nutrient Balance Concept; **NRF9.3:** Nutrient Rich Food Index 9.3; **NS:** NutriScore.*

Table 3: Food ranking depending on the nutritional, health or environmental indicator used

	HENI	NBC	NRF9.3	NS	Water scarcity	GhGe	Land use
Tomato	4	1	1	1	1	2	2
Salmon	2	2	3	4	5	4	4
Apple	3	4	4	2	2	1	1
Walnuts	1	6	2	5	6	1	5
Milk	5	3	6	3	3	3	3
Beef	6	5	5	6	4	5	6

Note: The ranking values decreases from 1 (green) as the one having the highest nutritional value or lowest EnvI to 6 (red), as the one having the poorest nutritional content or highest EnvI. The metrics represented in the table are: ***HENI:*** *Health Nutritional Index;* ***NBC:*** *Nutrient Balance Concept;* ***NRF9.3:*** *Nutrient Rich Food Index 9.3;* ***NS:*** *NutriScore.* ***Water Scarcity:*** *the data considered are Stress-Weighted Water Use (L/FU);* ***GhGe:*** *kg CO_2eq/FU;* ***Land use*** *(m^2/FU).*

Discussion

These results highlight the importance of choosing the adequate indicator when evaluating different food products. Effects on the results can be driven by: 1) qualifying/disqualifying nutrients considered in each indicator; 2) aspects of nutrient/health considered (quantity, quality, diversity, etc.); 3) dietary reference intake considered by different population groups (pregnant women, etc.); and 4) capping at the recommending intake and weighting nutrients to a set energy value. In addition, the results show the importance of including all NHE dimensions when evaluating food products and dietary patterns as opposite to only considering one metric. This research shows how the selection of a specific indicator will change the ranking of food products or diets, which needs to be taken into consideration when communicating the results to consumers. In addition, these indicators can be used as a functional unit (FU) or impact category to be included in the Life Cycle Assessment (LCA) of food products, meals or diets. However, in this case, the selection of the indicator should be dependent on the goal of the LCA study and the interpretation of the results should be done with caution as results using different FU might have different outputs. Also, this study focused on the evaluation of indicators for single food products, but other indicators might be needed when evaluating whole dietary patterns. In such cases, a nutrient content approach might not be sufficient when considering whole diets, where food matrix interactions are more relevant, and group D nutritional indices might be more adequate. In addition, when analyzing diets, aspects of diet adequacy against recommendations or food/nutrient diversity should also be discussed, thus, metrics pertaining to group B and C ought to be considered.

Conclusion:

Nutritional and health indices appear to be a useful tool when evaluating NHE dimensions of foods and diets. However, the results of this study showed that it is necessary to choose metrics carefully depending on the goal of the study, as well as when interpreting the results and its integration into LCA. While the food industry and policy stakeholders are aiming at developing a nutritional and health score which is easy to communicate to the consumer, it is important to ask for caution and not to oversimplify (especially when ranking health aspects of food products or dietary patterns) due to the complexity of the metrics.

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Design of an indicator-based agri-environmental direct payments system inspired by the LCA methodology

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Introduction

In order to reduce the negative environmental impacts of agriculture, policymakers are increasingly creating incentives for the "greening" of agriculture. In Switzerland, the Federal Office for the Environment (FOEN) has established Agri-Environmental Objectives (AEOs) in order to fulfil its constitutional mandate to promote sustainable and resource-efficient agricultural production. Direct payments constitute one means of achieving these objectives. Although the disbursement of direct payments is contingent on cross-compliance standards, and some direct payment contributions are already directly related to the environment (e.g. requirement of minimal biodiversity areas), the environmental objectives of agricultural policy have for the most part not been achieved.

Therefore, it is critical to devise eco-schemes that provide stronger incentives for environment-friendly agricultural practices. A conceptual study was launched in 2019 to investigate whether indicator-based direct payments (IBDP) could represent an alternative to the existing environment-related direct payments. The developed indicator-based direct payments system (IDPS) aims to approximate the environmental impacts at the farm level for several environmental aspects considered individually. The basic idea behind the new framework is—by linking the direct payments to the indicator values—to reduce the negative environmental impacts of the Swiss agricultural sector in a simpler and more effective way.

This paper shows how Life Cycle Assessment (LCA) modelling can be used in a pragmatic approach to developing feasible environmental indicators designed for application within the given policy context.

Approach and Methodology

The examination of different indicator systems, such as SALCA (Gaillard & Nemecek, 2009) or SMART (Schader et al., 2019), reveals that the majority of these are unsuitable for use in a direct payments system. This is mainly due to their complexity and the non-verifiability of the required input data; this in turn is linked to their focus on other purposes (research, monitoring or advising) than direct payments. Furthermore, indicators primarily based on expert judgment and/or qualitative data should not be used in the context of subsidy provision, as it is of critical importance to use verifiable input data. The use of Life Cycle Impact Assessment (LCIA) indicators at the midpoint or endpoint level, although theoretically desirable, was discarded as an approach, as both the data collection and calculation of indicators are too time-consuming and poorly controllable to be used in a direct payments context.

Therefore, we developed prototypes of agri-environmental indicators at the farm level that are tailored to use in a direct payments system and take into account the major driving forces. The indicators differ depending on the environmental issue: whereas some indicators are result-based, or at least contain result-based components (e.g. measurement of humus content), the majority focus on agricultural structures and measures (e.g. size of animal stock, avoidance of high-risk plant protection products). The disbursement of the direct payments is determined by the indicator values, the payment rates being generally based on existing damage cost estimates. In addition, threshold values have been defined, below which farm holders receive no payment.

To make the system as flexible as possible, we elaborated three different levels of complexity (simple, medium, detailed). These three variants differ in terms of the number and complexity of their indicators. In the detailed variant, we developed new quantitative indicators for the following eight environmental areas: (i) biodiversity, (ii) greenhouse gas (GHG) emissions, (iii) ammonia emissions, (iv) nitrate leaching, (v) phosphorus leaching, (vi) pesticide application, (vii) soil erosion and (viii) humus accumulation. The indicators for the detailed variant take into account the major driving factors and underlying processes, thus allowing farm managers sufficient flexibility in the choice of measures—in LCA language, due to the abovementioned constraints, we had to focus on Life Cycle Inventory (LCI) indicators instead of directly using LCIA models. In contrast, the simple system assesses the environmental impacts in a very generic manner, even allowing the use of one single indicator to describe several environmental impacts that are driven by similar physical processes: GHG emissions, ammonia emissions and nutrient leaching are merged into one single indicator, called "climate and nutrients"; moreover, soil erosion and humus accumulation are summarized under the topic "soil protection". A very limited set of input parameters is sufficient as an input for this simplistic approach. This minimizes the administrative effort for data acquisition and the time needed to check the correctness of the data. The medium variant lies between these two extremes.

The simple variant of IDPS was incorporated into the agent-based, structural Swissland agricultural model (Möhring et al., 2016) in order to analyse the associated costs and expected future structural changes of the Swiss agricultural sector. These evaluations are detailed in Gilgen et al. (2022).

To give the reader an idea of how we used *LCA thinking* in our approach, we present the procedure for the global warming potential (GWP) indicator. The procedure outlines a pragmatic way to approximate GWP by using verifiable LCI data that are easily accessible at the farm level. In the initial step (*classification*), we identified the most important GHG sources from the agricultural sector. In the second step, based on the Swiss national GHG inventory and LCA studies (e.g., Alig et al., 2015), we selected five emission sources/sinks (*elementary flows*) that contribute most to Swiss GHG emissions and for which there is great individual reduction potential at the farm level. These were: (i) methane (CH_4) emissions from ruminants by enteric fermentation, (ii) nitrous oxide (N_2O) emissions from agricultural soils, (iii) emissions from drained organic soils, (iv) carbon stored in trees and (v) CH_4 & N_2O emissions from stored slurry. In the third step, we developed simple parameterisations for these five emissions types by identifying relevant driving variables and by applying typical average values given in scientific publications (*LCI modelling*). For the example of methane emissions from ruminants (process (i)), this resulted in the following formula:

$$CH_{4,ruminants} = \mathrm{c} * \left(\frac{2 * lac + 2}{2 * 1.286 * lac}\right) * LU_{dairy\ cow} + c * LU_{other\ ruminants},$$

where *LU* is livestock unit, *c* is mean CO_2-equivalent emissions per *LU* (= 3 t CO_{2eq}/year) and *lac* is number of lactations. The factor 1.286 normalises the value within brackets for the observed mean number of lactations in Switzerland (*lac* = 3.5). Farms with lactation numbers smaller/greater than 3.5 thus achieve more/less than 3 t CO_2-eq/year per dairy cow. In order to express the total GWP (sum of all emissions considered) in the unit kg CO_2-eq/year, the following characterisation factors (CFs) were assumed: $CF_{N20} = 265$ and $CF_{CH4} = 28$ (*characterisation*).

All five abovementioned emission sources/sinks are accounted for at the detailed level of complexity, while the medium level ignores emissions from stored slurry and simplifies some other emissions sources/sinks. The simple level of complexity accounts only for the combined impact of GHG emissions, ammonia emissions and nutrient leaching, by a linear function of LU per hectare and total applied nitrogen.

Results & Discussion

The conceptual study demonstrates that it is not feasible to apply existing indicator-based systems for promoting environmentally friendly agriculture within a direct payments system. The evaluation process shows that strict application of LCIA midpoints and endpoints according to ISO norms are not suitable for IDPS due to excessive data acquisition related to overly complex models and the inclusion of upstream processes (again requiring the use of complex computer software).

Instead, it is necessary to develop, for relevant environmental impacts, revised indicators that address and include the main driving forces while taking into account various restrictions relating to agricultural policy. This study proposes agro-environmental indicators that, at least at the detailed level of complexity, go beyond using simple driving force indicators (e.g. total fuel consumption, amount of manure applied, number of livestock) by using LCA thinking in their development. The evaluation shows that, based on expert judgment and literature reviews, it is possible to construct indicators for relevant environmental impacts in a way that provides sufficient completeness and accuracy, and that meets policy-imposed conditions.

Stakeholders' feedback gathered during a one-day workshop and preceding discussion rounds in oral and written form revealed that the main challenge is to find the optimal compromise between the targeted improvements and the administrative burden for both the farm managers and the agricultural agencies involved. In addition, a high level of transparency and communicability of the indicators is crucial in order to secure acceptance of an IDPS.

Conclusions

This study shows that it is possible to develop an IDPS of low complexity based on LCA thinking that (i) accounts for relevant driving forces with regard to environmental impacts, (ii) is feasible with regard to time and financial constraints and (iii) is mainly based on a verifiable input dataset that can be compiled for all farms receiving direct payments. The IDPS is a promising approach for replacing the current direct payments system in a flexible and transparent manner while contributing to achieving Switzerland's ambitious AEOs. However, it is crucial to refine and test the proposed system on a sufficiently large sample of farms, to gain more insights into the efficiency and practicability of the entire system at all levels of complexity. In addition, a future implementation requires a thorough verification of possible conflicts with other parts of the current direct payments system and agricultural policy.

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Benchmarking lettuce supply chains produced through agroecological, hydroponic controlled environment, and field-based systems

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Abstract

We benchmark through an attributional Life Cycle Assessment (LCA) an agroecological, supply chain of a leafy greens "salad mix" in the Azores (Portugal) against ten supply chain structures of hydroponic controlled-environment agriculture (CEA) and conventional systems described in an existing study from (Casey et al. 2022) that use six distinct electricity types, varying transport modes, and regional to global distances. As the current agroecological supply chain delivers its products "hyper-locally" to consumers on the island, we model an additional, hypothetical scenario where the "salad mix" is transported to the United Kingdom for equal comparison with the other systems. While the hydroponic CEA system consumed around 15 kWh of electricity per kg of lettuce supplied, we expect the agroecological system to only require a fraction of this energy, with every action performed manually, as well as to have smaller burdens across other categories, such as eutrophication and climate change, due to smaller external inputs. Furthermore, the agroecological system is likely to provide ecosystem services that neither of the other two systems can provide. Therefore, in addition to the environmental footprint calculated through the LCA, the European RADIANT project aims to evaluate the eco-efficiency of the systems by performing further analyses looking at additional ecosystem services and income generation to the farmers.

Introduction

Leafy greens and in particular lettuce (*Lactuca sativa*) are important crops globally, with a production of lettuce and chicory (*Cichorium intybus*) exceeding 27 million tonnes in 2020 (FAO 2022). To meet the demand for all year-round supply of leafy greens, their trade occurs at multiple levels, from regional by refrigerated truck to global by air freight (Casey et al. 2022). An export of more than two million tonnes of the two crops were reported in 2020, with the top exporting country being Spain, followed by the United States and Mexico (FAO 2022). The production and transport of fresh leafy greens do not come without environmental costs, and different supply chains were linked with highly varying ecological footprints, as shown for example by (Hospido et al. 2009, Foteinis and Chatzisymeon 2016).

Hydroponics Controlled Environment Agriculture (CEA) is a production method that consists of growing crops with desired parameters in a soilless culture (Srivani and Manjula 2019). It has gained attention in recent years, as its highly controlled environment may help address some of the food system challenges, which include excessive greenhouse gas emissions and nutrient pollution due to large external inputs, and highly degraded soils and biodiversity loss through the standardisation of monoculture and intensive agricultural practices (Willett et al. 2019).

Instead, agroecological farming is an approach integrating ecology, health, society, ethics, and economy into food production systems, positively reinforcing food security and nutrition (Wezel et al. 2009, Kerr et al. 2021). An agroecological system often includes numerous crops through intercropping, rotation, agroforestry, simultaneous production of crop and livestock, soil health management. It was recognised as a sustainable food production practice (Willett et al. 2019).

This study aims to benchmark agroecological production against a diametrically opposed "cutting edge technology" system for the example of leafy greens supply, to highlight relative environmental advantages and disadvantages. We present to our knowledge the first LCA of a leafy greens agroecological value chain as a case study and benchmark it against a study with 10 hydroponics and conventional value chains of lettuce with varying electricity types, transport modes, and transport distances from (Casey et al. 2022). We hypothesise that the agroecological system can provide leafy greens to the city of London (United Kingdom) at a lower overall environmental cost than other systems studied.

Materials and methods

Primary data for the agroecological system were collected from a farm in the Azores (Portugal), Biofontinhas (Projecto 2022), whereas data on the hydroponic CEA and field-based systems were extracted from (Casey et al. 2022). System boundaries for the various case studies used were recorded in Figure 1, with *Agroecological* being the current value chain where the agroecological farm delivers its salad mix locally, and *Agroecological** being the hypothetical value chain where the agroecological farm delivers its salad mix to London. The OpenLCA software v.1.10.3 (GreenDelta 2022) was used to model the systems, with the use of Ecoinvent v3.8 database (Wernet 2016). The impact categories were those recommended by the Product Environmental Footprint (PEF) guidelines (European Commission 2018).

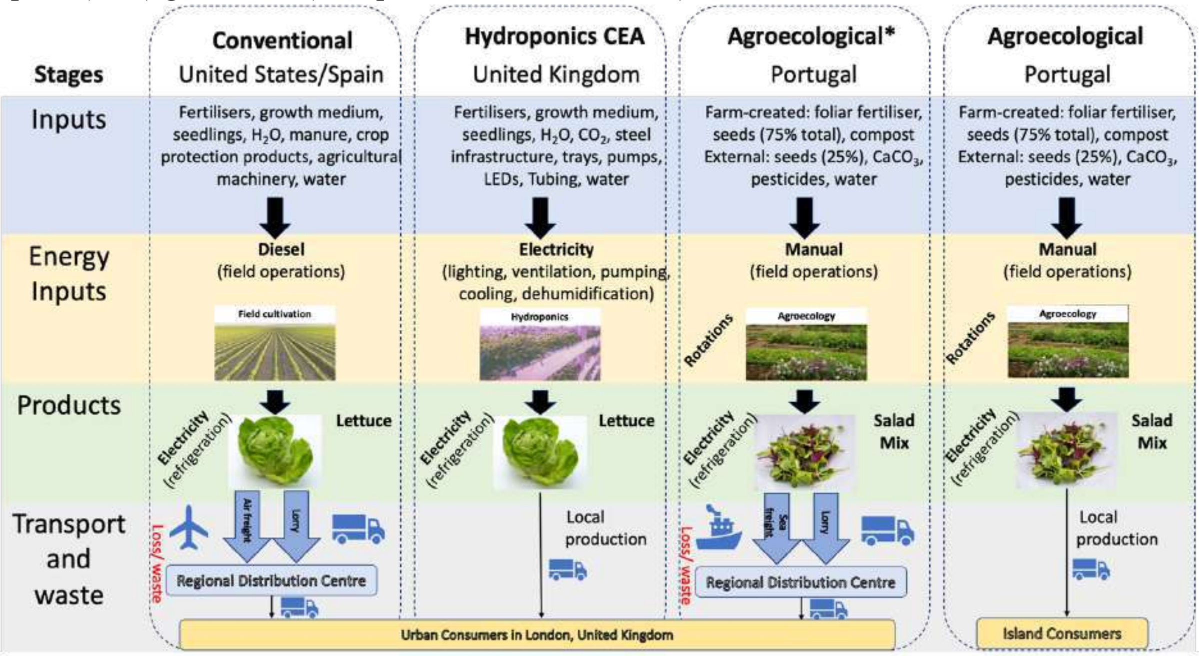

Figure 1. System boundaries of conventional (*Conventional*), hydroponics–controlled environment agriculture (*Hydroponics CEA*), agroecological (*Agroecological*), and agroecological with theoretic al export (*Agroecological**) systems benchmarked in this study. Adapted from (Casey et al. 2022).

The leafy greens produced through the agroecological system and present in the "salad mix" are part of a rotation consisting of lettuce, swisschard (*Beta vulgaris* subsp. *vulgaris*), golden purslane (*Portulaca oleracea*), garden orache (*Atriplex hortensis*), buck's-horn plantain (*Plantago coroponus*), and ten mustard plants from the Brassica genus, such as tatsoi (*Brassica rapa*). The crops are grown on a surface of 700 meters all year-round, representing 7 cycles yearly. This is possible thanks to the temperate, subtropical climate of the island. The leafy greens are grown on a volcanic soil, where no ploughing nor tilling occurs, with no engines at soil level. One operator works with a fork for five minutes per square meter to prepare the soil. Only 25% of the seeds sown are purchased, with the remaining having been collected on farm from previous cycles. No fertilizer is applied, apart from farm-owned compost and foliar fertilizer made on site with weeds. In addition, 35 g of calcium carbonate is applied per square meter every five years. Two pesticides, Pirecris and Turex, are applied 25 times a year. A total of 480 m^3 of municipal water is used yearly for the leafy greens, representing water applied through drip irrigation and manual spray, as well as water for washing harvested products. The leafy greens are harvested manually, washed four times, and packaged into 200 g and 500 g nano-perforated plastic bags for individual consumers and restaurants, respectively. The products are then refrigerated until the clients come to pick them up. Around seven restaurants come individually to the farm, once or twice a week, with a refrigerated truck. The distances travelled vary between 1 and 20 km, and other products from the farm are picked up at the same time. An additional hypothetical model representing an all-year round agroecological production of leafy greens system in the Azores that exports to London (United Kingdom) via refrigerated truck and ship for three days and fifteen hours (SeaRates 2022) was modelled to allow for better benchmarking with the hydroponics CEA and conventional systems.

Results

The eight impact categories with the highest normalised environmental burdens per kilogram of leafy green delivered for across all hydroponic CEA and conventional systems studied, as well as the hypothesis of how the agroecological system performs comparatively, were recorded in Table 1. The highest environmental burdens across the eight most relevant categories could consistently be found in the Hydroponics CEA systems, while the lowest burdens were found in the conventional systems across all eight categories excepted for terrestrial acidification and eutrophication, and respiratory inorganics. We expect the agroecological system to have lower environmental burdens across these same categories, due to the low inputs and high yields, despite the longer transport distances when compared to the hydroponics CEA systems.

Table 1. Lowest and highest characterized environmental burdens of the hydroponics controlled environment agriculture and conventional systems for the production of one kilogram of leafy greens from the case study in (Casey et al. 2022) across the 8 impact categories with the highest burdens, as well as hypotheses of how the agroecological system compares in these categories. The values in red and green represent the highest and lowest values across all systems, respectively. The results for the agroecological systems are characterized by an interrogation mark to represent the work in progress.

		Hydroponics CEA		Conventional		Agroeco logical*	Agroeco logical
Impact category	**Unit**	**Lowest**	**Highest**	**Lowest**	**Highest**		
Acidification terrestrial	**mol H$^+$ equivalents**	0.0018	0.045	0.0032	0.0099	?	?
Climate change	**kg CO_2 equivalents**	5.9E-05	0.0022	1.9E-05	0.0012	?	?
Eutrophication freshwater	**kg P e equivalents**	0.0019	0.081	0.00016	0.0018	?	?
Eutrophication marine	**kg N equivalents**	0.00026	0.017	0.00017	0.0087	?	?
Eutrophication terrestrial	**mol N equivalents**	2.1E-05	0.048	0.00014	0.0011	?	?
Resource use, energy carriers	**MJ**	6.3E-05	0.0037	2.2E-05	0.0022	?	?
Respiratory inorganics	**Disease incidence**	0.00042	0.0054	0.00067	0.0033	?	?
Water scarcity	**m^3 deprivation**	0.0015	0.0097	0.00019	0.0011	?	?

Discussion

The different systems compared show significant differences in terms of structure and environmental costs. They are, however, most likely to suit distinct environments, with the case of a well-managed hydroponic CEA being more suitable than any other system in an arid environment where water is scarce. The case of the agroecological farm in the Azores is an example of a well-established supply chain suitable to its geographical location, with favourable weather, land and water availability, and higher demand than availability. With a high demonstrated yield of leafy greens in the agroecological system despite the limited external inputs as well as a very short supply chain, the agroecological system is likely to yield more positive results than the other systems, as well as possess a higher resilience (Altieri et al. 2015). The *Agroecological** value chain would however incur additional challenges, such as higher loss and waste from additional transport. However, agriculture has multiple functions that exceed simple food (nutrients) provisioning, including (a) income generation for farmers, (b) landscape preservation through the appropriate use of land, and (c) provision of other ecosystem services (Hayashi et al. 2006), which may not be fulfilled in hydroponics CEA or conventional systems, but would in an agroecological one.

Conclusion

The systems studied showed radical differences in terms of inputs, capacity, and environmental costs. Moreover, their value chains differ in terms of scale and geographical coverage. Whether the agroecological system delivers the leafy greens at a lower environmental cost could suggest that such a system producing the crops elsewhere and shipping them to London should be further investigated. However, LCA has numerous limitations in terms of fully assessing the eco-efficiency of the salad supply chains, which may be misleading. Therefore, in addition to the environmental footprint calculated through this LCA, the European RADIANT project (RADIANT 2022) aims to evaluate the eco-efficiency of the systems by performing further analyses looking at additional ecosystem services and income generation to the farmers.

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Pegada de carbono de café Arábica torrado e moído: estudo de caso no Brasil

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Palavras-chave: Café, pegada de carbono, sustentabilidade, rotulagem, impacto ambiental

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Introdução

O Brasil é o maior produtor e exportador de café, além de ser o segundo maior consumidor mundial de café. Na safra de 2018/19, a produção brasileira alcançou 2,96 milhões de toneladas, com uma produtividade de 1.632 kg por hectare e uma área produtiva de 1,81 milhões de hectares. A produção de café Arábica foi de 2,06 milhões de toneladas, o que representa 69,5% da safra, enquanto a produção de café Conilon foi de aproximadamente 0,90 milhões de toneladas, correspondendo a 30,5% da safra (CONAB, 2019).
Há uma tendência mundial para a rotulagem e certificação de produtos em relação aos impactos ambientais, o que se tornou um dos requisitos para importação e comercialização de produtos (Rocha e Caldeira-Pires, 2019).
Desse modo, o objetivo deste estudo foi estimar os indicadores ambientais da produção de café no Brasil. A pegada de carbono do café torrado e moído, que é o impacto ambiental mais frequentemente usado em rotulagem de produtos, foi estimada e comparada com estudos disponíveis na literatura. Este é o primeiro estudo sobre café torrado e moído desenvolvido no Brasil e deverá contribuir para identificar pontos de melhoria na cadeia produtiva por meio do fornecimento de dados científicos para a melhoria ambiental do setor e desenvolvimento desta área de pesquisa, bem como subsídios técnicos para a rotulagem ambiental deste produto.

Métodos

O escopo do estudo foi avaliar o café arábica torrado e moído desde a extração dos recursos naturais, produção de energia (eletricidade e combustíveis), produção de fertilizantes, cultivo do café até o portão da indústria de moagem e torrefação. A Figura 1 apresenta o fluxograma com a fronteira do sistema estudado.

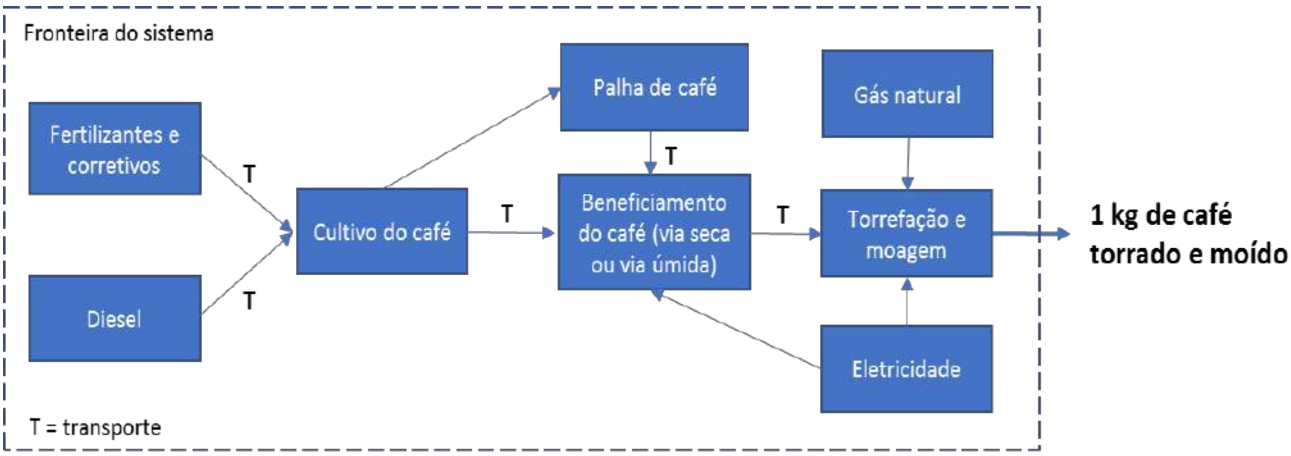

Figura 1. Fluxograma com as etapas avaliadas no estudo. UF = 1 kg de café torrado e moído.

O cultivo de café foi estimado a partir de dados fornecidos por produtores ou associações de produtores de fazendas localizadas em Minas Gerais, principal região produtora de café no Brasil e no Estado de São Paulo. Os dados foram obtidos de onze produtores de café para as safras 2017/18 e 2018/19 e duas indústrias de torrefação e moagem de café para os anos base de 2018 e 2019.
Todas as etapas de transporte foram incluídas na fronteira do sistema. Não foram considerados os bens de capital, ou seja, recursos e energia usados para construir e manter as indústrias, estradas, caminhões etc.
A unidade funcional adotada foi 1,0 kg de café torrado e moído.
Os dados de cultivo, torrefação e moagem foram compilados utilizando o software GaBi6, não incluindo as etapas de produção das embalagens, distribuição e consumo. A pegada de carbono ou potencial de aquecimento global (GWP100) foi estimada com base no método CML 2001 – *April* de 2013 – *Global Warming Potential* (GWP 100 anos).

Resultados e Discussão
As emissões de gases de efeito estufa – GEE do café torrado e moído foram estimadas e são apresentadas na Figura 2. Uma redução do consumo de fertilizantes e corretivos foi observada quando os resultados do cultivo de café convencional para as safras de 2016/17 e 2017/18 (Coltro et al, 2020) foram comparados com os valores obtidos no estudo realizado anteriormente para as safras de 2001/02 e 2002/03 (Coltro et al, 2006). Portanto, foi observada uma redução nas emissões de GEE (pegada de carbono) para o café grão verde produzido, o que indica a adoção de melhores práticas de produção.

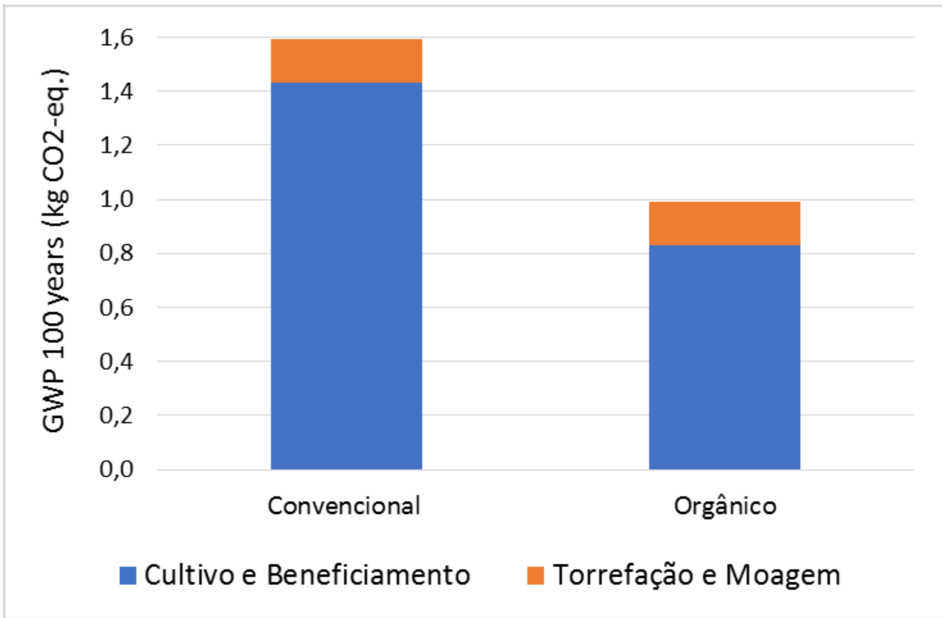

Figura 2. Emissões de GEE (GWP_{100}) do café torrado e moído para a unidade funcional de 1,0 kg.

As emissões de GEE do café convencional torrado e moído foram estimadas em 1,59 kg $CO_{2\text{-eq}}$. kg^{-1}, onde a etapa de cultivo do café contribuiu com 90% e a etapa de torrefação e moagem contribuiu com 10% das emissões de GEE. Em relação ao café orgânico torrado e moído, as emissões de GEE foram estimadas em 0,99 kg $CO_{2\text{-eq}}$. kg^{-1}, onde a fase de cultivo do café contribuiu com 84% e a fase de moagem e torrefação com 16% das emissões de GEE.
O impacto da produção orgânica é muito menor do que o impacto da produção convencional, pois a produção de fertilizantes sintéticos (NPK) requer muitos recursos naturais e energia, os quais contribuem para as emissões de GEE. O impacto da etapa industrial de torrefação e moagem é bem menor do que a etapa agrícola, o que já era esperado uma vez que o consumo de energia

(eletricidade e combustíveis) é bem menor nesta etapa do que na etapa de cultivo, a qual inclui os tratos culturais e colheita do café com o emprego de maquinário movido à diesel.
Como a etapa agrícola é a etapa de maior contribuição para a emissão de GEE as melhorias devem se concentrar nesta etapa, ou seja, aumento da produtividade, menor consumo de insumos, otimização das etapas de transporte são alguns exemplos que podem contribuir para a redução da emissão de GEE do produto.
O valor obtido no presente estudo para o café convencional é aproximadamente 15% menor que o resultado obtido por Giraldi-Diaz et al. (2018), que foi 1,89 kg de $CO_{2\text{-eq}}$. kg^{-1} de café torrado e moído produzido no México, com a fase de cultivo representando 67% das emissões de GEE. A maior contribuição da etapa de torrefação e moagem (33%) provavelmente deve-se à diferença na matriz energética dos dois países. A matriz energética brasileira é predominantemente hidroelétrica, o que contribui para menor emissão de GEE e melhor desempenho ambiental dos produtos brasileiros.

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Circular Economy and Environmental Impacts: An application of Territorial Life Cycle Assessment on a French integrated agricultural system.

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Introduction:

Current food systems are responsible for multiple negative impacts on the environment. The intensive use of resources, emissions of pollutants and greenhouse gases, contribute to negative externalities like resource shortages, climate change, and biodiversity decline. Hence, there is a need to design production systems that are more sustainable. As stated in the European Green Deal, Circular Economy (CE) is a key strategy to address the aforementioned issues as well as to achieve the Sustainable Development Goals. This concept aims to narrow, and slow down input loops, thereby increasing environmental efficiency and representing a sustainable pathway for the local economy. However, quantitative tools are needed to assess the environmental performance of these alternative systems. Among them, Life Cycle Assessment (LCA) and Integrated Assessment and Modelling (IAM) are recognized approaches to assess the environmental impacts of agricultural production. Recent proposals have been made to broaden the scope of LCA toward territorial systems (T-LCA) addressing methodological issues related to system boundaries and multifunctionality (Loiseau et al. 2018) while IAM has been recently applied to assess performances of territorial crop-livestock systems (Catarino et al. 2021). The study aims at applying a new approach coupling IAM and T-LCA for evaluating environmental sustainability performance of crop and livestock farming systems embedded into a linear global production market or a territorial circular one based on exchanges between both types of system (Moraine et al., 2016).

Material and method:

Investigated farming systems are located in the District of Pays de Pouzauges in the Vendée, centre-west of France, a rural area characterized by grassland used for livestock grazing and crop cultivations. A total of 7 farms (70 hectares), 5 arable farms (AF), and 2 livestock farms (LFV, 100 cows on average), are taken into account for the analysis. The baseline global market scenario is compared to a synergetic circular one in which livestock feed ingredients (grain legumes) and organic fertilizers (manure) are shared by AF and LFV. Catarino et al. (2021) developed and assessed these two scenarios using MAELIA, a spatial agent-based integrated assessment and modelling (IAM) platform.

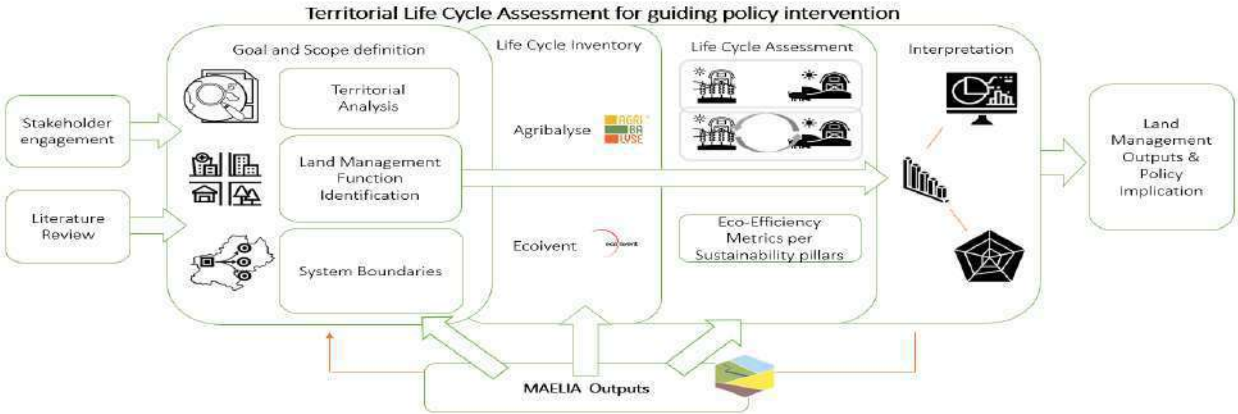

Figure 1: Summary of methodological steps. (Author elaboration)

The general methodology of the studies relies on the use of MAELIA simulation outputs from 2005 to 2017 to feed the T-LCA framework. The latter is then used to assess annual average of environmental performances of both scenarios (see Figure 1). Specifically, the first step of T-LCA defined as goal and scope (Figure 1), deal with system boundaries (SB) definition according to the total territorial perspective (Loiseau et al. 2014), and land management functions identification. SB definition means taking into account all direct and indirect impacts that occur inside the upstream and foreground system until the territorial gate as shown in Figure 2. The foreground system includes all agricultural practices from soil tillage to harvest for crops, and production of fodder, breeding, and tenure management for the livestock. The background system considers all the imports of products and services used by crop and livestock systems (i.e., feed, fertilizers, seeds, equipment,…). Concerning the design of scenarios, the main difference between SB is related to feed and manure. Those, in the baseline scenario, are included in the background system. Contrary to the synergic scenario where they fall into the foreground system.

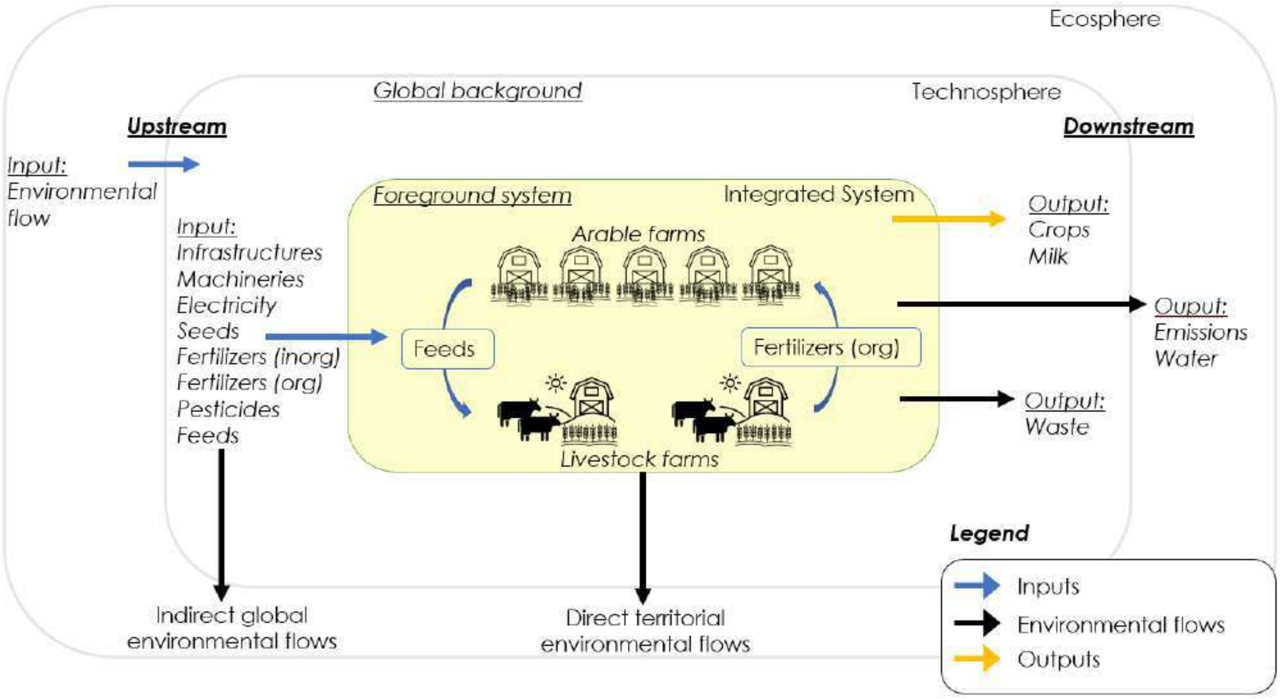

Figure 2 - System boundaries representation for the case study. (Author elaboration)

Land management functions are defined accordingly to the basket of services provided by the territorial integrated crop-livestock systems (Moraine et al. 2016). The following three main functions are defined and evaluated: i) energy production (MJ), ii) protein supply (kg), and iii) gross margin (€). The latter assesses the overall economic returns calculated as total revenue minus variable production costs and was used as a proxy of the economic function. The energy and protein contained in crop yields provide a proxy of the overall production capacity of the system. The protein content is also an important characteristic of crop yields for animal feeding.

The second step of T-LCA deals with life cycle inventory (Figure 1). Data collection follows a bottom-up approach and is based on two types of data: i) simulated outputs from MAELIA including yields, inputs (pesticides, fertilizers, water used) and gross margins averaged over the simulation period (2005-2017) and ii) LCA databases: Ecoinvent and Agribalyse. Some MAELIA outputs required processing to be used in the LCA inventories. This is particularly the case for the quantities of fertiliser used in crop systems. Hence, the AGEC-LCI calculator was used to estimate field emissions (Santeros et al., 2020). While emissions related to livestock were quantified accordingly to the Agribalyse report V1.2. Concerning the third step of T-LCA (Figure 1), the Life Cycle Impact Assessment method Recipe 2016 was used to estimate environmental impacts at both midpoint and endpoint levels. Then, as proposed by the territorial LCA framework, eco-efficiency metrics, i.e. a ratio between services provided and environmental impacts, were computed to compare the environmental performance of both scenarios concerning the main services provided.

<u>*Results and discussion:*</u>
Figure 3 shows a decrease of environmental damages in the synergic scenario for all endpoint categories. In the latter scenario, the introduction of grain legumes into rotation, the updated formula for feeding animals and the sharing process between farmers of crops for animal feed and manure as organic fertilizer, prove a reduction of impacts for damages categories for the whole synergic scenario. Specifically, results of endpoint analysis show a reduction of damage of 17% for the resource (RS), 11% for the human health (HH), and 10% for the ecosystem quality (EQ) categories.

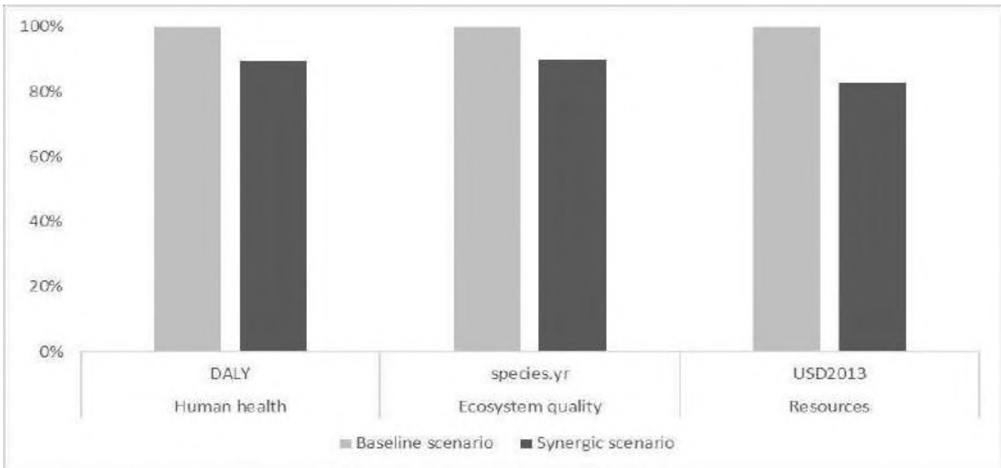

Figure 3 – Comparison of environmental damages between baseline & synergic scenario. Endpoint impact results on the territorial system.

The contribution analysis (Figure 4) provides a deeper insight into the endpoint results. Damages on HH are mainly due to the use of fertilizers and their emissions on the environment. The improvement in the synergic scenario (Figure 3) derived from a reduction in the use of inorganic fertilizers and emissions associated in the environment due to the introduction of the legume crops.

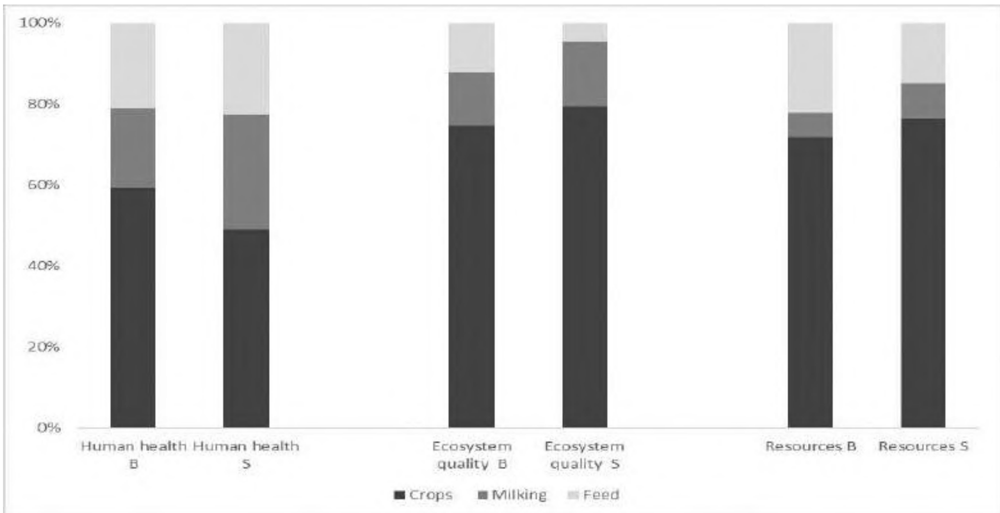

Figure 4 – Contribution analysis at the endpoint level for the baseline and synergic scenario.

For EQ, the main contributions to the damage come from land occupation use. In this case, for the synergic scenarios, the feeds for cow herd are derived from the farms' lands. Furthermore, the exclusion of soja bean as a feed ingredient per cows brings a relevant reduction of impact in the feeding process. Finally, for RS, heat, electricity, and fuel (transport) are the most impacting factors. The introduction of legume crops for animal feed in the foreground system reduces the impact on the feeding process by 7,16% of total damage, mainly reducing transport by see and lorry. Figure 5 shows the eco-efficiency results according to three indicators of functions, and the three end-point damage categories.

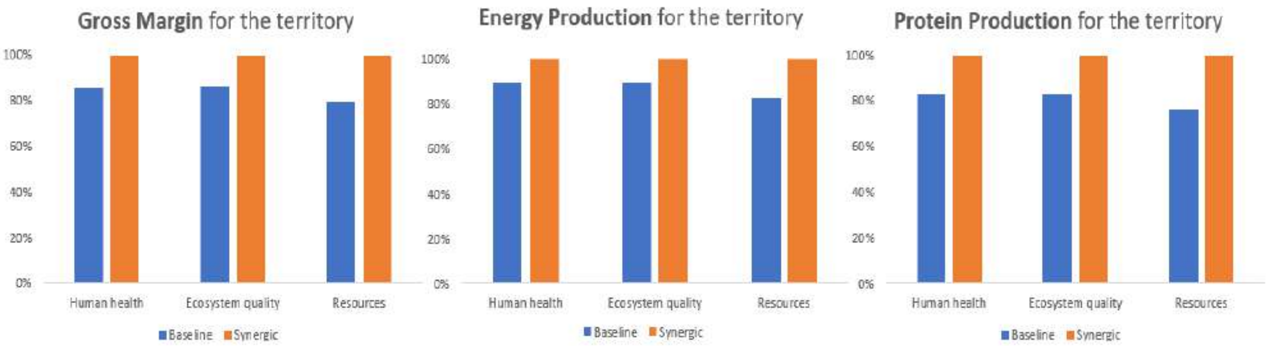

Figure 5 - Eco-efficiency results for the three investigated functions for the Baseline and Synergic scenarios. The higher the eco-efficiency, the more performant the scenario.

The eco-efficiency ratios indicate that the performances of the synergic scenario are higher than the baseline scenario regardless of the function or damage considered. Major results are achieved with protein production and gross margin. The introduction of legume crops for animals' feeds (fava bean and pea) with a low level of costs for LV increase the production capacity in protein content of the overall system reducing the environmental impacts. In addition, the synergic scenario has positive economic consequences on the profit margin for both LV and AF.

Conclusion:

The work carried out showed the feasibility and interest of coupling an IAM model such as MAELIA with T-LCA. MAELIA provides a large amount of relevant data for T-LCA. In return, T-LCA allows to account for environmental impacts of upstream and foreground activities and to assess eco-efficiency of scenarios. The analysis shown positive impacts for the environmental and economic consequences on the case study between territorial self-sufficiency and environmental performances when implementing a circular economy strategy.

Two main perspectives raised during this study. As shown by MAELIA outputs, food systems are highly variable due to climate and market conditions. Performing T-LCA for each year could be interesting to assess these variations and the effects on the performance values. Other interesting investigation would be to explore other perspective scenarios with MAELIA, in particular, the effects of climate change on the environmental performance of agricultural production.

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Environmental impact of biodegradable and polyethylene agricultural mulch film -case study for Norwegian conditions

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Keywords: *biodegradable mulch film; bioplastics; agriculture; environmental impact; LCA*

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Rationale and objective of the work

Plastic mulching materials are used in agriculture as they help to regulate soil moisture content, temperature, and limit the growth of weeds, thus helping to sustain or increase crop (often fruit and vegetables) yield (Steinmetz et al., 2016; Briassoulis and Giannoulis, 2018). Out of the approx. 80 0000 tons of agricultural mulching film that is used on the EU market, 95% are fossil based and up to 30% ends up as microplastics in the soil (resoilfoundation.org, 2021) which causes the current white pollution problem (Dauvergne, 2018). Recycling of fossil-based (Fb) mulch film is often difficult as the film is contaminated with soil and plant residues, which makes it time consuming and expensive for the farmers to collect (Briassoulis and Giannoulis, 2018). As a result, large amounts of plastic go to landfill which leads to negative environmental impact (Le Moine, 2014). Bio-based and biodegradable polymers, usually made from renewable raw materials such as lignin, cellulose, starch and bioethanol, provide crop production benefits comparable to fossil-based mulch film but in addition biodegradable (BioD) films can be tilled into the soil after use thereby offering a sustainable alternative to Fb materials, and lessening problems with agricultural plastic pollution (Razza and Cerutti, 2017). The EU encourages the use of BioD plastics (EC 2019), however, there is a lack of studies evaluating the environmental benefits of the use of BioD mulching films. This study aims to evaluate the environmental performance of Fb and BioD film in the Norwegian context.

Methodology

In this study an attributional LCA methodology was applied with a cradle-to-grave" approach. System boundaries are shown in Figure 1. System expansion was applied where the replacement of virgin polyethylene (PE) from recycling was included in the study.

Vegetable and berry production are the main systems using plastic mulching film in Norway and strawberry production was used to assess plastic mulch film characteristics and amounts used. The functional unit (FU) was set to "1 ha of mulched agricultural land" as it was assumed to be no differences in functionality of Fb and BioD plastic mulch film (Razza and Cerrutti, 2017). It is assumed that the material type does not affect yield levels, but the FU of "kg film used per kg of crop could also be used. Two types of BioD plastic films were included in the study. A film made of a polybutylene adipate terephthalate (PBAT) and starch blend and a film made of modified starch.

The PBAT in the BioD mulch film based on PBAT/starch was modelled from literature data (Brookes, 2007) and the ratio PBAT/starch was 70/20 (Borchani et al., 2015). The modified starch and PE mulch film from was based on Ecoinvent 2 and Ecoinvent 3 data respectively. All processes such as energy use, transport etc was modelled with Ecoinvent 3 data.

The BioD plastic was assumed to be produced in south of Europe and the Fb film in central Europe, then transported to Norway by truck. All mulch film were black, and the BioD mulch film was produced of PBAT and corn starch and had a thickness of 35 um, and weight of 40 g/m^2. The Fb plastic film made of Polyethylene (PE) had a thickness of 32 um, and weight of 50 g/m^2.

For 1 FU approximately 5850 m^2 plastic was needed, resulting in 234 kg of BioD and 292,5 kg of Fb film.

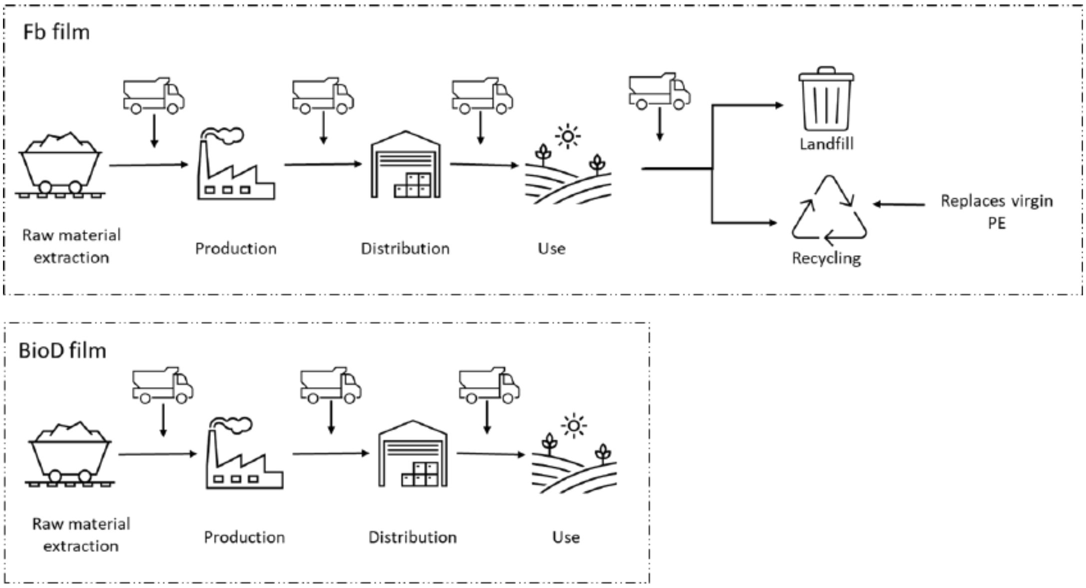

Figure 1. system boundaries of the plastic mulch film studied. FB film= conventional fossil-based film, BioD film= biodegradable film.

At the farm, the mulch film is applied to the soil by tractor. The BioD film is assumed to degrade in soil, but to what extent is currently investigated (Coutris, 2022). Potential emissions from the degradation of the BioD plastic was not accounted for due to lack of data. The Fb film is removed by tractor and transported to the closest waste management facility for either recycling or landfill.
Green dot Norway (Grønt Punkt) is responsible for the collection and recycling of agricultural mulching film in Norway. Approximately 2/3 is recycled at Folldal Gjenvinning, the remaining is exported to recycling plants in Europe, here assumed Germany. The collection rate is estimated at 86% (Mepex, 2018). There is a lack of knowledge regarding what happens to the remaining amounts (14%). It is not likely that a large portion of the film goes to incineration, as the size of the film would require pre-treatment (Mepex, 2018). Pre-treatment is challenging due to contamination of soil and gravel. It can therefore be assumed that the remaining 14% ends up in landfill.
The replacement rate of virgin PE to recycled PE was assumed to be 30%.
SimaPro 9.0 and ecoinvent 3.8 were used to perform the LCA with the Environmental Footprint 3 method (EF 3.0) the impact assessment method adopted in Environmental Footprint transition phase of the European Commission (Fazio et al., 2018; European Platform on Life Cycle Assessment, 2019).

Results and Discussion

Preliminary results show PE to have a lower carbon footprint than BioD mulch film made of PBAT/starch blend, mainly due to the emissions at the production step, see Figure 1. Due to the type of raw materials used and fossil energy use in production of biodegradable PBAT/starch blend, the emissions from recycling and landfill of PE does not outweigh these impacts. However, the modified starch blend has a lower carbon footprint than PE film, due to lower emissions at production compared to PE. For the modified starch blend, several environmental impact categories were lower compared to PE except for non-cancer human toxicity, marine eutrophication, terrestrial eutrophication, freshwater ecotoxicity, land use and water use (Table 1). The PBAT/starch blend performed worst in all impact categories.

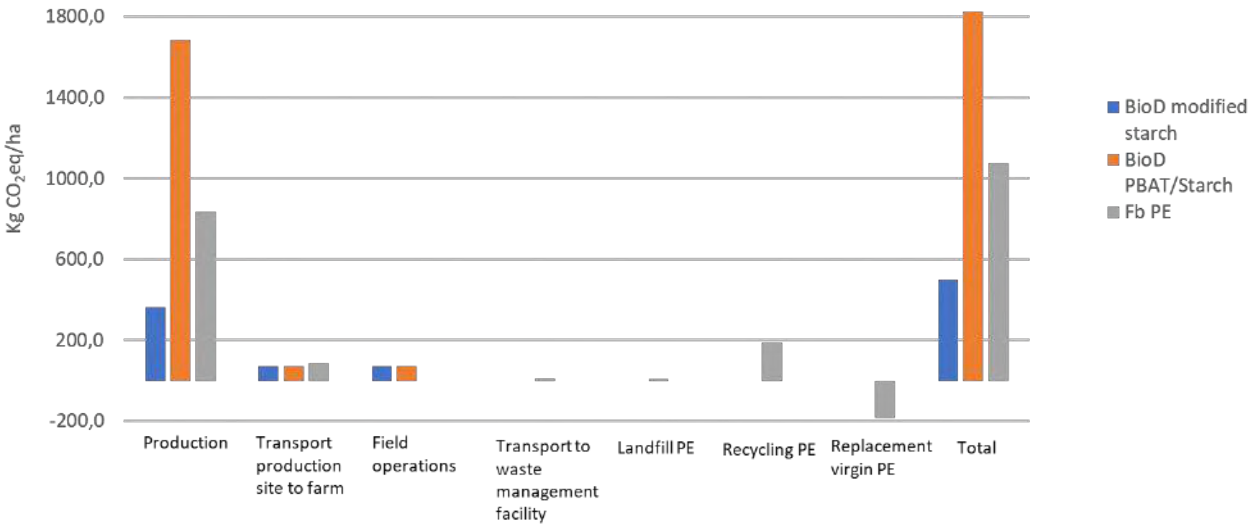

Figure 2. Climate change impact per life cycle step of three plastic mulch films, BioD modified starch, BiD PBAT/starch blend, and Fb PE.

Table 1. Environmental impact of BiOD modified starch and PBAT/starch blend compared to FB muching film, in % Red boxes indicate where the BioD film is performing worse than Fb film. CC=climate change, OD=ozone depletion, PCOF=Photochemical ozone formation, PM=particulate matter, AP= Acidification potential, EP_{fresh}= Freshwater Eutrophication Potential, EP_{marine}=Marine Eutrophication potential, $EP_{terrest}$= Terrestrial eutrophication potential, $Ecotox_{fresh}$=Freshwater ecotoxicity, LU=Land use, WU=water use, $RU_{fossils}$= resource use fossil, $RU_{minerals\ and\ metals}$, Resoource use minerals and metals.

	CC	OD	IR	PCOF	PM	$Ht_{non-cancer}$	HT_{cancer}	AP	EP_{fresh}	EP_{marine}	$EP_{terrest}$	$Ecotox_{fresh}$	LU	WU	$RU_{fossils}$	$RU_{minerals\ and\ metals}$
Unit	kg CO2 eq	kg CFC11 eq	kBq U-235 eq	kg NMVOC eq	disease inc.	CTUh	CTUh	mol H+ eq	kg P eq	kg N eq	mol N eq	CTUe	Pt	m3 depriv.	MJ	kg Sb eq
BioD film, modified starch	46 %	71 %	54 %	50 %	71 %	127 %	93 %	80 %	81 %	106 %	103 %	160 %	169 %	182 %	27 %	89 %
BioD film, PBAT/Starch	170 %	1240 %	167 %	94 %	125 %	135 %	200 %	132 %	178 %	103 %	108 %	160 %	129 %	218 %	95 %	129 %

There is a lack of studies evaluating biodegradable plastic films (Razza and Cerutti, 2017) but a previous LCA study found biodegradable mulch film to outperform Fb film in all impact categories studied, including different waste management options for Fb film (Razza et al., 2010). Biobased plastics share common characteristics with BioD plastics and data shows that it is unclear whether biobased plastics perform better than Fb plastics from an environmental perspective (Walker and Rothman, 2020) mainly due to methodological differences between studies. However, bioplastics can perform worse compared to Fb plastics when it comes to acidification, eutrophication and photochemical ozone potential and land use as crop production often is necessary to produce the material (Yates and Barlow, 2013). The carbon footprint of biobased material can often outperform the Fb based (Spierling et al., 2018) but is dependent on the raw material mix, which is in line with this study.

The data used for assessing biodegradable plastic films are old and possibly outdated. There is a lack of LCI data for biodegradable plastic, thus evaluating the possible benefits of replacing Fb plastic mulch film with BioD films is difficult. There is also the potential effect of degradation rate of the BioD mulch film, the microplastic littering and its effect on the soil environment, which are due to be assessed in this study.

Conclusion

The production phase appears to be the main contributor to the environmental impact for both Fb and BioD film and depending on raw material selection and energy source in production, BioD mulch film does not appear to be more environmentally sustainable compared to the PE film used in this study. However, the data available for production of BioD mulch film is old and need to be updated to enable a fairer comparison. There is a need for improved transparency in the production of BioD plastic film as there is currently not enough evidence to advise farmers to change to BioD mulch film for environmental reasons.

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Embedding circularity into the transition towards sustainable agroforestry systems in Peru

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Introduction
Peru is granting agroforestry concessions (i.e., here referred to as CUSAF), aiming to halt the deforestation of tropical forests caused by smallholder farmers (SERFOR 2017). However, deficient soil conservation practices and nutrient management are common among the targeted smallholders and could hamper the success of CUSAF (Van-Heurck et al. 2020; Pokorny et al. 2021). One solution for this could be applying soil amendments (i.e., compost, biochar, manure), which are beneficial for soil recovery and carbon sequestration (Gay-des-Combes et al. 2017; Shrestha et al. 2018).

In Peru, food loss and waste (FLW) is around 45% of the total food produced (Bedoya-Perales and Dal' Magro 2021). Most of this waste ends up in mismanaged disposition sites, but this is transitioning to the use of landfills, which could reduce its social and environmental impact (Ziegler-Rodriguez et al. 2019). However, most Peruvian landfills lack gas or energy recovery systems, which could lead to increases in greenhouse gases (GHG) emissions (Vázquez-Rowe et al. 2021).

Composting is a waste valorization practice that allows the reutilization of nutrients contained in biowaste as fertilizers. This could mitigate GHG emissions in Peruvian landfills and provide a soil amendment input for CUSAF, leading to a waste management 'circular urban-rural nexus'. Although previous studies explored the GHG mitigation potential of different waste management technologies for the Peruvian context (Vázquez-Rowe et al. 2021), composting was not assessed. Quantifying compost volumes that could be obtained from biowaste, and its GHG mitigation potential, is key to start the discussion on circular solutions for waste management, and also to dimension the potential provisioning of circular fertilizers for agricultural production systems such as CUSAF. To this aim, the objectives of the current study are to: i) calculate GHG emissions related to compost elaboration compared to current waste management strategies; and, ii) estimate the total area that could be fertilized with compost under the CUSAF mechanism.

Materials and Methods
In this study, we explore the potential of valorizing municipal biowaste as compost and using it as a soil amendment in coffee agroforestry systems and silvopastoral systems. This analysis was based on a purely biophysical basis and focused on four Peruvian coffee-growing regions (Amazonas, Cajamarca, Junín and San Martín) and the most populous city in each of them: Chachapoyas, Cajamarca, Huancayo and Tarapoto, respectively.

First, we estimated the potential area of agroforestry systems that could be included under the CUSAF mechanism using available geographical data (Vargas, Montalban, and Leon 2019; SINIA 2020; SERNANP 2022; MINCUL 2022; SERFOR 2020) and census data from IV CENAGRO (INEI 2012).

All data used to model the fertilization potential and GHG emissions (i.e., volumes of municipal biowaste, biowaste-compost ratios, compost emissions, compost nutrient composition) was obtained from the literature (Vázquez-Rowe et al. 2021; Gustavsson, Cederberg, and Sonesson 2011; Bogner et al. 2007; UNFCC 2017; IPCC 2013; EEA 2019; Wernet et al. 2016; Boldrin et al. 2009; Yeo et al. 2020; Mertenat, Diener, and Zurbrügg 2019).

After this, we calculated the area that could be fertilized with compost under the CUSAF mechanism. For lands under coffee production, it was assumed that 90 kg N ha^{-1} (i.e., 50% of the N requirements) should come from compost. This was based on previous research, which showed that a compost application of 50%N improves soil characteristics. In contrast, at a dose of 100%, different soil parameters (e.g., pH, P, and K, Ca and Mg antagonism) get unbalanced (Martins Neto et al., 2020). For pastures, the requirement was 40 kg P ha^{-1}, which has been successfully used in the establishment of silvopastoral systems in degraded pastures of the Peruvian Amazon (Alegre et al., 2017).

This study's methodology was based on available resources, which implied some limitations. CUSAF areas were estimated using the most precise available zoning maps and census data, which could be updated. Additionally, fertilization potential considered some rough FLW ratios and both GHG emissions and fertilization requirements were based on literature. Finally, the biophysical focus of this study omits some socio-economic implications, such as the drivers of stakeholders' participation in waste segregation, that could affect its practical application and should be assessed.

Results and discussion

We found that composting could lead to substantial GHG reductions compared with the current waste disposal methods (i.e., deep dumping and landfilling), as it only emits 5-10% of the GHG emissions produced with the other methods. This implies the potential to avoid 1223 – 2409 kg CO_2 eq. per tonne of biowaste. When accounting for all cities, composting could reduce waste-associated GHG emissions by more than 92,000 tonnes CO_2 eq per year and provide the food system with more than 20,000 tonnes of compost to be used as a soil amendment. Nonetheless, the area of agroforestry and silvopastoral systems that could be fertilized with compost obtained from the main city of each region is insufficient. If all compost were to be used for the coffee agroforestry system, less than 3% of the coffee agroforestry area could be fertilized, while only 4% of the pastures area would be attained. Large amounts of compost could be obtained from Lima (i.e., 226,000 tonnes), the most populated city in the country. Although transporting compost from Lima to the coffee regions would lead to additional GHG emissions, these additional emissions (i.e., from 121 kg CO2 eq to 131 kg CO2 eq per tonne of biowaste composted and transported 1000 km) would still result in overall GHG reductions compared to current practices.

Conclusion

We explored from a biophysical perspective the fertilization and GHG mitigation potential of an urban-rural circular system in which compost obtained from municipal biowaste is used to fertilize concessions of coffee agroforestry systems and silvopastoral systems in Peru. Although some estimates could be refined and socio-economical implications should be assessed, our study evidences that composting municipal biowaste could lead to drastic GHG emissions reductions in the Peruvian waste management system, compared to the current carbon-intensive dumping and landfilling practices. Furthermore, soil nutrient management and GHG emissions reduction could contribute to Peru's Nationally Determined Contributions (NDCs) related to agroforestry, soil management and waste management. However, the potential land fertilized with compost reported in this study is limited. This implies its mainstream use as fertilizer will require mixing with N-rich sources and assessing if bringing compost from other regions or smaller towns would be economically feasible.

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Life cycle effects of health promoting feed additives in Whiteleg shrimp (*Penaeus vannamei*) and Gilthead seabream (*Sparus aurata*) in aquaculture

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Abstract

Purpose. Seafood products have a crucial role in the global food systems being valuable sources of nutrients essential for healthy diets. Widespread and severely damaging diseases are a major challenge that threaten sustainability of farm operations. The use of functional feed ingredients and feed additives have shown to improve the animal performance and reduce the effect of diseases. In this study the environmental impact of the application of a functional feed additive was investigated.

Methods.

The lifecycle effect of Sanacore® GM was assessed in different application strategies for Whiteleg Shrimp (*Panneaus vannamei*), based on data obtained from a farm trial. In farm conditions with high disease pressure and for different disease pressures for Gilthead seabream (*Sparrus aurata*) in the Mediterranean sea based on insights from a veterinarian active in the region. The LCA study was performed according to ISO 14040/44 (2006; 2006), the LEAP guidelines for feed additives (FAO, 2020a) and the PEFCR for marine fish draft for public consultation (2021) using Simapro.

Results and discussion.

The carbon footprint of shrimp was reduced by approximately 15% to 40% compared to the baseline without Sanacore® GM. The environmental footprint of gilthead seabream 7.5% for all assessed impact categories. In both cases production of Sanacore® GM does not have a significant contribution to the footprint of the seabream. Various sensitivity assessments were performed. These showed that there are significant uncertainties in the absolute results. However, these uncertainties did not influence the conclusions substantially as the observed LCA effect remains the same.

Conclusion.

For the use of Sanacore® GM for aquaculture production we can conclude that the feed additive can significantly reduce the environmental footprint. In the case of shrimp production significant reductions were observed in both corrective application and preventive & corrective application of Sanacore® GM. For the use of Sanacore® GM for gilthead seabream production we can conclude that the environmental footprint of gilthead seabream production is significantly reduced in systems with low, medium and high disease. For both shrimp and seabream systems the production of Sanacore® does not have a significant contribution to the footprint of the seabream.

Introduction

Seafood products have a crucial role in the global food systems being valuable sources of nutrients essential for healthy diets (FAO, 2020b). Seafood is an important source of protein, providing 11.7% of the global animal protein supply (FAO, 2020b). Currently, more than 50% of the global shrimp supply originates from aquaculture with an estimated production volume between five and six million tonnes in 2018 (FAO, 2020b), making it one of the largest consumers of aquafeed (Tacon and Metian, 2015) and most valuable aquaculture production group [2,3]. However, Shrimp aquaculture still faces the major challenge to overcome widespread and severely damaging diseases that threaten sustainability of farm operations.

The use of functional feed ingredients and feed additives have shown to improve the animal performance and reduce the severity of infections (Dawood et al., 2018). Sanacore® GM is one of these feed additives that reduce mortality by supporting the gut function and immunocompetence of fish and shrimp resulting in better disease resistance and improved survivability (Coutteau, 2014; Palenzuela et al., 2020). However, the lifecycle impacts of these interventions remain relatively unknown.

The lifecycle effect of Sanacore® GM was assessed in different application strategies for Whiteleg Shrimp (*Penaeus vannamei*), based on commercial farm data with high disease pressure (Mamora et al., 2021) and for different disease pressures for Gilthead seabream (*Sparus aurata*) the Mediterranean sea based on insights from a veterinarian active in the region. The LCA study was performed according to ISO 14040/44 (2006; 2006), the LEAP guidelines for feed additives (FAO, 2020a) and the PEFCR for marine fish draft for public consultation (2021) using Simapro.

Methods

For the LCA of feed additives it is important that the overall animal value chain is defined in such a way that all potential impacts are included. A minimum requirement on system boundaries, is that all modes of change from the addition of the feed additive should be included (Blonk et al., 2021). The effect of Sanacore® GM is supporting the gut function and immunocompetence of the animal. This in turn reduces mortality and consequently improves the economic feed conversion ratio (EFCR) and system productivity. No effects on the composition, or quality of the aquaculture product have been identified. Therefore, system boundary considered in this study was the cradle to farm exit gate.

In this assessment we modelled 2 systems, an intensive Whiteleg shrimp *(Penaeus vannamei*) pond system in SE Asia (Indonesia) and a gilthead seabream (*Sparus aurata*) system in the Mediterranean Sea (Spain). For shrimp production potential of Sanacore® GM supplementation was assessed in two application strategies, corrective dosing after a disease outbreak was observed and corrective + preventive dose where a small amount of Sanacore® GM was applied throughout the production cycle in combination with an additional dose after a disease outbreak was observed. Data for feed composition, feed use, and energy use was obtained from a farm trial (Mamora et al., 2021). For Gilthead seabream the effect of Sanacore® GM supplementation was assessed based on low, medium and high disease pressures as observed in the Mediterranean Sea for production of 350gr and 500gr liveweight. Data for the farm construction and farm activities was obtained from literature as a representative farm in the Mediterranean (García García et al., 2016), representative data for feed composition and feed use was based on expert judgement at Adisseo and from a veterinarian active in the Mediterranean.

Sanacore® GM is a feed additive consisting of organic acids, inactivated yeast and yeast extracts with herbal extracts on a mineral carrier (Palenzuela et al., 2020). However, there was no data available on the production of the Sanacore® GM components the GFLI proxy was used. To assess the effect of the proxy we applied a factor to 3 to the impact of the GFLI proxy for Sanacore® GM.

Results and discussion

The use of Sanacore® GM has a strong effect in reducing the footprint of the Shrimp (Figure 1). The reduction in carbon footprint is approximately 16% and 39% relative to the baseline without Sanacore® GM for the 'corrective' and the 'corrective and preventive' scenario respectively. The strongest relative reduction is observed in the stages within the aquaculture farm where improved productivity reduces the energy use (diesel and electricity) and direct and indirect N_2O emissions. Also, the up-stream footprint of the feed is reduced substantially 12% and 36% relative to the baseline without Sanacore® GM for the 'corrective' and the 'corrective and preventive' scenario respectively. The footprint of the additive itself is minor with 0.1% (corrective) and 0.24% (corrective and preventive).

For the seabream the use of Sanacore® GM has a moderate effect in reducing the footprint (Figure 2). The reduction in carbon footprint is approximately 7.5% relative to the baseline without Sanacore® GM for the high, medium, and low disease pressure. The strongest reduction is observed in the upstream feed impact where improved FCR reduces the amount of feed used. Additionally, the impact of farm activities and facilities is reduced substantially due to the increased production. The additional footprint of the additive itself is minor, only constituting between 0.6 % and 1.3% of the total footprint in the intervention scenarios.

Sensitivity analysis

The sensitivity analysis for both the shrimp and the seabream for all soy from the US and all from South America. Shows that even though the impact of the choice of South American soy compared to US soy has a strong impact on the absolute result the relative impact of the intervention scenarios remains identical as feed as the improvement in FCR is the main pathway in which Sanacore® GM reduces environmental impact.

In the baseline the impact of Sanacore® GM is almost negligible, in the sensitivity analysis the increase of the impact of the feed additive production shows no significant effect of the use of the feed additive (Figure 13). Therefore, we can conclude that the use of the GFLI proxy for feed additives does not significantly influences the results of this study.

Conclusion

In the corrective scenario the carbon footprint of shrimp was reduced by approximately 15%. A combined preventive and corrective dose results in a further improvement of 30% relative to the corrective dose, for a total improvement of 40% compared to the baseline. The environmental footprint of gilthead seabream production reduces significantly in systems with low, medium and high disease pressure with approximately 7.5% for all assessed impact categories. In both cases the production of Sanacore® GM does not have a significant contribution to the footprint of the seabream.

In both the shrimp and seabream cases various sensitivity assessments were performed. These showed that there are significant uncertainties in the absolute results. However, these uncertainties do not influence the conclusions substantially as the the observed LCA effect remains the same. In addition, the effects of the Sanacore® GM interventions are robustly substantiated by both laboratory as field trials. Therefore, we can conclude that the addition of Sanacore® GM has a strong potential to reduce the environmental footprint of both shrimp and seabream aquaculture production.

Figure 1: Global warming impact (kg CO2 eq. per kg liveweight shrimp) of the 3 Shrimp scenario's: Without Sanacore® GM, corrective application of Sanacore® GM and preventive and corrective application of Sanacore® GM.

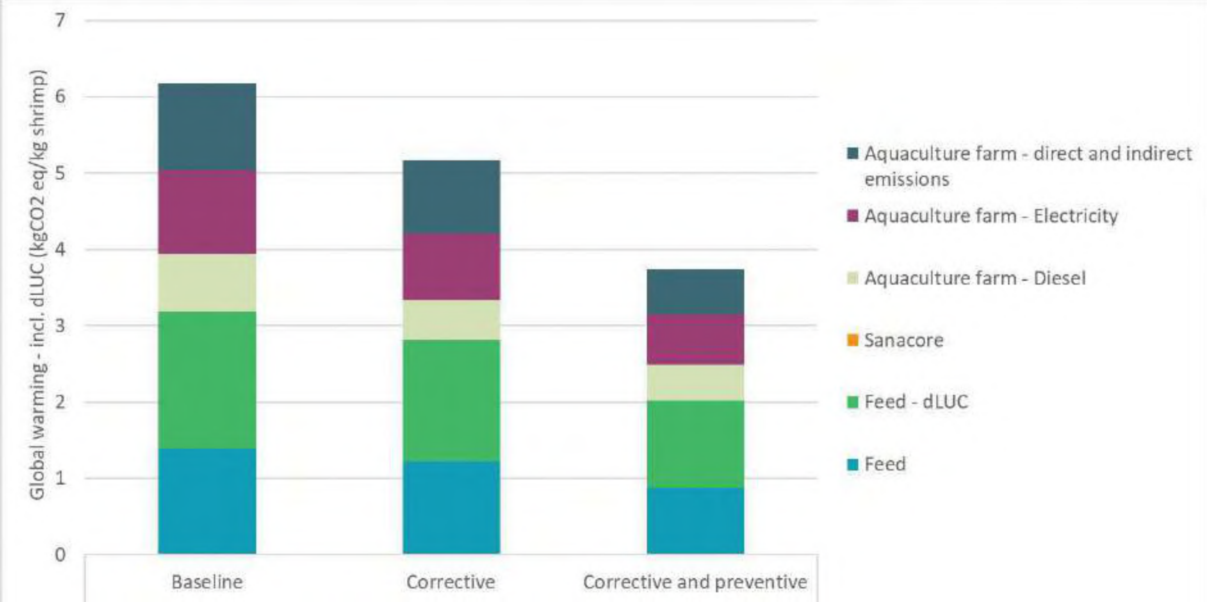
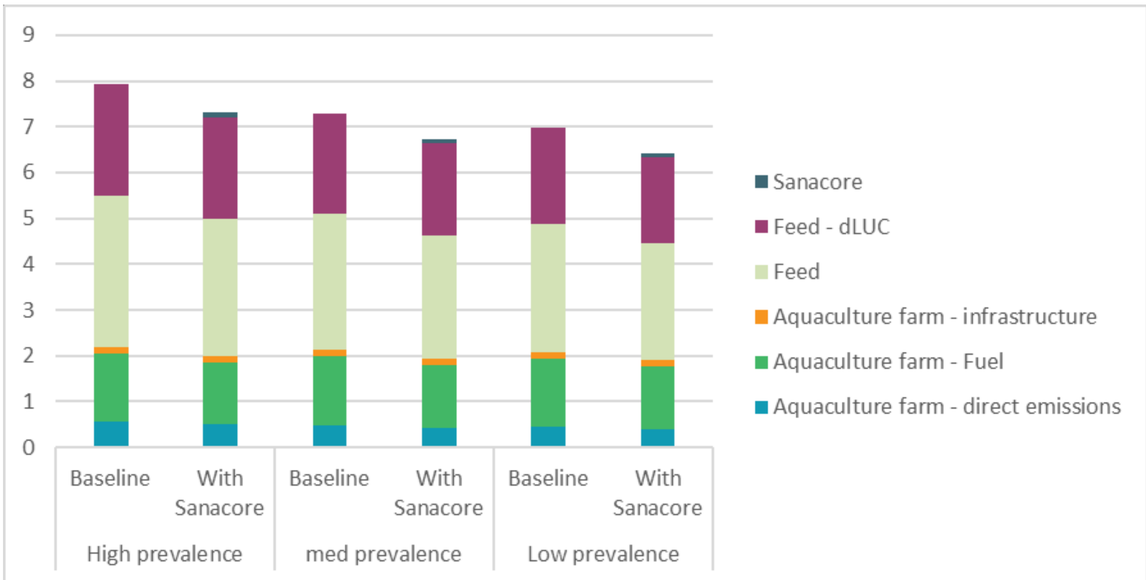


Figure 2: Global warming impact for 350gr seabream at aquaculture farm (kg CO2 eq. per kg liveweight seabream) of the 3 prevalence scenario's: High, med and low prevalence for both the baseline situation and the intervened Sanacore® GM scenario.



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Multifunctionality in rooftop greenhouses: Increasing energy and crop yields through improved covering materials

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Keywords: *urban agriculture; life cycle assessment; greenhouses; resource-use efficiency; integrated modelling; ETFE*

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Rationale and objective of the work

Buildings and greenhouses are great consumers of energy resources and need a plan to decarbonize. Green infrastructures such as rooftop greenhouses (RTG) can aid to improve building envelopes and take advantage of building waste heat to produce crops with fewer energy resources. Thus, RTGs are multifunctional infrastructures capable to produce, among other ecosystem functions, energy and crop yields in a more sustainable way. Thermal and solar energy gains are directly determined by greenhouse covering materials and are a key design parameter to maximize crop productivity. The more solar transmissivity is attained, the higher photosynthetic activity and resource use-efficiency of plants is achieved (Critten et al., 2002; Max et al., 2012). Moreover, covering materials largely contribute to the overall impacts derived from food production in unheated greenhouses (Antón et al., 2012; Boulard et al., 2011; Rufí-Salís et al., 2020; Torrellas et al., 2012), affecting both directly and indirectly the environmental impacts of protected crop cultivation. This work assessed energy and tomato crop yields and their environmental performance of a rooftop-greenhouse covered with a corrugated polycarbonate material in comparison with a flat polycarbonate, a single-4mm glass (with and without anti-reflective coating), and an ethylene tetrafluoroethylene (ETFE) film of 100 and a 60 µm.

Approach and methodology

Multiple side effects derive from choosing a specific covering material and need to be evaluated from an integrated perspective to understand all implications (He et al., 2021; Max et al., 2012). To this effect, here we combined multiple approaches using experimental data combined with energy, structural and crop yield modelling to assess all trade-offs and crop yield lifetime productivity for six assessed scenarios. We based our assessment in a RTG located in the ICTA-UAB building (Barcelona) extensively assessed from multiple perspectives to integrate all these possible trade-offs. All covering materials assessed within scenarios are compatible with the urban environment and displayed similar thermal resistance but differed in terms of photosynthetic active radiation (PAR) transmissivity and lifespans. Two functional units were used to evaluate environmental impacts at the building level (i.e., per m^2 and year), while at the productivity level environmental impacts were measured per kg of tomato produced, accounting for building infrastructure and agricultural production. We performed a life cycle assessment using Ecoinvent 3.8 database with Simapro 9.3. Multiple impact categories were chosen from ReCiPe 2016 and Cumulative Energy Demand impact methods to evaluate both greenhouse building and crop environmental derived impacts.

Main results and discussion

At the building level (per m^2 and year), integrating energy and structural and construction side-effects, environmental impacts varied between -33.2 and +21.0% (except for stratospheric ozone depletion) compared to the current scenario (corrugated polycarbonate). The flat polycarbonate displayed less structural resistance and thus, required more material, rising impacts up to 109%. At the productivity functional level (per kg of tomato, when crop productivity modeling were integrated into the assessment), the greenhouse average lifetime energy yields improved by up to 20.5% with a 4 mm-antireflective glass (AR) compared to the current corrugated polycarbonate covering. This led to an increase of tomato crop productivity from the current 13.6 ± 1.5 kg/m^2 to 19.9 ± 2.3 kg/m^2 with an AR-glass and 19.2 ± 2.2 kg/m^2 with a 60µm-ETFE film. In turn, this reduced impacts in all impact categories analyzed except for stratospheric ozone depletion. The highest reduction compared to the current polycarbonate was achieved with a 60µm-ETFE film (-34.8%), followed by an AR-glass (-33.3%). This resulted into 0.43 ± 0.1 kg CO_2 eq./kg of tomato using an ETFE-film, which is almost half of impacts found in heated conventional greenhouses (Ecoinvent, 2021).

Conclusion

We demonstrated AR-glass and 60µm-ETFE film improved the environmental performance of a polycarbonate-rooftop greenhouse by increasing average lifetime energy yields up to 20.5% and crop yields up to 46.6%. This resulted in 19.9 ± 2.3 kg/m^2 of tomato and a significant reduction of environmental impacts (-34.8%). These environmental values greatly differ from the results accounting only per m^2 and year of greenhouse, in which results were up to 21.0% higher. Thus, we demonstrate the importance of employing an integrated and life-cycle approach to combine multiple trade-offs and greenhouse dynamics within the environmental assessment. These results open the path towards improved environmental sustainability of urban agriculture.

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Contribution of aeroponic farm container system to food security and climate change in the UK

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Keywords: *vertical farming, controlled environment agriculture, life cycle assessment (LCA), climate change adaptation, food supply chains.*

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Introduction

Vertical farming or controlled environment agriculture (CEA) is seen as an alternative to both reducing environmental impact of food system and increasing food security, in particular for urban areas, as provides access to an all year around fast-grown food production system independent of climatic conditions, which could potentially decrease reliance on imported food (Stiles & Wootton-Beard, 2017). Other claims are related to lower requirements of land, reducing waste and water use, keep nutrients in close-loop systems, among other (Stiles & Wootton-Beard, 2017). However, vertical farming is constrained to crops with average high of 40cm (Kozai et al., 2016); for example, herbs and salads, tomatoes, peppers and berries, and flowers.

Literature shows several studies assessing environmental impacts of the most commons vertical farming techniques (Chen et al., 2020), and their comparison with conventional options (De Geyter, 2018). However, there is little known about aeroponic systems. Hence, this study aims to fill this gap by assessing the carbon footprint of aeroponic container farm (ACF) system in the UK to then identify its potential contribution to food security.

Methodology:

This study follows the ISO14040/44 methodology (ISO 206a,b) and uses GaBi Thinkstep Software to model the system, applying ReCiPe (Huijbregts et al. 2017) as impact assessment method to estimate impacts. The scope of the study is from 'cradle to gate', including the production and transport of raw materials and infrastructure, waste management, and operation of the aeroponic container farm. The functional unit is defined as 'the production of 1 kg of pea shoot at farm gate'. The inventory was developed gathering data directly from the system and the background data was sourced from Ecoinvent 3.6 (Moreno et al., 2019). The detailed description of the life cycle assessment including other 17 impacts can be found in Schmidt Rivera et al. (2022).

Results

As seen in Figure 1, the carbon footprint of ACF is estimated at 2.29 kg CO_2eq./kg of pea shoot. The main contributor (82%) is the energy required, in this case provided by the 2017-UK grid, for the operation of the system. It is then important to estimate how decarbonization pathways would make this system more competitive in relation to GHG emissions and contribute to reach climate targets. Figure 1 shows that the expected decarbonization pathways in the UK could reduce the impacts by 65% by 2030, and by up to 74% by 2034. Solar- and wind-powered ACF could also provide a competitive performance, reducing the impacts by up to 80% from the baseline.

a) Decarbonization of UK energy systems b) Aeroponic system vs imported food

Figure 1 Carbon footprint of aeroponic container system including UK decarbonization pathways and renewable energy powered systems

It is important to understand how ACF could contribute to food security and climate change targets. We compare then the production and transportation of imported food from Spain (large food importer in the UK) versus the production of it by ACF, using a representative food – lettuce – with high (3.67 kg CO_2eq./kg product) and low (0.27 kg CO_2eq./kg product) carbon intensity values. As seen in figure 2, ACF performs well when the food production method is high, regardless of the transportation type. However, the solar- and wind-powered ACF systems show the lowest impacts, reducing the greenhouse gas emissions by between 10% and 50% of the impacts of imported lettuce from Spain by any transport type.

Conclusion

Aeroponic container system could contribute to reduce environmental impacts of food production and increase food security in the UK, however the source of power is crucial. This study provides evidence to support industry and policy maker, however a full economic and social assessment is required to understand all the dimensions of sustainability. Finally, vertical farming will not replace conventional agriculture, but it could complement locally grown food initiates in urban and rural areas.

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Life Cycle Assessment of the production of different margarine types in Peru

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Abstract

Purpose: The production of margarine requires a food manufacturing process in which multiple fat-based oils from different types of crops and agricultural practices are used, as well as specific supply and processing. In this regard, this study assessed the environmental profile of five products with different formulations of margarine for the Peruvian domestic market.
Methods: The LCA method was applied with an attributional approach. Production chain data were collected through direct communication with company personnel, suppliers, and the scientific literature. Likewise, an economic allocation approach was considered in the multifunctional processes involved in the manufacture of margarine, from the agricultural stage to its packaged form with a functional unit of 500 g for distribution. To verify the robustness of the results, scenario and sensitivity analyzes were performed for a number of parameters (allocation method, functional unit, energy use, N2O emission factors from managed agricultural soils).
Results and discussion: The global warming potential (GWP) results ranged from 0.52 kg CO2eq. and 0.9 kg CO2eq. Agricultural operations had the highest environmental burdens in most impact categories due to fertilizer use in terms of GWP, eutrophication, or acidification. In addition, the crude oil extraction processes also showed relevant impacts in terms of climate impact and the formation of fine particles, due to emissions into the atmosphere from the effluent ponds of the palm oil plant (POME) and the combustion of the boilers, respectively. On the other hand, the packaging and refining stage had a relatively small impact.
Conclusions: It was found that the environmental impacts vary substantially depending on the type of formulation, quantity and type of fat evaluated, as well as the efficiency of the packaging. Consequently, the key mitigation opportunities include a series of actions to reduce the impacts generated through all phases of production, mainly through the design of the product recipe and better management of agricultural practices.

Keywords: *multi-ingredient foods; palm oil; soybean.*

Introduction

Margarine is a food product that is commonly used for spreading, baking and cooking. Although it is usually seen as a substitutive of butter, its worldwide production is high, making it an important commodity in the food manufacturing sector (Silva et al., 2021). Its production is based on a cocktail of different plant based raw materials, including sunflower, palm, rapeseed and/or soybean as fatty base d oils, which tend to be acquired from a variety of geographical locations. The production of these raw materials and their processing are critical in the production of different margarine formulations (O'Brien, 2008). Therefore, there is a need to evaluate and understand the gap around what happens with the various agricultural products in different regions and how this affects the consumer market. Consequently, the main aim of the current study was to analyze the production of margarine in Peru from a cradle to gate perspective in order to understand the environmental profile of a set of different margarine formulations destined for the Peruvian domestic market.

Material and methods

The scope of the study was focused on a Peruvian food processing company dedicated mainly to the production of multi-ingredient processed foods. A Life Cycle Assessment (LCA) was carried out to calculate the environmental impact of a total of five different margarine items throughout their supply chain from the production of the plant-based raw materials to the final packaging and storage stage prior to domestic distribution to regional distribution centers (Figure 1). Subsystems I and II are linked to the production and transport of the main fatty ingredients that make up margarine: soybean oil from Bolivia, and palm oil and interesterified fat from Peru. Subsystem III focuses on the recipe formulation stage, and other operations that take place within the margarine manufacturing plant. The evaluated products have different levels of fats and amounts contained in different packages. Formulation A (Product 1) and B (Product 2 and 3) contain only 40 and 50% vegetable fat, respectively. In contrast, formulation C (Product 4 and 5) contains 65% vegetable fat, which is mixed with a small amount of powdered milk (approximately 1%). Product 1 has typical aluminum foil wrappers, while the other products are packaged in polypropylene pots of different weights. In order to estimate the environmental impacts of margarine production the present study defined 500 g of packaged margarine recipe (products intended for spreads) as the main functional unit (FU).

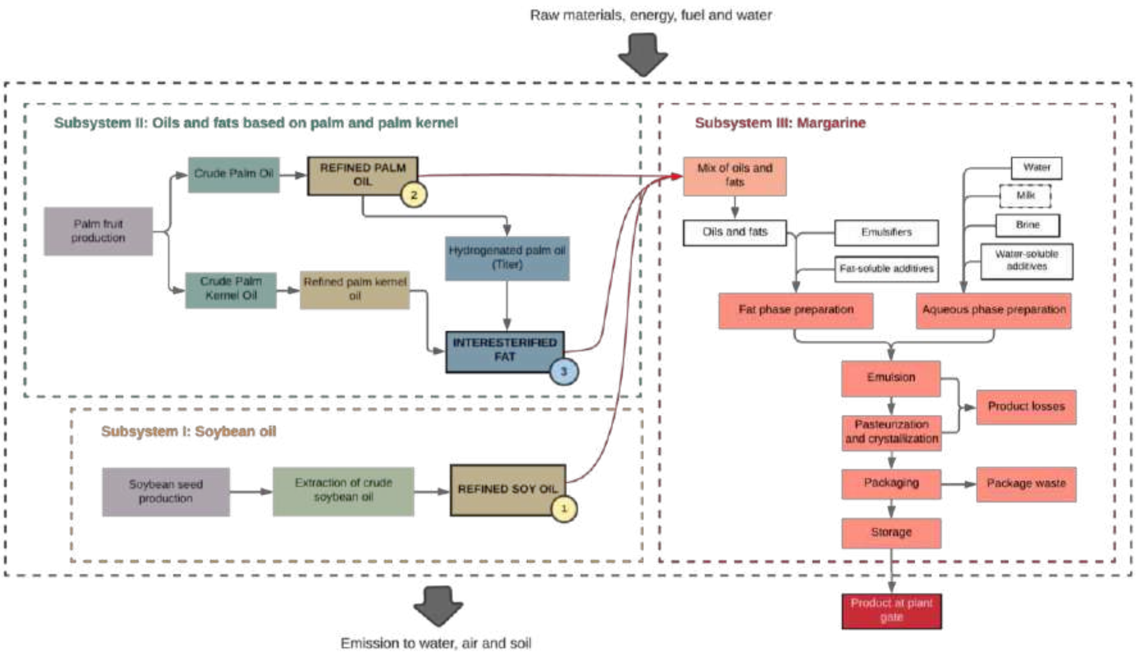

Figure 1. System under study for the production of margarine

The approach used for the analysis was attributional. Primary data from the margarine production chain (i.e., raw materials, processing, packaging, and logistics) were collected through direct communication with company staff and suppliers, whereas the secondary data for the foreground system were retrieved from the scientific literature. The life cycle modelling was performed using the ecoinvent 3.7 database for background information. An economic allocation approach was used in order to account for the co-products that are generated in the production of soybean and palm oil. The life cycle impact assessment results were estimated using ReCiPe 2016, although IPCC 2013 was used to computed greenhouse gas (GHG) emissions. The software used for computation was the SimaPro v9.3 software. In addition, a sensitivity analysis was carried out for a series of parameters or key aspects (e.g., allocation method, alternative functional unit, energy use for production of the different margarine products, emission factors to estimate direct N_2O emissions from managed agricultural soils) in order to verify the robustness of the results and to evaluate the influence of uncertainty on the comparison with other margarine products in the literature and butter

(Nilsson, 2010; Liao et al., 2020). Likewise, a scenario analysis was conducted in order to account for differences in palm production in the Peruvian Amazon.

Results and discussion

Results, which include 18 impact categories, were reported for each final packaged margarine product. In this way, the results of the global warming potential (GWP) ranged between 0.52 kg CO_2eq. and 0.9 kg CO_2eq., mainly due to differences in packaging and type of formulation (Figure 2).

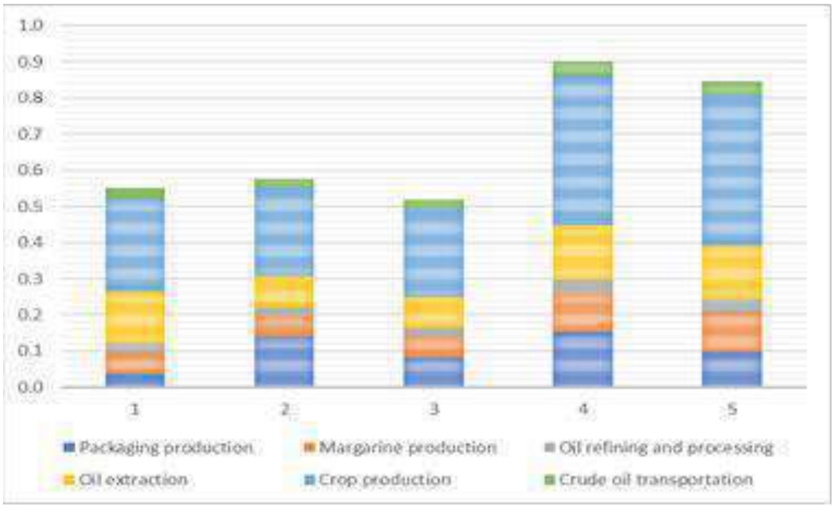

Figure 2. Environmental burdens for each individual product by GWP impact category (reported data per functional unit: 500 g mass per packaged product ready for distribution)

The production of the ingredients that are incorporated into the emulsion (fat phase + aqueous phase) constituted more than 67% of the total impact per finished product. Fundamentally, the emissions are linked to the proportion of the fat component of the different recipes. These represent more than 90% of the CO2eq of emissions of the total impact of the emulsion, the largest contributions were attributed to the production of refined soybean oil (SBS I, with the highest contribution), interesterified fat (SBS II) and, finally, refined palm oil (SBS II). GHG emissions related to other raw materials only represented an average 2.3% in the case of formulation A and B (products 1, 2 and 3), of which emulsifiers are the main contributors with a 1.5% contribution. In the case of margarine products 4 and 5 (Formula C), the contribution of the production of other raw materials amounts to approximately 7.3%. This more than five-fold increase is basically derived from reconstituted skim milk in the aqueous phase of the emulsion, whose emissions increase from the production of raw milk to its modification into skimmed milk powder, within the manufacturing process (Allia et al. al., 2018). Thus, a relationship between the amount of fat present in the recipe and the impact associated is clarified, which is why formulation C has greater impacts.

For the group of margarine formats studied, agricultural operations had the highest environmental burdens in most impact categories, driven by on-site fertilizer production and emissions in terms of GWP, eutrophication, or acidification (see Table 1). On the one hand, crude oil extraction processes also showed relevant impacts in terms of climate impact and formation of fine particles, due to air emissions from the palm oil mill effluent (POME) ponds and the combustion of the boilers, respectively. The main air emission from the POME ponds during the anaerobic digestion was biogas which is mainly composed of methane (50-75%), among other gases in lower concentrations. On the other hand, the packaging stage had a relatively small impact. However, the choice of polypropylene production for pots rather than aluminium foil translated into higher impacts. Finally, the refinery was the stage with the least impact throughout the entire system, even below the impact caused by the transportation of crude oil from other regions of the country and abroad.

Consequently, the formulation of the recipe, the agricultural practices, the choice of oil ingredients or the supply chain sourcing triggered the main variations of environmental impact that were identified among the margarines.

Table 1. Environmental burdens for each individual product by impact category (data reported by functional unit: 500 g of mass per packaged product ready for distribution).

Impact categories	Unit	1	2	3	4	5
Global warming potential	kg CO2 eq	5.51E-01	5.76E-01	5.18E-01	9.00E-01	8.46E-01
Stratospheric ozone depletion	kg CFC11 eq	4.31E-06	3.73E-06	3.72E-06	6.58E-06	6.56E-06
Ionizing radiation	kBq Co-60 eq	8.29E-03	8.40E-03	7.90E-03	1.35E-02	1.27E-02
Ozone formation, Human health	kg NOx eq	2.04E-03	1.96E-03	1.85E-03	3.14E-03	3.03E-03
Fine particulate matter formation	kg PM2.5 eq	1.14E-03	9.58E-04	9.04E-04	1.58E-03	1.53E-03
Ozone formation, Terrestrial ecosystems	kg NOx eq	2.14E-03	2.04E-03	1.92E-03	3.27E-03	3.15E-03
Terrestrial acidification	kg SO2 eq	2.99E-03	2.44E-03	2.30E-03	4.20E-03	4.06E-03
Freshwater eutrophication	kg P eq	1.70E-04	1.61E-04	1.52E-04	2.62E-04	2.50E-04
Marine eutrophication	kg N eq	5.27E-04	3.64E-04	3.60E-04	6.57E-04	6.49E-04
Terrestrial ecotoxicity	kg 1,4-DCB	2.21E+00	1.68E+00	1.63E+00	2.79E+00	2.73E+00
Freshwater ecotoxicity	kg 1,4-DCB	2.11E-01	2.45E-01	2.43E-01	4.10E-01	4.08E-01
Marine ecotoxicity	kg 1,4-DCB	1.62E-01	1.23E-01	1.21E-01	2.04E-01	2.02E-01
Human carcinogenic toxicity	kg 1,4-DCB	1.02E+00	5.53E-01	5.50E-01	9.30E-01	9.27E-01
Human non-carcinogenic toxicity	kg 1,4-DCB	1.52E+00	1.02E+00	9.85E-01	1.67E+00	1.63E+00
Land use	m2a crop eq	8.76E-02	7.26E-02	7.02E-02	3.86E-01	3.81E-01
Mineral resource scarcity	kg Cu eq	1.89E-03	2.14E-03	2.00E-03	3.48E-03	3.34E-03
Fossil resource scarcity	kg oil eq	1.00E-01	1.76E-01	1.35E-01	2.33E-01	1.99E-01
Water consumption	m3	1.02E-02	1.48E-02	1.21E-02	1.84E-02	1.63E-02

The scenario analysis revealed that the climatic impacts of the products could vary according to the production region, whose changes are mainly associated with agricultural practices and soil types. On the other hand, from the analysis of the emission factors, it is identified that the GHG emissions derived from in situ fertilization were mainly related to N2O emissions. For example, in tropical areas similar to Venezuela, N2O emissions could be substantially lower (Marquina et al, 2013).
Regarding the sensitivity analysis, the economic allocation attributes a greater portion (at least 34%) to the environmental burden of the products of interest throughout the production chain compared to the mass allocation, especially in the processes of crude vegetable oil extraction. This gives us insights that the economic allocation application is a fairly conservative allocation approach. In addition, the alternative FU analysis was carried out to determine if the differences in the environmental impact of butter and margarine are attributable to the product content necessary to provide 500 g of fat depending on the type (animal or vegetable), since most of margarines have a lower fat content than butter. The results corresponding to the FU with equivalent fat content in butter and margarine showed a percentage increase of 25% in kg CO2eq and at least 117%, respectively, compared to the results obtained considering a FU based on mass. In this way, in line with recent studies (Liao et al., 2020), despite range of results obtained, results for margarine production had a significantly lower climate impact compared to the production of butter according to the scientific literature (Nilsson, 2010; Djekic et al., 2014; Üçtuğ, 2019). This occurs regardless of the choice of functional unit (mass or fat based) or grain/oilseed allocation approach.

Conclusions

This study contributes to the environmental understanding of multi-ingredient processed products from plant-based fat carried out in Latin America. To sum up, it is identified that the environmental impacts computed vary substantially according to the type of formulation (i.e., quantity and type of fat evaluated) and the efficiency of the packaging. Consequently, the key mitigation opportunities include the reduction of impacts generated by the cultivation of oilseeds through the design of the product recipe and better management of agricultural practices. Improvement practices also involve other stages in the supply chain such as the capture of biogas as a source of renewable energy in the extraction stage, the efficiency of packaging or the evaluation of alternative containers analyzed in the downstream.

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Análisis de efectos ambientales del modelo de economía circular de la valorización de descartes y mortalidades de salmones

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Chile es el segundo productor y exportador de salmón a nivel mundial con más de 800 kt anuales, aportando en torno al 30% de la producción mundial, siendo sólo superado por Noruega con 44% (Cerda, 2019). Además, exporta el 82,6% de su producción nacional, principalmente en productos como filete fresco enfriado a Estados Unidos, entero congelado a Japón y entero fresco enfriado a Brasil, generando ganancias de 5.160 millones de dólares, equivalente al 1,7% del Producto Interno Bruto (Banco Central, 2020). En Chile el 70% de los smolts son producidos en piscicultura, un 14% en lagos, un 6% en estuarios y un 4% en ríos (Quiñones, 2018). En el año 2019 se cosecharon 989 kt de salmónidos, concentrándose la actividad de cultivo en la zona sur del país, específicamente en la IX región de Aysén (49%), X región de Los Lagos (40%), y XII región de Magallanes (11%) (SUBPESCA, 2018).

La producción de salmones genera residuos en las distintas etapas de su ciclo de vida. Los principales son lodos, mortalidades, y descartes del procesamiento del salmón. En la etapa de cultivo se generan mortalidades, En el año 2018 la tasa de mortalidad de la industria salmonera fue de un 6% (SalmonChile, 2019). En Chile, se utiliza el método de ensilaje para el manejo de las mortalidades. Este método consiste en la transformación de la mortalidad mediante una molienda y adición de ácido fórmico. Esto permite generar valor agregado en la cadena de producción, a través de la generación de productos como aceites, y alimentos proteicos para el consumo animal. Cosechado el salmón, se estima que entre el 50% al 65% es aprovechable para consumo humano, el porcentaje restante corresponde a descartes (vísceras, cabezas, colas y desechos de recortes). Dependiendo de la especie, entre el 50% al 61% de los descartes corresponden a cabezas y hueso collar; entre el 11% al 16% a cola y espinas, mientras que el resto, corresponde a hígado, ovas, tracto digestivo y corazón (Wing,2018). A nivel mundial se ha estimado que las cantidades anuales de descartes oscilan entre 42 y 44 Mt (Abdollahi, 2020). En Chile, el 74,4% de los residuos generados por la salmonicultura se dispones en rellenos sanitarios, el 24,4% se recicla, y 1,2% tiene otra disposición (SUBPESCA, 2018). En general, La mayor parte del sector de la pesca mundial no está organizado y tiene problemas para eliminar los descartes asociado a los procesos de producción de productos para el consumo humano. Muchos de estos residuos, son depositados en vertederos, que en ocasiones pueden no estar controlados (Kumar, 2010). Por este motivo, el objetivo de este estudio fue analizar los efectos impactos del ciclo de vida del modelo de economía circular de la valorización de mortalidades y descartes de la industria salmonera.

La metodología de análisis del ciclo de vida fue utilizada siguiendo los requisitos metodológicos establecidos en la ISO 14044. En este sentido, se analizó el ciclo de vida de los productos que nacen a partir de 2 procesos de valorización de residuos de la industria de salmones. El primero es el proceso de hidrolizado, el cual utiliza los descartes de salmones para producir harina, aceite, e hidrolizado proteico. El segundo, el proceso de ensilaje que utiliza las mortalidades del sector para producir aceite y producto proteico. El alcance consideró desde la generación de los residuos de la

industrial de salmón, hasta la obtención de productos a partir de ellos. Debido a que el sistema en estudio es multifuncional, se analizarán 2 tipos de unidades funcionales. Las primeras asociadas a los productos que se pueden producir a partir de los descartes y mortalidades, los cuales varían en función del proceso productivo que se realice (1 kg de harina, 1 kg de aceite, 1 kg de hidrolizado proteico, 1 kg de producto rico en proteína), y la segunda, asociada a la gestión de residuos de la industria salmonera (1 kg de descartes gestionado, y 1 kg de mortalidades gestionadas). Esta última permitirá a la empresa entregar indicadores de impacto ambiental a las empresas generadoras del residuo, con el fin de poder evidenciar los beneficios ambientales de una valorización versus la disposición en un relleno sanitario o vertedero. Los datos de inventario fueron obtenidos directamente desde la empresa de valorización, ecoinvent y estadísticas nacionales. El método de evaluación de impacto fue Recipe Midpoint (H), considerando las 18 categorías de impacto.
Los resultados muestran que la producción de hidrolizado enzimático genera mayores impactos ambientales en todas las categorías de impactos ambientales estudiadas. Esto último debido a sus altos consumos de gas natural (493 m3/t hidrolizado proteico) y energía eléctrica (781 kWh/ t hidrolizado proteico). Al comparar la harina de hueso con el aceite, este último genera mayores impactos ambientales en las categorías de impacto de calentamiento global, formación de material particulado, acidificación terrestre, eutrofización marina, y agotamiento de recursos fósiles. Para estas categorías de impacto, el principal punto crítico está asociado al consumo de gas natural utilizado en las etapas de calefacción para la obtención del aceite, y en la etapa de secado para el caso de la producción de harina de hueso. El transporte de descartes, que se realiza en un camión a diésel con refrigeración es el punto crítico 15 de las 18 categorías de impacto analizadas, contribuyendo entre el 17% al 96% de los impactos. En cambio climático, el hidrolizado enzimático, aceite y, harina de hueso, generan un impacto de 1,86 kg CO_2 eq, 0,76 kg CO_2 eq, y 0,65 kg CO_2 eq, respectivamente.
Desde el punto de vista de la gestión de residuos, se observó que existen beneficios ambientales en 4 de las 18 categorías de impacto evaluadas. Esto se debe a la multifuncionalidad del sistema de gestión de residuos que genera productos evitados. El mayor beneficio se genera debido a la producción de aceite, seguido de la producción de proteína. En sentido opuesto, los principales puntos críticos ambientales están asociados al uso del ácido fórmico, gas natural, y transporte.

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Huella de carbono de la producción de peras argentinas incorporando el secuestro de carbono en las cortinas forestales y los suelos

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INTRODUCCIÓN

La fruticultura es la principal actividad económica regional en los valles irrigados de Río Negro y Neuquén, de donde proviene más del 90% del volumen de fruta fresca exportado por el país (Villarreal et al., 2011). El cultivo de peras posee la mayor superficie implantada en la región con unas 18.266 ha en producción (SENASA, 2021). Argentina manteniene una participación del 7% en la producción mundial, liderando la exportación desde el hemisferio sur, seguida por Sudáfrica y Chile (MHFP, 2016).

El marco metodológico referencial del Análisis de Ciclo de Vida (ACV) constituye un enfoque sistémico y complejo de evaluación del uso, cargas e impactos de todo el intercambio existente entre los sistemas productivos y el ambiente. Con este fin, la metodología emplea inventarios internacionales de referencia de tales intercambios, construidos para los procesos de producción y los productos originados en países desarrollados, con sus especificidades agroecológicas y tecnológicas. Además de ser un requerimiento creciente en muchos mercados de exportación (Conte Grand y D'Elia, 2017), constituye una herramienta para mejorar la sustentabilidad de productos y servicios fronteras adentro. Conocer la huella de carbono de la producción de peras es estratégico tanto para el comercio exterior como para el mercado doméstico.

Existen evidencias, para el caso de la producción agrícola de peras argentinas, de importantes inconsistencias de la información disponible en los inventarios de análisis de ciclo de vida de referencia internacional (Romagnoli y Thomas, 2021). El punto de mayor controversia concierne al cómputo de las emisiones y remociones que provienen del cambio de uso de suelo y la fijación de CO_2 en la biomasa del cultivo.

MATERIALES Y METODOS

La Huella de Carbono de Producto (HCP) es la "*suma de las emisiones de gases de efecto invernadero (GEI) y remociones de GEI en un sistema producto expresadas como CO_2 equivalente y basadas en una evaluación del ciclo de vida utilizando la categoría de impacto única de cambio climático*." (ISO, 2018).

El alcance del presente estudio abarca desde la cuna de los insumos hasta la cosecha del producto en la puerta del establecimiento productor ("chacra") (*from cradle to the farm gate*). Se incluye la extracción de materias primas, producción y transporte de los insumos (plantas de vivero, semillas, agroquímicos, fertilizantes, combustibles, entre otros), la producción de sus envases, todas las labores del campo, las emisiones derivadas de la quema de combustibles y de la aplicación de fertilizantes.

Se seleccionó un paquete tecnológico de nivel medio-alto que corresponde a una producción convencional con alta densidad de árboles (1.250 árboles/ha) y conducción en espaldera con eje central, recomendado para realizar nuevas plantaciones (INTA, 2004). El sistema de riego considerado es gravitacional por surcos. La representatividad regional del sistema evaluado respecto de la conducción en espalderas corresponde al 73,5% de la superficie y respecto al sistema de riego superior al 80% (CAR, 2005).

El alcance temporal de los inventarios corresponde a 25 años del ciclo productivo completo de un monte frutícola, considerando como referencia el paquete tecnológico establecido en el documento denominado *Pautas tecnológicas para frutales de pepita*, realizado en 2004 y actualizado en la publicación *Pera Williams Manual para el productor y el empacador* en el año 2010, ambos coordinados por INTA con participación de los principales referentes técnicos regionales de la actividad.

Para los AVC de cultivos perennes frutícolas, Cerutti et al. (2014) y Alaphilippe et al. (2016) recomiendan utilizar complementariamente unidades funcionales de masa y de superficie a fines de evitar un resultado parcial que presente ecoeficiencias que no se corresponden con la realidad.

Las unidades funcionales (UF) que son analizadas en el presente trabajo son dos:

- UF en unidades de masa: una (1) tonelada de fruta cosechada, en la tranquera del campo.
- UF en unidades de superficie: una (1) hectárea de cultivo de peras durante 25 años.

Una vez confeccionado el inventario de entradas y salidas de cada proceso productivo, se obtuvieron en bases de datos de referencia internacional (Agri-footprint, Ecoinvent) las emisiones unitarias asociadas a cada una de esas entradas: insumos, materias primas y energía.

En la Tabla 1 se exponen los parámetros que caracterizan al sistema frutícola evaluado en este trabajo.

Concepto	Valor	Unidad	Observación
Plantas frutales	1.375	unidades por ha.	1250 unid. año 1 + 10% replante
Plantas cortina forestal	100	unidades por ha.	
Fertilizantes (Nitrógeno)	2.570	kg N – 25 años	adulto 102 kg N /ha/año
Herbicidas	51,19	kg ppa/ha – 25 años	
Insecticidas	111,64	kg ppa/ha – 25 años	
Aceite de Invierno	957,83	kg ppa/ha – 25 años	
Combustible diesel	11.012	L/ha – 25 años	promedio anual 440 L/ha/año
Producción peras	1.025	t/ha. - 25 años	adulto 50 t/ha/año

Tabla 1: Principales características del sistema frutícola evaluado

Las plantaciones arbóreas poseen la capacidad de capturar el CO_2 de la atmósfera, almacenándolo de forma estable en los órganos estructurales de los árboles (troncos, raíces y ramas). A diferencia de los inventarios de ciclo de vida (ICV) de Ecoinvent, en este trabajo no fueron consideradas las variaciones en el stock de carbono de la biomasa de los frutales. Motivaron esta decisión, la inexistencia de antecedentes locales que permitan disponer de datos sólidos acerca de la magnitud de la biomasa arbórea en perales, y la fuerte controversia que existe respecto de los criterios para su cómputo.

En el Alto Valle de Río Negro y Neuquén es común el uso de cortinas rompevientos naturales o artificiales, por esta razón se incluyó como parte del sistema una cortina forestal de 100 álamos *Populus x canadensis* por hectárea.

En esta región, caracterizada por su clima árido con bajos niveles de materia orgánica en el suelo (MOS), la utilización del sistema de riego gravitacional para cultivo de frutales presenta un elevado potencial de secuestro de carbono (Mendía et al, 2015).

A nivel local, un trabajo de la Universidad Nacional del Comahue y el INTA, a partir de una red de ensayos con 29 parcelas de cultivos de pera con riego gravitacional por surco y mantenimiento de coberturas verdes permanentes, desarrolló una ecuación que estima de manera significativa que el incremento promedio en toneladas de C ha^{-1} $año^{-1}$ fluctúa entre 0,50 t C ha^{-1} en los primeros 15 años a 0,17 t C ha^{-1} $año^{-1}$ en los siguientes 30 años. Estableciendo un valor promedio para todo el ciclo (45 años) de 0,28 t C ha^{-1} $año^{-1}$ (Mendía et al., 2015).

En 2016 se realizó la medición de las variables dasométricas de una cortina rompevientos de álamo euroamericano (*Populus* x *canadensis* 'Conti 12') de 28 años de edad ubicada en la Estación Experimental Alto Valle de Río Negro del INTA. Las variables medidas fueron el diámetro a la altura del pecho (DAP) y la altura total (Ht) de los individuos de la cortina. El promedio de DAP y Ht fue de 45,5 cm y 30,5 m respectivamente (Cancio Hernán, comunicación personal). Para estimar el volumen de biomasa del fuste se utilizó una ecuación de volumen total con corteza (Vtcc) para álamos deltoides (*Populus deltoides*) cultivados en el Delta del Paraná: $Vtcc=0{,}06263*DAP^{1,63496}*Ht^{1,31769}$ (Fernandez Tschieder et al., 2011)

A partir de esta ecuación, el Vtcc promedio estimado del fuste es de 1,629 m3/árbol para los álamos de la cortina rompevientos. Luego, teniendo en cuenta las proporciones de biomasa estimadas en las diferentes partes de los árboles (fuste, ramas, brotes y hojas y raíz) de una forestación de álamos deltoides en el Delta del Paraná (Ceballos, 2011), se estimó la biomasa anhidra total dando como resultado un promedio de 0,908 t/árbol.

Para estimar la biomasa acumulada en la cortina forestal hasta los 25 años de edad se utilizaron datos de crecimiento de una forestación de álamos de 21 años ubicada en el Delta del Paraná (Álvarez Javier, comunicación personal). Se utilizaron los datos de incremento anual del DAP durante los últimos años de esa forestación para calcular las proporciones de crecimiento respecto del incremento medio anual del DAP (IMAdap), y a partir de esa información se restó el crecimiento de los últimos tres años de la cortina rompevientos de 28 años de edad. Por lo tanto, la biomasa total estimada para la cortina forestal de 100 álamos a los 25 años de edad es de 81,45 t/ha. A partir de este valor, y considerando el factor que permite convertir el valor de toneladas de biomasa anhidra a toneladas de CO2 equivalente (1,8), se estima que los álamos de la cortina rompevientos considerada en el modelo productivo tiene un potencial de secuestro de **146,62 t CO2eq/ha.**

La vida útil de las cortinas forestales supera largamente el periodo de alcance del trabajo, generalmente supera los 50 años, por lo que el carbono retenido en la madera de los álamos continúa en el sistema en forma de envases (p.e. bins), postes para espalderas del monte frutal o en construcciones.

RESULTADOS

A continuación se cuantifican las emisiones GEI asociadas a la producción de un monte de peras en todo el ciclo de vida definido (25 años), considerando los iniciales años improductivos o de baja producción necesarios para la formación de la estructura productiva, y su estado adulto o de plena producción.

Los valores de emisión de GEI se presentan en la Tabla 2, considerando el ciclo completo del cultivo (25 años), estimados de acuerdo a las dos unidades funcionales del presente trabajo. En la segunda columna se expresa en unidad funcional de área y en la tercera columna en unidad funcional de masa.

Concepto	**U.F. Área** $\mathbf{t\ CO_2eq\ ha^{-1}}$	**U.F. masa** $\mathbf{kg\ CO_2eq\ t\ fruta^{-1}}$
Plantas y estructura apoyo	2,220	2,17
Fertilizantes	30,168	29,43
Fitosanitarios	12,275	11,98
Combustibles	48,968	47,77
Total	**93,630**	**91,35**

Tabla 2: Emisiones CO2eq para ciclo completo de cultivo

En la Tabla 3 se presenta la huella de carbono para una hectárea de pera en ciclo completo de 25 años, de acuerdo al alcance definido en el trabajo. Puede observarse que se han integrado los efectos relacionados con el uso de los insumos para el cultivo durante todo período, el carbono secuestrado en las cortinas forestales y el carbono secuestrado en los suelos.

Concepto	$\mathbf{t\ CO_{2eq}\ ha^{-1}}$ **25 años**	**kg CO2eq** $\mathbf{t\ producto^{-1}}$	**Observación**
Insumos	93,63	91,35	Emisión
Cortinas Rompevientos	-146,62	-143.04	Remoción
Suelos	-33,65	-32,82	Remoción
HC	**-86,64**	**-84,51**	**Secuestro neto**

Tabla 3: Huella de carbono ciclo completo 25 años (UF área y UF masa)

La huella de carbono para una hectárea de peras en 25 años de cultivo, resulta una remoción neta de **86,64** t CO_2 eq ha^{-1}. Las emisiones correspondientes a los insumos de producción, **93,63** t CO_2 eq ha^{-1} son compensadas por las remociones en biomasa de las cortinas forestales (**146,62** t CO_2 eq ha^{-1}), y el incremento de carbono en suelos (**33,65** t CO_2 eq ha^{-1}).

Considerando la UF de masa, la huella de carbono de una tonelada de peras, implica una remoción neta de **84,51** t CO2eq t $fruta^{-1}$. Las emisiones correspondientes a los insumos de producción, 91,35 t CO_2eq t $fruta^{-1}$ son compensadas por las remociones en biomasa de las cortinas forestales (143,04 t CO_2eq t $fruta^{-1}$), y el incremento de carbono en suelos (32,82 t CO_2eq t $fruta^{-1}$).

Resulta notable el impacto que presentan las cortinas forestales, quienes en 25 años tienen la capacidad de neutralizar e inclusive generar una importante remoción neta de carbono en el sistema de producción frutícola.

Por lo tanto, puede concluirse que la etapa de producción agrícola de peras en sistemas de alta densidad de la región genera un importante beneficio en materia de cambio climático. Los valores presentados en este trabajo, resultan altamente conservadores. En los próximos años a partir de datos de campo y nuevos estudios sobre stock de carbono contenido en árboles frutales y suelos, seguramente serán obtenidos valores de remoción de GEI superiores para la producción frutícola en esta región.

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"ESTRATEGIA PARA LA VALORIZACIÓN DE LA CASCARILLA DE ARROZ COMO ALTERNATIVA DE SOSTENIBILIDAD ENERGÉTICA EN EL DEPARTAMENTO DE TOLIMA COLOMBIA"

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Important notes:

Palabras clave: *Sostenibilidad energética, cascarilla de arroz, biomasa, economía circular, energías renovables.*

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El cultivo de arroz inició hace aproximadamente 10.000 años en diferentes regiones de Asia y se ha convertido en el segundo cultivo más amplio a nivel mundial después del Trigo (Acevedo, Castrillo, Belmonte, 2006). En Colombia, la producción de arroz representó durante el año 2017 el 5% del PIB agropecuario y el 0,4% del PBI nacional, llegando a tener hasta 1,3 billones de pesos como valor del arroz producido (Becerra, Díaz, García, Giraldo, Gonzales, Maluendas, Quintero, Reina, Ortegón, Samacá & Viveros, 2020). Para el año 2019, Colombia tenia un área de cosecha del arroz de 518 mil hectáreas que aumentó un 12% a lo largo de el año 2020, llegando a tener 580 mil hectáreas y creciendo en el mercado hasta un 40% en comparación con el año anterior, este aumento corresponde al aumento de la productividad y rendimiento en todas las zonas arroceras de la nación, y el aumento de los precios que manejan los distintos productores (FEDEARROZ, 2021).

La iniciativa que se desarrolla en el proyecto tiene como objetivo evaluar la transformación y el uso de la biomasa proveniente de la cascarilla de arroz, el cual es generado como subproducto o residuo del proceso productivo de este cereal, investigando las distintas propiedades y beneficios que esta cascarilla posee, identificando así su potencial energético y valorándola como una alternativa de sostenibilidad energética en el departamento de Tolima (Colombia). La cascarilla de arroz es un residuo que no cuenta con propiedades nutritivas, y cuenta con altos contenidos de Dióxido de silicio (SiO_2) imposibilitándolo para ser consumido por el ser humano (Sierra, 2009).

Posterior a la recolección y extracción del arroz, se identifican los subproductos o residuos que se producen, siendo la harina de arroz y la cascarilla los principales subproductos del proceso (Fernández, 2014), siendo la cascarilla de arroz el mayor subproducto obtenido, llegando a tener hasta un 20% del peso de la producción (Belén, Munitz y Resnik, 2020).

Tomando como referencia el modelo planteado por la economía circular, es necesario reconocer las propiedades con las que cuenta la cascarilla de arroz, con la finalidad de estudiar el proceso al cual debe ser sometida la cascarilla de arroz para generar energía, garantizando su reutilización.

A lo largo de los años, la energía se ha producido mediante distintos combustibles fósiles, que contribuyen al calentamiento global debido a su producción de gases de efecto invernadero (El Poder del Consumidor, 2021). En consecuencia, se ha iniciado la búsqueda de la producción de energías limpias, que contribuyan a la reducción de la huella de carbono producida, partiendo del potencial energético de Colombia para la producción de energía mediante biomasa residual del sector agrícola, como residuos de la producción de caña de azúcar, palma de aceite, café, maíz, banano y arroz (Escalante, 2020).

En el proyecto se analiza la producción de energía eléctrica mediante la cascarilla de arroz teniendo en cuenta algunos antecedentes prácticos en Colombia y los análisis vinculados al ciclo de vida de la producción de arroz, específicamente en la valorización de sus residuos como la cascarilla de arroz, vinculándolo a estrategias de economía circular.

Para esto, se realiza una propuesta de sostenibilidad energética, vinculando las actividades que promueven la triple cuenta de la sostenibilidad, la cual ha tomado cada vez más relevancia en diferentes países latinoamericanos incluyendo Colombia (Agencia de Sostenibilidad Energética [ASE], s.f.), con la finalidad de masificar las energías renovables no convencionales, entrando así al mercado energético, el cual ha ido aumentando durante los últimos años, llegando a tener hasta el 6% de las inversiones mundiales , lo que implica un crecimiento positivo del sector energético y ayudando al sector ambiental minimizando las emisiones de carbono (IRENA, 2016).

Se lleva a cabo un análisis de la cascarilla de arroz del departamento del Tolima, encontrando altos niveles de Carbono orgánico (38,04%) Sílice (18,39%), Nitrógeno total (0,74%) y Celulosa (3,05%), lo cual indica que la cascarilla de arroz colombiana beneficia al proceso de producción debido a que su composición aporta para una buena combustión. Teniendo en cuenta los resultados obtenidos por la cascarilla se realiza una búsqueda bibliográfica para generar una simulación utilizando el Simulador SAM el cual permite modelar la combustión de biomasas mediante plantas de energía, realizando modelos financieros e identificando los rendimientos energéticos que proporciona la biomasa. Para lo cual se realizó una recolección de las variables necesarias para la creación de una planta productora de energía utilizando la cascarilla de arroz como materia prima, teniendo en cuenta la ubicación de esta, y las propiedades que tiene la cascarilla de arroz en la región del Tolima.

Con la finalidad de identificar el interés de las empresas productoras de arroz, se realizó una encuesta, la cual permitió validar la potencial participación de las empresas y pequeños productores, evidenciando que el 70% de los encuestados le parece una buena idea la creación de una planta de energía utilizando los residuos de la producción de arroz, adicionalmente el 96,7% posee interés en participar en el diseño, implementación y operación de la planta. Estos resultados son positivos en cuanto al interés de la población, y en caso de llegar a implementarse mejorará la calidad del ambiente y será una nueva fuente de empleo en el sector.

De acuerdo a lo obtenido dentro la investigación que el procesamiento de la cascarilla de arroz para la creación de energía eléctrica es ambiental y socialmente viable en pro del desarrollo de la comunidad, y esta manera también se promueve la economía circular, debido a que se reutiliza un subproducto que es desechado en la producción de arroz, disminuyendo así el uso de distintos combustibles fósiles, que tienen una alta producción de huella de carbono, al contrario de este proceso que genera menores proporciones en emisiones de gases contaminantes al medio ambiente, sin embargo al no utilizar este subproducto y ser desechado, este si genera gases de efecto invernadero, como es el caso del dióxido de carbono.

Mediante simulación realizada a lo largo del proyecto, se logró evidenciar que la planta de procesamiento de cascarilla de arroz para la producción de energía es económicamente factible a mediano plazo, estableciendo limites de 5 años en donde los ingresos superaran a los egresos, teniendo en cuenta una Tasa de Interés de Oportunidad (TIO) del 20%, se establece un Valor Presente Neto (VPN) de 69.132.741, utilizando la misma formula, se establece la Tasa Interna de Retorno (TIR) teniendo en cuenta el VPN igual a 0, esto da como resultado un TIR del 26%, evidenciando que el TIR es mayor que el TIO un 6% lo que establece que el proyecto es rentable y cumple con las expectativas de las ganancias. .

Al reutilizar estos desechos, se fomentan iniciativas como la producción de energías renovables, que permiten minimizar el uso de los combustibles fósiles, potencializar estrategias de economía circular y finalmente permitiendo una valorización de residuos.

Propiedades fisicoquímicas de la cascarilla de arroz en Tolima

Las propiedades fisicoquímicas de la cascarilla de arroz proveniente del departamento de Tolima se determinaron mediante diferentes pruebas de laboratorio realizadas por Chemilab, el cual es un laboratorio acreditado por el Instituto de Hidrología, Meteorología y Estudios Ambientales (IDEAM). Dichas pruebas de laboratorio permitieron identificar que la muestra de cascarilla de arroz analizada cuenta con una cantidad de carbono orgánico del 38,04%, sílice 18,39% y nitrógeno 0,74%, mientras que se caracteriza por tener un pH de 6.41, una humedad del 7.68%, cenizas del 19.4% y una baja presencia de carbonatos del orden de <0.01%. La composición fisicoquímica en términos de macronutrientes de este tipo de biomasa es 39,05% de celulosa, 22,80% de lignina, 3,56% de proteínas, 6,60% de extracto no nitrogenado y 0,93% de extracto con éter; por su lado, en términos de micronutrientes, específicamente de minerales de ceniza, se destaca mayor presencia de sílice con un 96,51% y en menor medida, de manera descendente, sulfatos, óxido de potasio, óxido de sodio, óxido de calcio y óxido de magnesio, con un 96.51%, 1.13%, 1.10%, 0.78%, 0.25% y 0.23%, respectivamente.

Comportamiento energético en el proceso de combustión

El comportamiento energético de la cascarilla de arroz en el proceso de combustión se evaluó mediante el simulador SAM (System Advisor Model), permitiendo identificar que el calor transferido en el interior del motor de la caldera donde se lleva a cabo la combustión de la cascarilla de arroz es constante sobre 3180 kW, mientras que la eficiencia del rehervidor oscila entre 50-52%, ambos en función del tiempo que son los 12 meses del año.

Específicamente la simulación realizada en el simulador SAM permitió identificar que el calor transferido es constante alrededor de los 3180 kW durante los primeros 8 días del mes, momento en el cual se experimenta un comportamiento cuadrático de manera creciente hasta que se alcanza el valor máximo de calor cerca de los 12 días del mes y, posteriormente, este empieza a decrecer con el paso de los días hasta llegar nuevamente a los 3180 kW, que era el valor inicial. Sin embargo, la simulación realizada determina que en los meses de enero, febrero, abril, mayo, junio, julio, agosto, septiembre y octubre se alcanzan los valores máximos de calor cerca de la mitad del mes con magnitudes que se encuentran en un intervalo de 3230 – 3240 kW.

Teniendo en cuenta lo descrito anteriormente es importante destacar que el funcionamiento del motor es eficaz al pasar el tiempo, pues el calor liberado es similar de un día a otro y también, de un mes a otro y, por tanto, permite que el proceso de combustión se realice de manera óptima sin importar el tiempo en el que se esté implementando dicho equipo al no perder funcionalidad.

Análisis encuestas de percepción de procesamiento cascarilla de arroz

Durante el desarrollo de la presente investigación se realizó una encuesta con el fin de conocer la impresión y apreciación de llevar a cabo la ejecución de una planta de procesamiento de la cascarilla de arroz, por parte de los actores que están directa o indirectamente relacionados con la industria en el departamento del Tolima; la muestra seleccionada se conforma de 30 personas de las cuales son 10 trabajadores directos, 10 campesinos cultivadores de arroz y 10 personas civiles.

Los resultados de la encuesta permitieron identificar que la gran acogida al diseño y construcción de una planta de procesamiento de cascarilla de arroz, puesto que el 70 % (21 encuestados) piensan que sería excelente, 23,3% (7 encuestados) muy bueno y 6,7% (2 encuestados), adicionalmente, la totalidad de las personas encuestadas considera que la planta procesadora de cascarilla de arroz generaría empleo y mejores ingresos económicos para la población del departamento de Tolima, sin embargo, solo el 96,7% (29 encuestados) manifiestan su interés en ser partícipes de las fases para la implementación del presente proyecto.

Parámetros técnicos –financieros, ambientales y sociales

La planta química adoptara un proceso de pirolisis para la transformación de biomasa, logrando obtener mediante este proceso bioaceites, biogás y biocarbón. La planta se desarrollará mediante una inversión privada y estará ubicada en el municipio de Espinal en el departamento de Tolima, pronosticando una gran acogida del proyecto al tratarse de biocombustibles que son de origen renovable, ofrecen mayor seguridad energética, menores emisiones de gases contaminantes a la atmósfera y fomentar el desarrollo del campo colombiano.

Por medio de la planta de procesamiento de cascarilla de arroz se suministra energía limpia con sostenibilidad económica y ambiental, mediante la cual se otorga una valoración a los residuos de la industria arrocera garantizando el aprovechamiento de la cascarilla de arroz y minimizando los residuos. A nivel social el proyecto traerá gran desarrollo y posibilidades de empleo, apoyando el talento investigativo de la región mediante el apoyo a proyectos de emprendimiento y programas sociales, culturales, recreativos y deportivos.

Análisis financiero

El análisis económico realizado para evaluar la viabilidad financiera de la estrategia de aprovechamiento de la cascarilla de arroz para obtener bioaceites, biogás y biocarbón mediante un proceso de pirolisis permitió identificar la rentabilidad del proyecto puesto que el modelo matemático VPN tiene un valor de $ 69.132.741 que es >0 y el modelo financiero TIR es de 26% que es >TIO=20%. Bajo dichos términos, los ingresos debido a las ventas de los tres biocarburantes es de $ 819.848.012 cuya cifra es constante en los 5 años del horizonte de planeación, destacando que el valor del salvamento de los equipos de la planta química en el último año es de $385.664.525; contrariamente, los costos de producción, los gastos de administración y los gastos financieros son para los años 1, 2, 3, 4 y 5, $ 644.198.285, $ 671.628.314, $ 700.665.009, $ 731.629.423 y $ 764.668.516, respectivamente. De acuerdo con ello, las ganancias y/o utilidades al finalizar cada año son $ 175.649.726, $ 148.219.698, $ 119.183.002, $ 88.218.588 y $ 440.844.021, respectivamente.

Conclusiones

La cascarilla de arroz es un subproducto de la industria arrocera que representa una oportunidad para el desarrollo de proyectos de economía circula, siendo uno de ellos la planta de procesamiento de dicho subproducto como alternativa de sostenibilidad energética en el departamento de Tolima la cual presenta una viabilidad ambiental, social y económica.

La planta de procesamiento de cascarilla de arroz permite utilizar este producto como materia prima para generar energía más limpia que reduzca la huella de carbono al no generarse emisiones de gases contaminantes garantizando la viabilidad ambiental del proyecto; adicionalmente el desarrollo de esta estrategia de sostenibilidad energética conlleva un desarrollo económico de la comunidad del Espinal, Tolima, puesto que es una actividad económica alterna a la producción de arroz que generar el aumento de la oferta laboral al requerirse mano de obra durante las etapas de diseño, construcción y funcionamiento de la planta de procesamiento. Finalmente, se garantiza la viabilidad económica de este proyecto durante un periodo de 5 años al evidenciarse que los ingresos superan a los ingresos permitió identificar la rentabilidad del proyecto puesto que el modelo matemático VPN tiene un valor de $ 69.132.741 que es >0 y el modelo financiero TIR es de 26% que es >TIO=20%.

La impresión y apreciación de llevar a cabo la ejecución de una planta de procesamiento de la cascarilla de arroz en el municipio de Espinal, Tolima es buena tomando como referencia la apreciación de 30 personas encuestadas, obteniendo un 70% de aprobación del proyecto; adicionalmente, la totalidad de las personas encuestadas considera que este proyecto generaría empleo, sin embargo, solo el 96,7% manifiestan su interés en ser partícipes en el proyecto.

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Análisis de los impactos ambientales del ciclo de vida del nexo agua-energía-alimento de hogares de Santiago de Chile

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El crecimiento de la población y los cambios socioeconómicos, han provocado un aumento en la demanda de los servicios y recursos vitales, como la energía, alimento y la disponibilidad de agua (Food and Agricultural Organization of the United Nations, 2009; Mountford, 2011; IEA, 2015). Se proyecta que para el año 2050 la demanda mundial de agua, energía y alimento aumentarían en un 55%, 80% y 60% respectivamente, lo cual conllevaría a la escasez de suministro de estos tres recursos (Chen et al., 2020). La disponibilidad de agua, energía y alimentos es fundamental para la estabilidad y el desarrollo sustentable de un área, país o región (Chen et al., 2020). Alrededor del 30% de la energía consumida en el mundo (Mannan et al., 2018), y el 70% del total mundial de agua dulce son utilizadas en la producción de alimentos (FAO, 2012). Durante el año 2011 en la conferencia Nexus realizada en Alemania, salió a la luz el concepto nexo agua-energía-alimento (AEA), un enfoque que ayuda a comprender las complejas interdependencias y sinergias entre los recursos naturales (Li y Ma, 2020). Los estudios del nexo AEA se han realizado a nivel regional, nacional e internacional, sin embargo, a escala urbana aún son escasos (Caputo et al., 2021). Esto es preocupante, ya que analizar las ciudades bajo este enfoque es importante, porque las zonas urbanas son centros de grandes poblaciones, por lo que determinan la intensidad de los flujos de recursos globales (Caputo et al., 2021). Cabe considerar que estos sistemas están en constante crecimiento, pues se espera que la tasa de urbanización aumente en un 28% en los próximos quince años, de modo que la demanda de agua, energía y alimento también aumentaría (Li et al., 2019). Particularmente en Chile, alrededor del 87,8% de la población habita zonas urbanas urbana (INE, 2018). Por lo tanto, considerando el aumento de la demanda de recursos en los últimos años (lo cual es proveniente del aumento demográfico y urbanización), es de vital importancia el desarrollo de estudios respecto a los impactos del consumo de recursos asociados al nexo AEA, especialmente en la población urbana. Del mismo modo, también es importante la evaluación del ciclo de vida de estos recursos demandados por los hogares de las ciudades, ya que evaluar los impactos ambientales del ciclo de vida del nexo agua-energía-alimento, permitiría determinar las localidades afectadas por el consumo de estos recursos, ya que las etapas del ciclo de vida de los alimentos, agua y energía podrían ocurrir en diversos lugares, por lo que sus impactos ambientales involucrados no solo podrían afectar a una localidad en específico. Por estos motivos, el objetivo de este estudio fue analizar los impactos ambientales del ciclo de vida del nexo agua-energía-alimento en hogares de la ciudad Santiago de Chile.

La metodología de análisis del ciclo de vida fue utilizada siguiendo los requisitos metodológicos establecidos en la ISO 14044. El alcance de la investigación fue de "la cuna a la tumba", es decir, desde la extracción de los recursos hasta su fin de vida. De este modo se consideraron los flujos provenientes desde la extracción, producción, distribución, tratamiento y disposición final de los recursos, asociados al nexo agua-energía-alimento en los hogares de la ciudad de Santiago. En este estudio la unidad funcional fue definida como "un habitante de un hogar equivalente en un año" (López-Eccher et al., 2021), de modo que esta unidad funcional fuera representativa para realizar análisis comparativos del comportamiento del sistema del nexo AEA en base a las diversas composiciones de un hogar de Santiago. Los datos de inventario fueron obtenidos mediante 300 encuestas realizadas a hogares de Santiago de Chile, el marco del proyecto Fondecyt 11170992 y los resultados presentados por López-Eccher et al., (2021), El método de evaluación de impacto fue Recipe Midpoint (H), considerando las categorías de impacto de calentamiento global, acidificación terrestre, eutrofización de agua dulce, ecotoxicidad de agua dulce, toxicidad cancerígena humana, formación de material particulado y escases de recursos fósiles.

Los resultados muestran que los impactos ambientales al cambio climático de 1 habitante de Santiago de Chile son 3,9 t CO_2 eq/hab/año. Donde el principal punto crítico es la energía con un 71% de contribución, seguido de los alimentos con 25% y el agua con 4%. En el caso de la energía, los impactos están asociados a la fase de uso de los combustibles, principales a los utilizados en el transporte privado y público, y la calefacción y cocina de los hogares. Esto debido a que la combustión de la gasolina, diésel, gas licuado de petróleo, queroseno, entre otros, emiten gases de efecto invernadero al ser combustionados, contribuyendo en mayor parte en la categoría (Morales, 2015). Al analizar el flujo de los alimentos, para todas las categorías de impacto a excepción de la ecotoxicidad de agua dulce, el principal punto crítico está asociado a la producción de los alimentos. En la categoría de calentamiento global el 61% de la contribución es por la producción de alimentos, seguido por la disposición final de los alimentos con un 32% y el transporte con un 7%. Para la categoría de ecotoxicidad de agua dulce, los impactos son producidos principalmente por la disposición final de alimentos con 82% de contribución, seguido por la producción con 18%.

En el caso del flujo de agua para las categorías de calentamiento global, formación de material particulado y agotamiento de recursos fósiles los principales impactos están producidos por la extracción del agua cruda. En las categorías de eutrofización de agua dulce, toxicidad carcinogénica humana, ecotoxicidad de agua dulce, acidificación terrestre, formación de material particulado y cambio climático, el tratamiento del agua es un punto crítico con una 81%, 59%, 85%, 52%, 32 y 33%, acidificación terrestre, formación de material particulado y cambio climático

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Towards the ecological transition of the small ruminant sector. Insights from an Italian case study

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Introduction

The island of Sardinia (Italy) is an important region in the sheep cheese world trade. With 3.1 million dairy sheep raised in around 10.000 active farms, Sardinia produces about 320 kt of milk yr^{-1} transformed by about 50 cheese factories (BDN, 2020). However, Sardinian sheep sector faces cyclical economic crises caused by external global market equilibrium and policy changes, and internal structural problems along the supply chain. The Sardinian sheep sector is also associated with relevant environmental implications: it contributes to about 5% of total GHG emissions of the Italian agricultural sector, albeit providing a wide range of ecosystem services. This indicates the need of efficiency improvements and radical innovation (Arru et al., 2020). The aim of this paper was to show the more effective ecoinnovation strategies to mitigate the environmental impact of Sardinian dairy sheep sector, based on Life Cycle and System thinking approaches, and inspiring the transition of the small ruminant sector towards a more sustainable bioeconomy-based society.

Materials and methods

The evaluation of the environmental footprint of the Sardinian dairy sheep systems (from cradle to farm gate) using an LCA approach was the key action of the ecoinnovation strategy. The Environmental Footprint (EF) 2.0 evaluation method was applied, in line with the Product Environmental Footprint Category Rules (PEFCR) for Dairy Products" (EDA, 2018). Two functional units (FU) were used: 1 kg of fat and protein corrected milk (FPCM) and 1 ha of utilized agricultural area (UAA). Data were collected in 2016/2017 in 18 dairy sheep farms located all over the island, selected from the National Database of Farm Animals to represent the main local farming systems. The farm sampling method considered farm density and total milk production in the areas, pedoclimatic conditions, flock size (number of ewes) and stocking rate (ewe/ha) of each farm. Surveyed farms were selected also considering their availability to supply reliable data as well as their interest in Research & Development initiatives. Two farm groups were considered respectively belonging to: Zone I) effusive and granites rocks, mean annual precipitation >800 mm (n=10; 6.6 ewe ha^{-1}); Zone II) sedimentary soils, mean annual precipitation <800 mm (n=8; 6.3 ewe ha^{-1}). A "from cradle to farm gate" system boundary was adopted and accounted for all activities and inputs/outputs related to the milk production (from feed production to animal diet and related emissions, from water and energy use to consumable materials) (Figure 1).

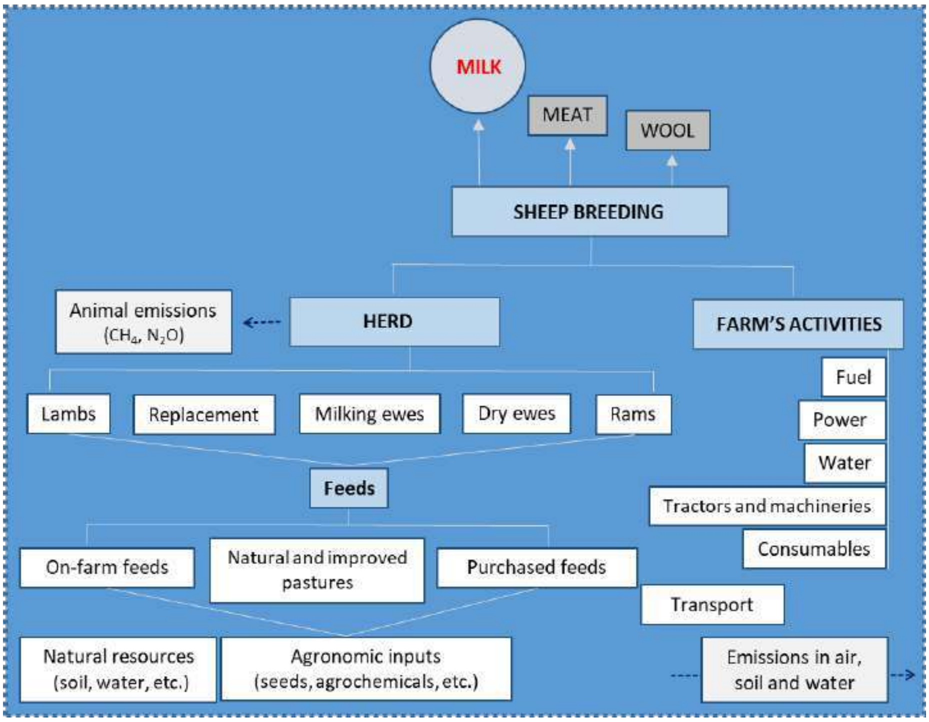

Figure 1. System boundary diagram of the sheep milk production.

Methane (CH_4) emissions from ruminal fermentation were estimated from CH_4 energy emissions, calculated as a function of the metabolizable energy intake (assessed using primary data for digestibility and energy content of feeds) and the net energy requirements (Vermorel et al., 2008). The impact assessment of animal excreta included only the nitrous oxide (N_2O) emissions from faeces and urine, because animals spend most of their time outdoor. These emissions were estimated by IPCC method (2019), using emission factors indicated for "sheep and other animals". Moreover, N daily emissions were estimated using the empiric equations formulated by Decandia et al. (2011), for lactating ewes, pregnant ewes, rams, replacement ewes and lambs. NO_x in air, heavy metals, PO_{3-}, P and NO_{3-} in water and heavy metals in soils were estimated using equations reported in Ecoinvent report N.15 (Nemecek and Kägi, 2007). NH_3 emission in air were calculated in line with a Tier-2 IPCC (IPCC, 2019) approach, using the national emissions factors published by ISPRA (2011).
In order to identify the relevant environmental impact categories, results were normalized and weighted, then only the impact categories which cumulatively contribute to at least 80% of the single score were selected. Differences between groups were tested with One-way ANOVA ($P < 0.05$). Considering LCA outcomes and experts' interviews, a causal loop diagram (CLD) was drawn to stimulate insights for policy formulation (Atzori et al., 2022).

Results and discussion

Climate Change, Land Use, Water Scarcity, Resource use, minerals and metals resulted the main relevant impact categories. The two farm groups statistically differed for the main technical and productive features, and for some environmental impact category performance associated with the pedoclimatic zones (Table 1). Focusing on Climate Change, when emission intensity was expressed per kg of FPCM, GHG emissions varied from a min of 3.05 (in a farm located in Zone II) to a max of 6.02 (Zone I) kg of CO_2eq/kg of FPCM, with significant difference in average values among zones. When GHG emissions were expressed per ha of UAA, they were not significantly different and varied from 1855 (Zone I) to 6136 (Zone II) kg of CO_2eq/ha of UAA. Indeed, increasing pressure on the system to reduce emission per unit of product generates higher emission intensities per unit of process input, such as animal (Capper et al., 2009) or owned land (Escribano et al., 2020). On the other hand, it is important to highlight that emissions expressed per ha of UAA resulted in a broader difference from the mean per kg of milk, which could be helpful to describe the sectors variability.

	Zone I	Zone II		Zone I	Zone II
Utilized Agricultural Area (UAA)	89	85	*EF per 1 kg FPCM*		
Natural pasture (% UAA)	75 (a)	21 (b)	Climate Change	5.00 (a)	3.89 (b)
Feed self-sufficiency (%)	62 (b)	74 (a)	Land Use	2542 (a)	1370 (b)
Milk yield (kg FPCM ewe^{-1})	117 (b)	188 (a)	Water Scarcity	12.03	18.68
Milk yield (kg FPCM ha UAA^{-1})	580 (b)	969 (a)	Ru-m&m	3.0E-05	3.8E-05
Dry Matter Intake - DMI (kg ewe^{-1} $year^{-1}$)	446 (b)	508 (a)	*EF per 1 ha UAA*		
Dairy efficiency (kg DMI kg $FPCM^{-1}$)	0.24 (b)	0.34 (a)	Climate Change	3592	4018
Use N fertilizer (kg ha UAA^{-1})	4 (b)	43 (a)	Land Use	1.7E+06	1.4E+06
Use P_2O_5 fertilizer (kg ha UAA^{-1})	7	23	Water Scarcity	8.4E+03	2.0E+04
Use H_2O (m^3 ha UAA^{-1})	45 (b)	239 (a)	Ru-m&m	2.2E-02 (b)	4.0E-02 (a)

Table 1. Farms characteristics and Environmental Footprint (EF) of the two farm groups located in different geo-pedological and climatic zones. Only impact categories that cumulatively contribute to at least 80% of the total environmental impact are shown. Within rows, different letters indicate significant differences at $P < 0.05$. FPCM: Fat Protein Corrected Milk; Ru-m&m: Resource use, minerals and metals.

A contribution analysis identified the following hotspots for Climate Change impact category: animal emissions from enteric CH4 and manure N2O (68%), methane being by far the most relevant, purchased feeds (18%), on-farm feeds (8%), tractors & machineries (1.5%), electricity (1%). However, there was a high variability among farms that can be mainly explained by production level in terms of milk delivered per ewe/year (Atzori et al., 2022). In addition, farms with similar production levels showed different values of emission intensities, suggesting different aspects of farm efficiency and opportunities to optimize resource use with targeted mitigation strategies. High variability in emissions among farms also indicated a large mitigation margin at the regional level.

Results confirmed that: i) higher production efficiency and higher feed self-sufficiency levels in Zone II can reduce environmental footprint per kg of FPCM, benefiting production systems located in areas suited for intensification; ii) farms in Zone I with lower stocking rate have better environmental performances per ha of UAA, as in Arca et al. (2021). The LCA also showed that the key areas for effective mitigation are i) low milk production, ii) low digestibility of diets that generate higher methane emission potential per kg of dry matter intake, iii) high purchase of off-farm produced feeds (mainly protein concentrates), iv) high fertilizer use in annual crops vs. appropriate natural pasture management, and v) energy consumption. The system structure described with feedback loops in Figure 2 showed that ecoinnovation policies in the Sardinian sheep sector could enable the adoption of good practices, fostering socio-economic and environmental benefits. In particular, the proposed eco-innovation strategy defined intervention points for public investments to promote GHG emission mitigation plans aimed at improving the sustainability performance of agricultural production systems (Notarnicola et al., 2017). From our viewpoint, public policies should be oriented to improve farm efficiency in those farms with the greatest milk-production potential, and to drive the enhancement of ecosystem services in those farms with a higher potential for nonmarketable goods. This would allow maintaining the regional milk deliveries, sustaining the income level of the farmer families and the accomplishment of high ecological benefits and its transfer from farms to the society as a whole.

Four casual links were highlighted to enable the green balancing loop (Figure 2): i) switching from payments per head to payments based on eco-innovation design and indicators (e.g., capacity to improve production efficiency and to provide ecosystem services); ii) indirect payments should stimulate investments in precision farming ICT equipment, innovative facilities and tools, and the application of good practices in resource management and land use; iii) a large capacity building effort should be made to increase knowledge and interaction among technicians, farmers, and other stakeholders; iv) applied research and extension should support capacity building in the sector.

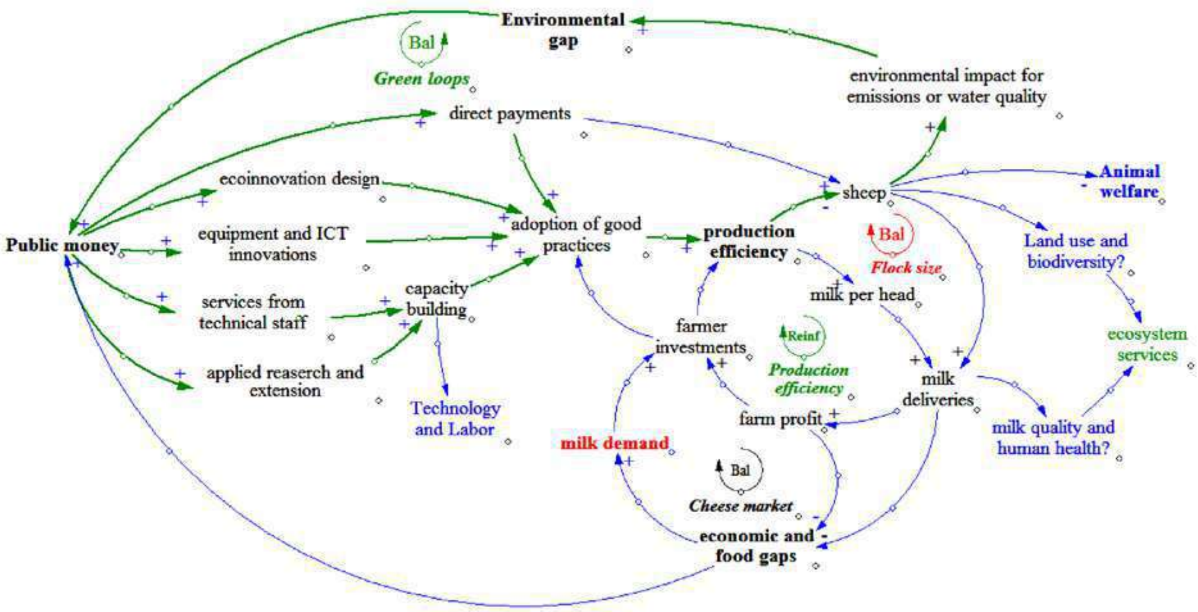

Figure 2. Causal loop diagram (CLD) of the Sardinian sheep sector ecoinnovation policies.

Conclusions

This paper summarizes a strategy based on a Life Cycle and System Thinking approach to promote the ecological transition of the Sardinian (Italy) dairy sheep supply chain through a territorial plan for GHG mitigation. The environmental hotspots defined with a detailed LCA study on the Sardinian sheep milk production allowed to identify key areas for environmental improvement that include both feed supply chain and production efficiency enhancement. The CLD revealed that the most sustainable links for the Sardinian dairy sector could be enabled with policy emphasis on dairy flock efficiencies, care for ecosystem services, and deep stakeholder capacity building investments to guarantee the effectiveness of mitigation plans. Public policies should promote farm efficiency improvement in farms with highest milk yield potential and ecosystem services enhancement in farms with high natural value. This work provides effective methodological blueprint to be applied to other regions with similar features and sustainability challenges.

Acknowledgments

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Social and environmental sustainability of tropical livestock systems in Mexico

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Abstract
Performing regionalized LCA studies in livestock systems derives from the necessity of the wide variety of existing farming systems and the influence of site-specific characteristics on the environmental and social impacts. The purpose of this research was to generate evidence on the performance of the tropical extensive livestock systems in Mexico in the social and environmental dimensions of sustainability from the life cycle assessment perspective. The objective was to evaluate and compare the production of 1 kg of live weight of calf under tropical production systems, called monoculture (MC) and silvopastoral (SP) systems. The results showed that the MC system performed better than the SP in three of the four environmental impact categories evaluated. However, the social evaluation did not show significant differences in the performance of the livestock systems analyzed. It was observed that the implementation of technologies in calf production systems did not influence their social performance, but rather that the socioeconomic context is decisive in the behavior of livestock organizations.

Introduction
It is a fact that the climatic and anthropological contexts generate livestock production systems that adapt to each reality (Romano-Armada, et al., 2014). In Mexico, cattle production in tropical conditions presents variants in its management that generate diverse environmental impacts (Herrero, et al, 2013, 2016; Rivera-Huerta et al., 2016). In addition, in rural areas of developing economies in Latin America, livestock practices tend to negatively impact human rights, particularly of workers (FAO, 2017).

According to the above, the regional variability of cattle production systems generates functional differences whose social, economic, and environmental effects must be evaluated and compared (IAASTD, 2009). Therefore, it is important to assess the sustainability of livestock production systems based on site-specific data. In this study, the life cycle approach is used to evaluate the environmental and social dimensions of the sustainability of livestock systems in the Mexican tropics.

Material and methods
This work was carried out from a life cycle approach using the Life Cycle Assessment (LCA) (ISO 14040/44, 2006) for environmental LCA (E-LCA) and the methodological framework proposed by the United Nations Environmental Program/Society of Environmental Toxicology and Chemistry (UNEP/SETAC) (2009) for Social Life Cycle Assessment (S-LCA) (UNEP/SETAC, 2009).

Goal and Scope Definition

System boundary

This research aimed to assess the environmental and social dimensions of sustainability of two calf production systems located in the Yucatan Peninsula, Mexico. The system boundaries were from the gate to gate of the farm and considered the cow-calf system, which includes the reproductive management of cattle, pregnancy and calving, lactation, and the calf's weaning.

Functional unit

The functional unit (FU) was 1 kg live weight (LW) of the calf and focused on two productive systems: silvopastoral (SP) and monoculture (MC). The life cycle inventory of the Environmental LCA was related to the FU, but this is not the case in the Social-LCA because there is no direct correlation (Dreyer et al., 2006).

System description

In the Mexican tropics, calf production is characterized by cow-calf herds (*Bos indicus* x *Bos taurus*) maintained on tropical pastures. The MC system is characterized by using cultivated grasses as the main diet of livestock, plus a commercial supplement. The SP system includes cultivated grasses and legumes, as the basis of the diet, which is complemented with commercial concentrate. In both systems, calves are weaned at 226 days with an average weight of 170 kg.

Life Cycle Inventory

The life cycle inventory was calculated from data collected through semi-structured interviews in six farms in Yucatan State, Mexico, three for each production system. Since the systems are based on grazing feeding, a dry matter (DM) intake of 3% of the live weight was assumed in replacement bulls and heifers, in agreement with Ku-Vera et al. (2018) and Lyons et al. (1999). Feed intake of lactating cows was calculated on a dry matter basis according to Rivera-Huerta et al. (2016). Methane (CH_4) emissions from enteric fermentation and manure management, nitrous oxide (N_2O) emissions from managed soils, and ammonia (NH_3) emissions to air were estimated according to Chapters 10 and 11, Vol. 4 of the Panel Guidelines Conference on Climate Change (IPCC) (Dong et al., 2006). Enteric methane emissions were calculated using emission factors (EFs) estimated with the IPCC Tier 2 methodology (Dong et al., 2006).

Life Cycle Impact Assessment

The evaluation methods used were ReCiPe 2016 midpoint-H v. 1.03 (Huijbregts et al., 2016) for environmental assessment, and a scoring approach with a performance scale ranging from 1 (very poor) to 4 (outstanding) (Padilla-Rivera et al. (2016) was employed for social impact assessment. The criterion for assigning performance values was specific to each subcategory based on national and international regulations. Performance scale ranging was associated to one color (performance/color): 1= very poor/red; 2= poor/blue; 3= acceptable/yellow, and 4= outstanding/red. The social analysis included the category of stakeholder group workers.

The environmental impact categories analyzed were climate change, terrestrial acidification, freshwater eutrophication, and fossil fuel depletion. The social impact subcategories evaluated were "child labor", "equal opportunities", "freedom of association and collective bargaining", "fair salary", "working hours", "job satisfaction" and "forced labor", which are grouped into the categories of human rights and working conditions.

Results and Discussion

The results showed that calves produced under the MC system save 7%, 11%, and 50% of the emissions that contribute to climate change, terrestrial acidification, and freshwater eutrophication, respectively, per 1 kg of LW of the calf, compared with the SP system (Figure 1). However, the SP saves 17% per 1 kg of LW of the calf in the use of fossil fuels compared to the MC system.

In the climate change category, enteric fermentation is the main contributor, followed by manure management. While in the terrestrial acidification and freshwater eutrophication categories, manure management shows the highest values of affectation (Table 1). Pasture management contributes significantly (from 70% to 76%) to the impact of the fossil resource depletion category due to the use of irrigation systems, as well as the production of pesticides and fertilizers. Different authors (Picasso et al., 2014; Ruviaro et al., 2015; Tichenor et al., 2017; Bragaglio et al., 2018) have obtained similar results.

Figure 1. Comparison of the normalized impact categories according to the system with the highest impact value.

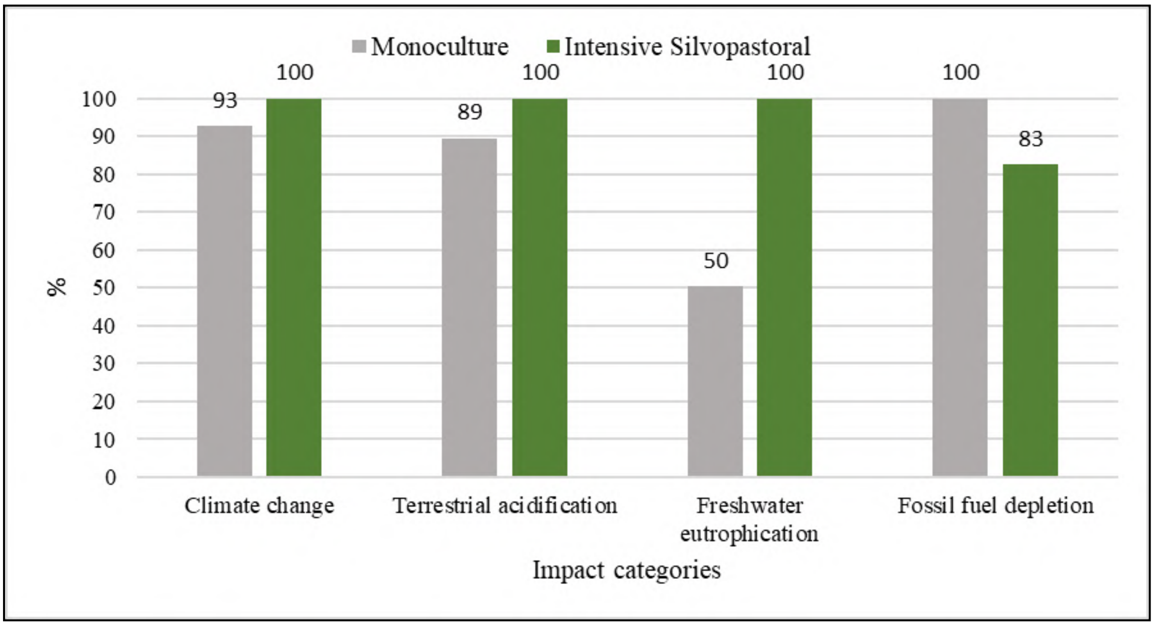

Table 1. Environmental impact for the FU (1 kg of LW of weaning calf) in absolute values and percentage relative contribution.

Impact category	**Unit**	System	**Score**	**Relative contributions (%)**				
				Enteric fermentation	Manure management	Pasture management	Feed	Others
Climate change	kg CO2 eq	MC	30.15	41.20	26.13	19.48	11.77	1.42
		ISP	32.51	46.70	28.00	16.84	6.55	1.91
Terrestrial acidification	kg SO2 eq	MC	0.43	0.00	86.54	4.81	7.94	0.72
		ISP	0.49	0.00	88.72	4.12	5.03	2.13
Freshwater eutrophication	kg P eq	MC	0.02	0.00	63.70	21.97	13.42	0.91
		ISP	0.04	0.00	83.32	11.70	4.18	0.80
Fossil fuel depletion	kg oil eq	MC	2.47	0.00	0.00	70.41	27.10	2.49
		ISP	2.04	0.00	0.00	76.43	19.72	3.85

On the other hand, the Social-LCA showed that 2 out of 7 impact subcategories had a good performance (Table 2), but the rest of the subcategories had a poor and very poor performance in both livestock systems. The results highlight that "equal opportunities", "freedom of association and collective bargaining", and "fair salary" subcategories had the poorest performance, these results are in line with other studies that evaluated agricultural products (Franze and Ciroth, 2011; Chen and Holden, 2017). There was no significant difference in the average performance of the two calf production systems, and there was only a favorable difference for the SP system in the "job satisfaction" subcategory.

The above indicates that under the context of the Mexican tropics the application of different technologies did not reflect differences in the social performance of livestock systems. The results for the social performance of livestock systems evaluated can mainly be explained by their social context and not by the type of production system. These results are in line with that reported by Dumont and Baret (2017), the socioeconomic and political context, history, work orientation, and sociocultural heritage exert a greater influence on producers' working conditions than does their degree of mechanization.

Table 2. The score for the subcategories of social impact in MC and SP.

	Human rights			Working conditions				
	Freedom of association and collective bargaining	Child labor	Equal opportunities and discrimination	Fair salary	Working hours	Forced labor	Job satisfaction	Mean
Monoculture	1	3	1	1.5	2	3	1	1.8
Silvopastoral	1	3	1	1	2	3	2	1.9

Conclusions

In the environmental dimension, the monoculture system had the best performance in climate change, the main environmental concern of today's human society; however, this system is also the one that generated the greatest fossil fuels depletion, whose scarcity puts human well-being at risk. For this reason, efficient systems for the use of energy and increasing the use of clean energy must be incorporated into cattle production processes. Furthermore, it is suggested that land use change impacts from cattle production are assessed to have an integral assessment of different tropical cattle production systems. In the social dimension, the results show that the tropical extensive livestock production systems of southeastern Mexico are far from favoring human rights and working conditions, so intervention is urgently needed through public policies based on workers to meet the basic workers' rights. It is important to continue with studies to evaluate the social and environmental performance of livestock in this region, for which it is suggested to have a comprehensive evaluation tool for the performance of tropical agricultural systems based on regional data. This will allow having elements that support the transition to the sustainable development of beef production.

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Huella de Carbono del Cacao en Grano en Perú

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1. Introducción

En el Perú, más de 100 mil familias se dedican al cultivo y producción de cacao, posicionando al país como el noveno productor mundial de cacao en grano y segundo productor mundial de cacao orgánico (Midagri, 2020). Además, el Perú posee el 60% de la biodiversidad de cacao existente en el mundo (material genético) y según la Organización Internacional del Cacao, el 75% de las exportaciones peruanas corresponden a cacao fino y de aroma (ICCO, 2021). En este sector agroalimentario, la sostenibilidad ambiental ha emergido como una necesidad crucial para adaptarse a los cambios climáticos futuros y; sin embargo, aún faltan más estudios y evaluaciones ambientales propios del cacao. Bajo ese requerimiento, el presente estudio tiene como objetivo medir, interpretar y analizar la Huella de Carbono (HC) de los Sistemas Agroforestales (SAF) y de procesamiento del cacao en grano en Perú para el diseño de modelos de producción sostenibles, mediante la aplicación de la herramienta Análisis de Ciclo de Vida (ACV).

2. Metodología

La cuantificación de los impactos ambientales del SAF y de procesamiento del cacao en grano se realizó con la herramienta ACV. El alcance es de la cuna a la puerta. Incluye las etapas de cultivo (manejo agronómico y cosecha), poscosecha (fermentado, secado, clasificado) y el transporte del cacao en grano al puerto más cercano. La etapa de semilla y vivero fue excluida debido a que en estudios previos se demuestra su muy baja contribución de emisiones respecto al total. Se utilizó la metodología ISO 14040:2006, la base de datos Ecoinvent v3.06 y para los cálculos, el software SimaPro. La categoría de impacto ambiental a analizar es el potencial de calentamiento global (kg CO_2 eq) para calcular la HC. La unidad funcional es un (1) kg de cacao en grano puesto en puerto.

El horizonte temporal considerado es la campaña del año 2019 y la data corresponde a los departamentos de Amazonas y Junín. El levantamiento de los datos se obtuvo de cuestionarios, gracias a la colaboración de los técnicos, previa capacitación, y estuvo monitoreada a distancia por el grupo de investigación debido al contexto de la pandemia. En total, se analizó 12 productores de la cooperativa de Junín y 15 de la región de Amazonas (Tabla 1).

Tabla 1
Datos generales de cada cooperativa

Datos generales	Cooperativa A (n=12)	Cooperativa B (n=15)	Unidad
Terreno de cultivo	58	27	ha
Densidad cacao	928	731	árboles/ha
Densidad sombra	35	13	árboles/ha

Para la estimación de la captura potencial de carbono del SAF se emplea el uso de ecuaciones alométricas. En el estudio se usa dos dimensiones básicas de las plantas (altura y diámetro) y con ellas se estima la biomasa, la cual se convierte en materia seca y finalmente en stock de carbono (resultados que luego se transforman a CO_2 para el balance de la HC). En la Tabla 2 se presentan las diferentes ecuaciones alométricas para la estimación de la captura de carbono del cacao, así como para las especies forestales de sombra presentes en las fincas. Para la asignación de impactos se toma en cuenta el valor económico y el peso de cada subproducto. Es decir, se pondera el precio de los productos y su peso.

Tabla 2
Ecuaciones alométricas para estimar la captura potencial de carbono

Especie	Ecuación alométricas	Fuente
Theobroma cacao	Log Y= (-1.684 + 2.158*Log(d_{30}) + Log(alt))	CATIE (s.f.)
	Y=-2.01539+0.191278*E-0.00037E^2	Ortiz et al. (2008)
Genérica (sin especificar)	Y=0.25D^2H Y=0.15D^2H	Oyamakin et al. (2014)
Cordia alliodora	Log Y=(-0.94+1.32*Log(dap)+1.14*Log(alt))	CATIE (s.f.)
Mangle	Y=exp [-2.977+Ln(rD^2H)]	Chave et al. (2005)
Palma	Y=10+6.4(H)	Frangi y Lugo (1985)
Musa sp	Y=0.0303D^2.1345	Harianh et al. (2001)
Citrus sinensis	Y= 6.64+0.279(AB)+0.000514$(AB)^2$	IPCC (2001)
Bactris gasipaes	Y=0.74*alt^2	Szott et al. (1993)
Árboles maderables	Y=(21.3-6.95*(dap)+0.74(dap^2))	Brown e Iverson (1992)
Árboles frutales	Log Y=(-1.1`+2.64*Log(dap))	CATIE (s.f.)

Nota. Y: Biomasa en kg. (árbol)-1; D: diámetro normal en cm a 1.3m; H: altura total en m; r: densidad de la madera en g.cm-3; AB: área basal en cm^2; Log: logaritmo base 10; dap: diámetro del tronco a la altura del pecho (cm), d30: diámetro a la altura de 30 cm; alt: altura total (m); V: volumen; E: edad en años.

3. Resultados y discusión

La Tabla 3 muestra el inventario (las entradas y salidas principales) para la etapa de cultivo en cada una las cooperativas que pertenecen al proyecto y en la Tabla 4 se resume las entradas y salidas en la etapa de poscosecha; es decir, de todas las actividades que pertenecen al fermentado, secado y selección en cada organización. Además de los datos mostrados en las tablas de inventario, se ha considerado el transporte del cacao en grano al puerto de exportación. Las ubicaciones de los puertos son Paita y el Callao y las distancias del traslado son de 466 km y 486 km, respectivamente.

Tabla 3
Inventario de la etapa de cultivo para la obtención de 1 t de cacao en baba

ENTRADAS	Cooperativa A (n=12)	Cooperativa B (n=15)	Unidad
Fertilizantes			
Bocashi	396.1	-	kg
Guano de isla	276.5	38.0	kg
Guano de cuy	19.5	-	kg
Dolomita	119.9	-	kg
Compost-pulpa de café	12.6	109.2	kg
Roca fosfórica	44.1	2.4	kg
Sulpomag	29.4	-	kg
Transporte de fertilizantes	18.0	1.5	tkm
Gasolina (uso motosierra)	3.5	5.3	kg
Sacos polipropileno	0.7	1.2	kg
SALIDAS			
Cacao en baba	**1**	**1**	**t**
Rendimiento cacao en baba	1.47	1.37	t/ha
Cáscaras de mazorcas	4.64	4.23	t/ha

Tabla 4
Inventario de la etapa de poscosecha para la obtención de 1 t de cacao en grano

ENTRADAS	Cooperativa A (n=12)	Cooperativa B (n=15)	Unidad
Cajones (madera)	1.965	1.423	cm^3
Sacos (yute o pp.)	0.034	0.059	g
Cilindros (plástico)	0.008	-	g
Mantas (plástico)	94.201	209.575	g
Mantas (rafia)	62.173	-	g
Sacos de polipropileno	235.502	327.461	g
Parihuelas (plástico-madera)	64.528	196.477	g
Máquina de selección (acero)	-	567.817	g
Energía eléctrica	-	0.491	kWh
SALIDAS			
Cacao en grano de exportación	**1**	**1**	**t**
Cacao en grano de segunda	0.013	0.012	t

Los resultados de las emisiones totales para 1 kg de cacao en grano puesto en puerto se muestran en la Tabla 5. La columna denominada "total" muestra la suma de las emisiones de todas las etapas descritas anteriormente en unidades de kg de CO_2 eq / 1 kg de cacao en grano.

Tabla 5
Emisiones de kg CO_2- eq por 1 kg de cacao en grano puesto en puerto

Cooperativa	Cultivo y cosecha	Poscosecha	Transporte a puerto	Total	Unidad
A	7.020	0.194	0.078	**7.29**	kgCO_2-eq/1kg de cacao en grano
B	7.644	0.095	0.082	**7.82**	kgCO_2-eq/1kg de cacao en grano

3.1. Captura de carbono

La captura de carbono está constituida por la fijación de los árboles de cacao y de los árboles sombra. A causa de la variedad de ecuaciones alométricas de distintos autores, se trabajó con dos métodos (ecuaciones) para los resultados de la captura de carbono de los árboles de cacao y para la captura de los árboles sombra se consideró el promedio ponderado de los resultados de las ecuaciones y la cantidad de árboles sombra. La Tabla 6 muestra los resultados de la captura de carbono correspondiente a los árboles de cacao, sombra y el total (suma de ambos). Para obtener la captura en base a la unidad funcional, se utilizó la producción de cacao en grano por hectárea al año de cada cooperativa. La cooperativa A tiene una producción de 515 kg de cacao en grano/ha-año y la cooperativa B produce 564 kg de cacao en grano/ha-año.

Tabla 6
Captura de carbono de árboles de cacao y árboles sombra

Cooperativa	Método captura cacao	Captura de árbol de cacao kg CO_2/kg cacao en grano	Captura de árbol sombra kg CO_2/kg cacao en grano	Captura total (cacao y sombra)
A	1	**5.944**	**0.245**	**6.189**
	2	**0.176**	**0.245**	**0.421**
B	1	**2.991**	**3.573**	**6.564**
	2	**-0.207**	**3.573**	**3.366**

Nota. El método 1 de captura de cacao, considera el diámetro y la altura, mientras que el método 2 considera solo la edad del árbol.

Los resultados de la captura de carbono se ven afectados por las variables utilizadas en las ecuaciones alométricas. En ambas cooperativas se muestra que el método 2 de captura de carbono presenta resultados menores que el método 1. No obstante, el método 1 utiliza dos variables (diámetro y altura) en sus ecuaciones y por ello muestra mayor consistencia en los resultados totales para ambas cooperativas (6.189 y 6.564), además de ser un método usado con mayor frecuencia.

3.2. Balance de carbono

Para calcular la huella de carbono es necesario realizar el balance de carbono entre las emisiones y la captura, asegurándose de que sus valores tengan las mismas unidades. Para las emisiones se considera el resultado total (suma de las emisiones de todas las etapas) y en la captura se tomará en cuenta la captura total en el método 1. Al realizar el balance (emisiones menos la captura) se obtiene un resultado de 1.10 y 1.26 kg CO_2-eq/kg cacao en grano para las cooperativas A y B, respectivamente. La HC obtenida de las cooperativas indica que para producir 1 kg de cacao en grano puesto en puerto se emite más de 1 kg de CO2-eq al ambiente. Por lo tanto, es necesario una mejor gestión del SAF y de los procedimientos en la cadena de valor del cacao para reducir esa HC y lograr mejorar su desempeño ambiental.

4. Conclusiones

De los resultados obtenidos, se concluye que la etapa que más contribuye con el potencial de cambio climático es la etapa de cultivo y cosecha, con un 97.7% y 96.3% para las cooperativas A y B, respectivamente. Dentro de esta etapa, la cáscara del cacao (mazorcas) es el principal elemento que emite GEI, ya que el manejo de este residuo es pobre y al dejarlos a la intemperie, se descomponen y emiten metano. La cáscara de mazorca por sí sola, contribuye en ambas cooperativas un 93.7% del total de las emisiones.

La cantidad de CO_2 capturada de los árboles sombra de la cooperativa B es superior a la de los árboles de cacao en la cooperativa A. La diferencia es debido a las características del sistema agroforestal y a las dimensiones de los árboles por cada cooperativa. Mientras que la cooperativa A tiene árboles de cacao más grandes y menos árboles sombra; es decir un marco de plantación menos denso, en la cooperativa B se disponen de árboles de cacao más pequeños y con mayor densidad de árboles sombra. De ese modo, el diseño del Sistema agroforestal (SAF) influye en el balance de carbono, porque la densidad de árboles y sus características son insumos para las ecuaciones alométricas y para el cálculo de la captura total. Se recomienda mantener un SAF que incluya una mayor densidad de árboles sombra que, mientras este optimice la producción de cacao deseada, a su vez también contribuya en la captura de carbono. Lo mencionado tiene estrecha relación con un estudio en el sudeste asiático que concluyó que, si se planifica adecuadamente, las plantaciones de cacao bajo una cubierta de árboles sombra permiten combinar un alto rendimiento productivo con beneficios para el secuestro y almacenamiento de carbono, además de niveles más altos de la diversidad animal y vegetal (Abou Rajab, 2016).

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Transforming agriculture with Agroecological Symbiosis, integrating alternative protein production – Environmental impacts assessment

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Introduction:

Food systems are a major contributor to climate change, accounting for 34% of global greenhouse gas emissions (Crippa et al. 2021). Besides, it has associated many other environmental impacts, such as water use and pollution, land use change, and biodiversity loss (Campbell et al. 2017). More specifically, livestock production accounts for greater impacts, when compared to other foods (Poore and Nemecek 2018). Since food production is necessary for humanity, part of these impacts is unavoidable, although many efforts are placed on reducing the impacts related to food systems. Some proposals are to drive changes in the dietary patterns to reduce the intake of livestock products, by either avoiding those products or by replacing them with alternatives that mimics their function, in a wide range of options. Among those alternatives, plant-based products and cellular agriculture (e.g. cultivated meat and precision fermentation) are leading commercial and funding proposals (Wood and Tavan 2022). While plant-based alternatives are widely commercialized, cellular agriculture industry is still in a developing stage. Thus, current estimations about the costs and environmental impacts of an industrial scalation that could provide competitive prices and satisfy the increasing meat demand, are surrounded by big uncertainties (Stephens et al. 2018). Some studies have shown cellular agriculture as a potential solution to decrease environmental impacts related to livestock production, when this technology is supported by using renewable energy (Järviö et al. 2021). However, there have been concerns raised about the challenges that cellular agriculture would face in the industrialization phase, that would delay its implementation and its effects on mitigating climate change (Fassler 2021). The design of efficient and sustainable food systems involving cellular agriculture is to be decided in the next decades. Thus, it is important to assess the impacts and services of different designs during the development stage of the industry.

The access to renewable energy seems to be a crucial feature determining alternative proteins production sustainability (Tuomisto 2019). In an attempt of bringing together the use of renewable energy and a farm-scale production strategy, we propose to apply the concept of Agroecological

Symbiosis (AES) to alternative protein production. AES system aims resilient agricultural techniques and circular economy by locating food and bioenergy producers and processors in proximity, allowing efficient material and energy integration (Koppelmäki et al. 2019). In AES, an anaerobic digester produces biogas as a renewable energy source from crop residues, cover crops, and clover-grass leys incorporated into the crop rotations, as well as from manure and biowaste from neighbouring food processing plants and communities. This energy can meet the demand of the companies located near the system. Besides, AES can improve the sustainability of plant production in areas where livestock production cannot be integrated with crop production; the digestate created during the anaerobic digestion can be used as an organic fertilizer, effectively recycling nutrients back into the field.

The objective of this research is to assess the cradle-to-farm gate global warming potential of replacing the current way of livestock production with plant-based and cellular agriculture alternatives, in a farm-scale and by using an AES system as a way of integrating food and biogas production. A focus on the production of biogas by using waste streams (e.g. manure, and crop residues) is given, to assess the feasibility of anaerobic digestion technology to support the energy demand from alternative protein production.

Methodology:
Life Cycle Assessment (LCA) methodology was used to assess 3 different scenarios where production is based in a farm located in Southern Finland. The base scenario (Scenario "Cow") considers the production of milk and meat in a dairy farm with an agricultural area of 100 ha approximately. This farm is designed to be self-sufficient in production, importing only a small portion of the feed required. The other scenarios assume the same production of milk and meat but produce their respective alternatives; a) plant-based scenario (Scenario "Oats") which considers oats-milk and pulled-oats as substitutes and, b) cellular agriculture scenario (Scenario "Cellular") with production of oat milk (97%) supplemented with casein produced by precision fermentation (3%) and cultivated meat. Pulled oats are a plant-based proteic product developed and commonly used in Finland, made of oats, rapeseed oil, and fava bean and pea protein concentrate. No further adjustments were performed to liken nutritional equivalencies between the compared products (e.g. cow milk with oats milk). In all scenarios, crop residues and manure, when produced, are used as feedstock for biogas production in an anaerobic digester.

The assessment was performed using OpenLCA software. Data regarding production processes and emission factors were taken from literature, while EcoInvent 3.7.1 and Agri-footprint 5.0 databases were used for the background data. The ReCiPe 2016 Midpoint (H) 2.1.1 method was selected to calculate the GWP100. The functional unit (FU) of the system is the total kg production of raw milk and meat at farm gate, when using 100 ha of agricultural land. Facilities were excluded from the scope of the study.

Preliminary results:
The preliminary results show that the base scenario requires 99.6 ha of agricultural land to produce 425.3 tonnes of milk and 4.7 tonnes of meat yearly. Besides, the system produced 184,844 Nm^3 of biogas from crop residues and manure. Supplementation with inorganic fertilizers was required to fulfil the nutritional requirements of the crops (3.6 tonnes N and 0.23 tonnes P). In "Oats scenario" 34% less of agricultural land is required to produce the same amount of oats milk and pulled oats (65.6 ha in total). Further, it produced the lowest amount of biogas (107,277 Nm^3 in total), which consist of 42% reduction from the base scenario. In this scenario, only supplementation with inorganic N fertilization was required (4 tonnes N). Finally, the "Cellular scenario" requires 12.5% less of agricultural land than the base scenario (87 ha in total) and produced 29% less biogas

(132,000 Nm^3 in total). Supplementation with inorganic N and P fertilizers was also needed (4.3 tonnes N, 0.04 tonnes P).

The total energy requirement for each scenario shows high variability. Oats and cellular scenarios required more electricity than the base scenario (28% and 52% more, respectively). By integrating the anaerobic digestion technology, all scenarios produced more electricity than what was required to perform their activities. The base, oats, and cellular scenarios produced 355,881 kWh, 66,510.4 kWh, and 21,281.6 kWh of extra energy, respectively, that could be uploaded to the electrical grid.

In terms of fertilizer recycling, the base scenario demonstrated the highest proportion in organic N fertilizer recycling (69%), while oats scenario showed the lowest proportion (31%). This might be related to lower fertilization requirements in the base scenario, where 49 ha (50% of the total agricultural land) are used to grow clover-gras silage mixture, which do not require any type of fertilization.

Regarding environmental impacts, the global warming potential of the base, oats, and cellular scenario was equal to 503.7 tonnes CO_2-eq, 99.7 tonnes CO_2-eq, and 94.6 tonnes CO_2-eq, respectively. The results suggest that substituting milk and meat production from dairy farms to plant-based and cellular-based alternatives could decrease the greenhouse gas emissions 80 and 81%, respectively, in case renewable energy is used.

Table 1: Preliminary results of annual milk, meat, biogas, and electricity production for base, oats, and cellular scenario. Agricultural land, and inorganic fertilizers use to support that production are also included.

	Base Scenario	Oat Scenario	Cellular Scenario
Agricultural land (ha/year)	99.63	65.61	87.16
Agricultural land reduction (%)	0.00	34.15	12.51
Milk production (t/year)	425.31	425.31	425.31
Meat production (t/year)	4.68	4.68	4.68
Biogas production (Nm3/year)	184,844.24	107,277.32	131,999.99
Inorganic N fertilizer use (t N/year)	3.62	3.98	4.34
Inorganic P fertilizer use (t P/year)	0.24	0	0.04
Electricity net production (kWh/year)	355,881.03	66,510.37	21,281.64
Global warming potential (t CO_2-eq/year)	503.72	99.75	94.63

Conclusion:

This study estimated that less agricultural land is required to produce plant-based and cellular-based alternatives for milk and meat. The highest reduction in agricultural land was seen for the oats scenario. However, it is worth mentioning that the major land use for cellular scenario was related to oats milk production (land uses were 20% for cultured meat, 70% for oats milk, and 5% for casein). Thus, the agricultural land requirements for producing cultured milk by using only precision fermentation are expected to be lower.

The results suggest that the incorporation of a farm-scale anaerobic digester would support the production of the total electricity. This production is sufficient even when considering high-electricity demanding technologies, such as cellular agriculture. Moreover, the anaerobic digester can turn the farms into net-energy producers, while ensuring an efficient way of farm-related waste management. It also encourages the reduction of inorganic fertilizers use, by providing the opportunity of recirculating the nutrients from the crop residues or manure back into the field.

Finally, an 80% decrease in greenhouse gas emissions was estimated for the alternative scenarios. However, the nutritional content of the compared products was not equivalent; further analysis should be performed to take nutritional differences in consideration.

In conclusion, this study focused on alternative protein production supported by biogas as a renewable energy source. Future research should further explore the use of the spared land of these alternative scenarios, which can be significant to produce more food or biogas.

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Life cycle assessment of microalgae as protein source: comparison of drying technologies

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Objective of the study

Microalgae have been recognized as promising food item to close the protein gap of the growing global population (Caporgno and Mathys, 2018). Previous life cycle assessment studies of microalgae as protein source have shown disadvantageous results when compared the other protein sources due to the high energy demand of the production processes (Smetana et al., 2017; Taelman et al., 2015). This study evaluates the potential of innovative drying technologies to improve the environmental performance of microalgal protein in the framework of the EU research project PROFUTURE (www.pro-future.eu).

Methodology

The study focuses on two protein-rich microalgae species approved as foodstuff: *Chlorella vulgaris* (32% protein) and *Tetraselmis chui* (40% protein). Three innovative drying technologies – agitated thin film drier, pulsed combustion drier and solar drier – are benchmarked against two conventional technologies – spray drier and freeze drier. *C. vulgaris* is cultivated heterotrophically in a fermenter using glucose as carbon source. *T. chui* is cultivated photo-autotrophically in photobioreactors using liquid carbon dioxide as carbon source. Data for the cultivation of the two species were collected on industrial-scale from project partners located in Portugal, while the drying technologies were implemented on pilot-scale. The environmental impacts were calculated for the functional unit "1 kg protein" using the environmental footprint 3.0 method since it supports the regionalized assessment of water flows, support single score evaluation and is commonly applied in Europe and EPDs.

Results and discussion

Despite having a higher protein content and lower drying losses, *T. chui* showed consistently higher environmental impacts than *C. vulgaris*. This is due to two reasons: (i) *C. vulgaris* is a freshwater specie and does not require chemical-intensive sea-water cleaning, (ii) high growth rate of heterotrophic cultivated *C. vulgaris* compared to autotrophic cultivated *T. chui*.

All innovative drying technologies tested outperform the conventional spray drier. The results show a large correspondence with the drying losses, while the environmental impacts of the freeze drier are in the same order of magnitude as the impacts of the innovative technologies. For *C. vulgaris*, the pulsed combustion drier shows the best result, while for *T. chui*, the solar drier performs slightly better due to lower losses of biomass. Compared to animal protein, microalgal proteins dried with new technologies have lower environmental impacts than beef protein, and it some cases reaches the same order of magnitude as pork protein. However, plant proteins have still considerably lower environmental impacts than microalgal protein (see Figure 1 and Figure 2).

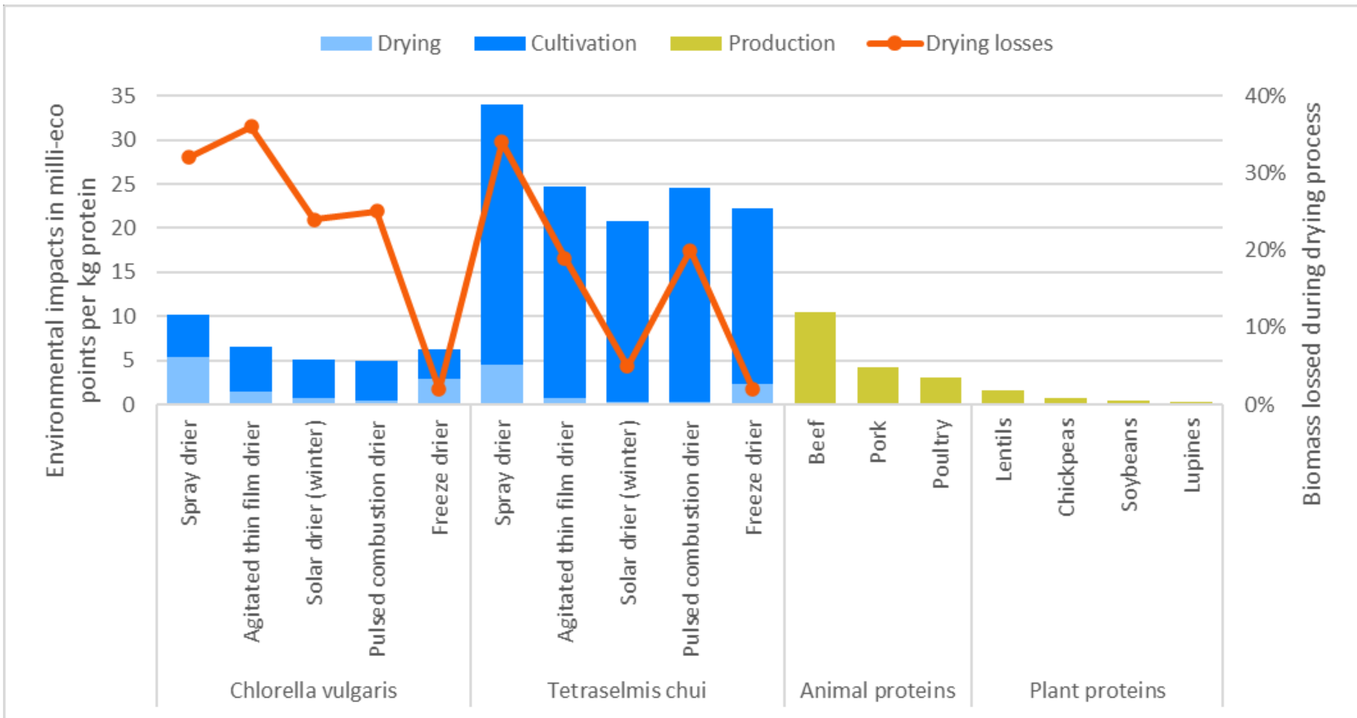

Figure 1: Aggregated environmental impacts of microalgal protein and reference products in milli-ecopoints.

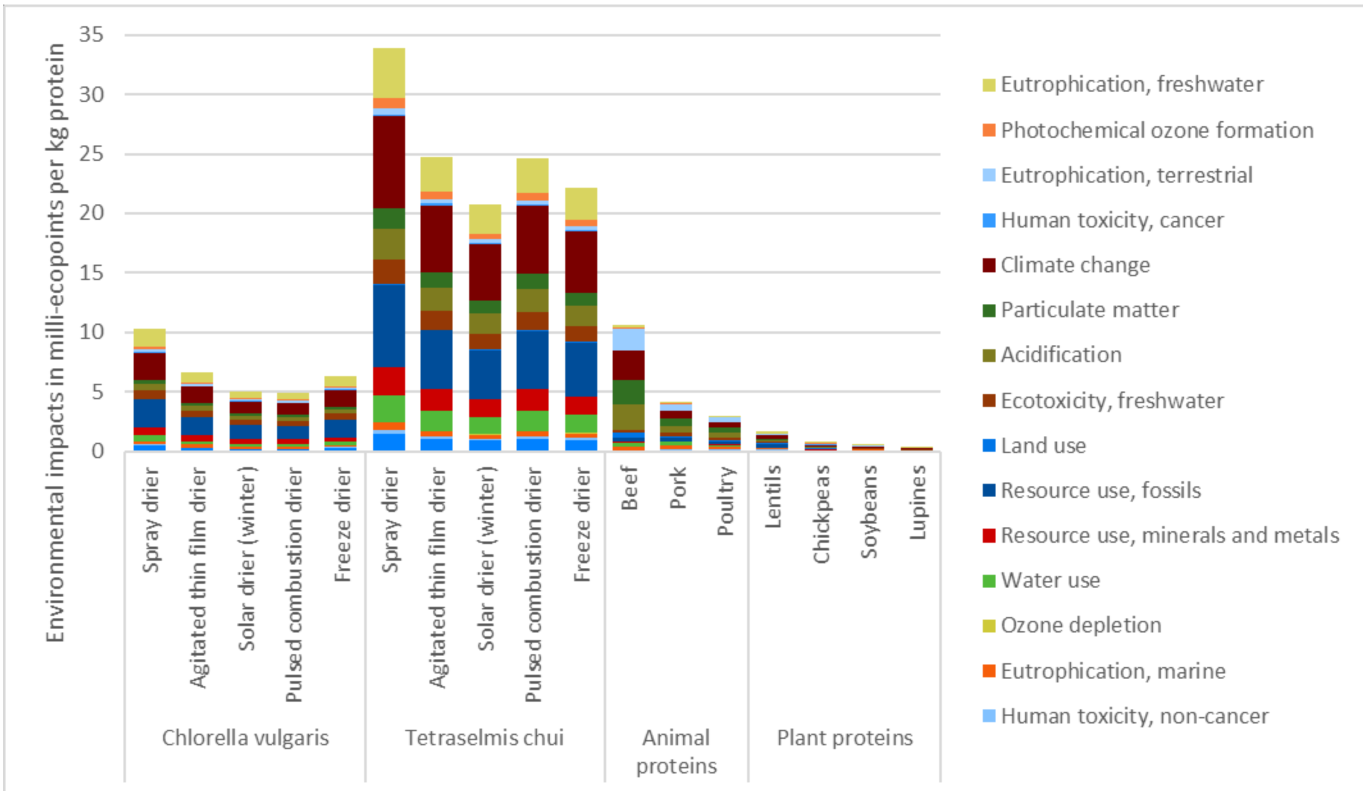

Figure 2: Contribution of midpoint indicators to aggregated impacts of microalgal protein and reference products in milli-ecopoints.

The spray drier has the highest environmental impacts for proteins from *C. vulgaris* in all categories except for cancerous human toxicity, where the freeze drier has higher impacts. The pulsed combustion drier ranks best in most impact categories, followed by the solar drier and the freeze drier. The agitated thin film drier shows the second or third worst results for all impact categories.

Microalgae protein is outperformed by animal proteins in most impact categories. For particulate matter, terrestrial eutrophication and land use microalgae proteins from *C. vulgaris* - independent of the drying technology - show lower impact than beef. Except for the spray drier, microalgae proteins from *C. vulgaris* have lower acidification impacts than beef. The land use of solar, pulsed combustion and freeze drier is in the same order of magnitude as for pork. Poultry protein is advantageous over microalgae protein in all impact categories (Table 1).

Three key drivers of the environmental impacts of proteins from *C. vulgaris* were identified in a hotspot analysis: electricity, glucose as carbon source and propane. Propane, used for equipment sterilization, and glucose are solely consumed in the cultivation stage which further indicates the importance of this stage, while electricity is used during cultivation and drying except for the pulsed combustion drier which uses natural gas as energy source. Increasing the yield of the solar drier to 95% as it is the case for *T. chui* could reduce the environmental impacts of proteins from *C. vulgaris* by around 20%.

Table 1: Midpoint results for 1 kg protein from *C. vulgaris* and meat. Values higher than all meat alternatives are shown in red, values lower than all meat alternatives are shown in green.

Impact category	Unit	Pork	Poultry	Beef	Spray drier	Agitated thin film drier	Solar drier	Pulsed combustion drier	Freeze drier
Climate change	kg CO2 eq	5.14E+00	4.10E+00	2.10E+01	8.60E+01	5.11E+01	3.87E+01	3.88E+01	5.32E+01
Ozone depletion	kg CFC11 eq	1.29E-07	1.26E-07	1.19E-07	6.35E-06	4.72E-06	3.75E-06	4.11E-06	4.05E-06
Ionising radiation	kBq U-235 eq	1.94E+00	1.95E+00	1.46E+00	4.05E+01	1.97E+01	1.42E+01	1.25E+01	2.42E+01
Photochemical ozone formation	kg NMVOC eq	1.92E-02	1.42E-02	2.85E-02	2.04E-01	1.34E-01	1.03E-01	9.95E-02	1.27E-01
Particulate matter	disease inc.	8.60E-07	6.35E-07	2.87E-06	2.32E-06	1.87E-06	1.51E-06	1.47E-06	1.55E-06
Human toxicity, non-cancer	CTUh	1.32E-07	9.01E-08	-2.15E-07	1.07E-06	7.68E-07	6.10E-07	5.72E-07	6.75E-07
Human toxicity, cancer	CTUh	3.52E-09	2.52E-09	1.95E-09	4.56E-08	3.60E-08	2.59E-08	2.46E-08	5.30E-08
Acidification	mol H+ eq	1.24E-01	9.32E-02	4.11E-01	5.17E-01	3.43E-01	2.68E-01	2.55E-01	3.25E-01
Eutrophication, freshwater	kg P eq	2.02E-03	1.78E-03	2.43E-03	8.39E-02	4.78E-02	3.41E-02	3.11E-02	4.74E-02
Eutrophication, marine	kg N eq	4.86E-02	3.46E-02	5.05E-02	1.99E-01	1.84E-01	1.28E-01	1.30E-01	8.74E-02
Eutrophication, terrestrial	mol N eq	5.33E-01	3.99E-01	1.82E+00	1.05E+00	8.15E-01	6.49E-01	6.39E-01	6.74E-01
Ecotoxicity, freshwater	CTUe	1.10E+02	8.12E+01	1.10E+02	1.58E+03	1.27E+03	9.89E+02	9.59E+02	9.70E+02
Land use	Pt	3.58E+02	2.78E+02	8.63E+02	5.58E+02	4.56E+02	3.95E+02	3.60E+02	3.75E+02
Water use	m3 depriv.	8.60E+00	5.25E+00	9.18E+00	2.69E+01	1.91E+01	1.50E+01	1.44E+01	1.72E+01
Resource use, fossils	MJ	4.67E+01	4.67E+01	5.37E+01	1.86E+03	1.13E+03	8.62E+02	8.53E+02	1.15E+03
Resource use, minerals and metals	kg Sb eq	8.12E-06	6.08E-06	1.66E-05	4.93E-04	4.28E-04	3.66E-04	3.39E-04	3.47E-04

The spray drier is outperformed by the four other technologies in all impact categories for proteins from *T. chui*. The solar drier shows the best results in all impact categories followed by the freeze drier, with the exception for cancerous human toxicity, where the freeze drier is the second worst option. The pulsed combustion drier and the agitated thin film drier show similar results in all impact categories. Except for the spray drier, microalgae proteins from *T. chui* have lower terrestrial eutrophication impacts than beef. Proteins from pork and poultry showed lower impacts than proteins from *T. chui* in all impact categories (Table 2).

The most important hotspots for proteins from *T. chui* are the electricity used during cultivation and the sodium thiosulfate used for sea-water cleaning. Since the impacts of sodium thiosulfate were approximated by stoichiometric conditions, the impacts might be underestimated. The use of carbon dioxide is especially relevant for non-carcinogenic human toxicity and for the use of mineral and metals, while sodium nitrate is important for marine and terrestrial eutrophication as well as for mineral and metal depletion. The impact of carbon dioxide might be reduced if an alternative carbon source (e.g. a carbon-rich flue gas) is used. The direct land use of the cultivation stage causes around 15-20% of the total land use. Stainless steel, which is used to estimate the equipment, is a key driver for carcinogenic human toxicity. Wastewater treatment is important for marine eutrophication and reduced the net amount of water used.

Table 2: Midpoint results for 1 kg protein from *T. chui* and meat. Values higher than all meat alternatives are shown in red, values lower than all meat alternatives are shown in green.

Impact category	Unit	Pork	Poultry	Beef	Spray drier	Agitated thin film drier	Solar drier	Pulsed com-bustion drier	Freeze drier
Climate change	kg CO2 eq	5.14E+00	4.10E+00	2.10E+01	2.98E+02	2.16E+02	1.82E+02	2.16E+02	1.95E+02
Ozone depletion	kg CFC11 eq	1.29E-07	1.26E-07	1.19E-07	2.76E-05	2.11E-05	1.79E-05	2.15E-05	1.83E-05
Ionising radiation	kBq U-235 eq	1.94E+00	1.95E+00	1.46E+00	1.27E+02	8.82E+01	7.37E+01	8.62E+01	8.21E+01
Photochemical ozone formation	kg NMVOC eq	1.92E-02	1.42E-02	2.85E-02	6.91E-01	5.08E-01	4.27E-01	5.05E-01	4.54E-01
Particulate matter	disease inc.	8.60E-07	6.35E-07	2.87E-06	1.11E-05	8.67E-06	7.34E-06	8.70E-06	7.45E-06
Human toxicity, non-cancer	CTUh	1.32E-07	9.01E-08	-2.15E-07	4.00E-06	3.00E-06	2.54E-06	2.99E-06	2.64E-06
Human toxicity, cancer	CTUh	3.52E-09	2.52E-09	1.95E-09	1.60E-07	1.21E-07	1.00E-07	1.19E-07	1.25E-07
Acidification	mol H+ eq	1.24E-01	9.32E-02	4.11E-01	2.29E+00	1.73E+00	1.46E+00	1.73E+00	1.52E+00
Eutrophication, freshwater	kg P eq	2.02E-03	1.78E-03	2.43E-03	2.45E-01	1.71E-01	1.41E-01	1.67E-01	1.56E-01
Eutrophication, marine	kg N eq	4.86E-02	3.46E-02	5.05E-02	3.89E-01	2.72E-01	2.12E-01	2.73E-01	2.19E-01
Eutrophication, terrestrial	mol N eq	5.33E-01	3.99E-01	1.82E+00	2.42E+00	1.77E+00	1.48E+00	1.76E+00	1.59E+00
Ecotoxicity, freshwater	CTUe	1.10E+02	8.12E+01	1.10E+02	4.66E+03	3.48E+03	2.91E+03	3.47E+03	3.03E+03
Land use	Pt	3.58E+02	2.78E+02	8.63E+02	1.38E+03	1.04E+03	8.91E+02	1.03E+03	9.22E+02
Water use	m3 depriv.	8.60E+00	5.25E+00	9.18E+00	1.84E+02	1.44E+02	1.22E+02	1.45E+02	1.23E+02
Resource use, fossils	MJ	4.67E+01	4.67E+01	5.37E+01	5.36E+03	3.82E+03	3.20E+03	3.79E+03	3.50E+03
Resource use, minerals and metals	kg Sb eq	8.12E-06	6.08E-06	1.66E-05	1.96E-03	1.53E-03	1.31E-03	1.53E-03	1.32E-03

Conclusion

Innovative drying technologies can reduce the environmental impacts of microalgal protein to an order of magnitude comparable to animal protein from beef. The most important parameter influencing the result of the drying technologies is the drying yield due to the high contribution of the cultivation stage. The higher the yield, the less biomass needs to be cultivated for 1 kg protein. More research in improving the cultivation stage as well as in higher yields of downstream processes is required to increase the environmental competitiveness of microalgal protein even further. The hotspot analysis suggests that for both species measures should be tested to reduce the electricity consumption of the cultivation stage. In addition, nutritional inputs such as glucose, carbon dioxide and sodium nitrate are contribution considerably to the environmental impacts. Nutrient-rich waste streams should be evaluated as alternative.

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More out of agrifood co-products – LCA platform of novel food and feed pathways

Abstract code : 25

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Keywords: *Bioeconomy, Life cycle analysis, Insects, Fermentation, Circular economy, Alternative proteins*

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Introduction

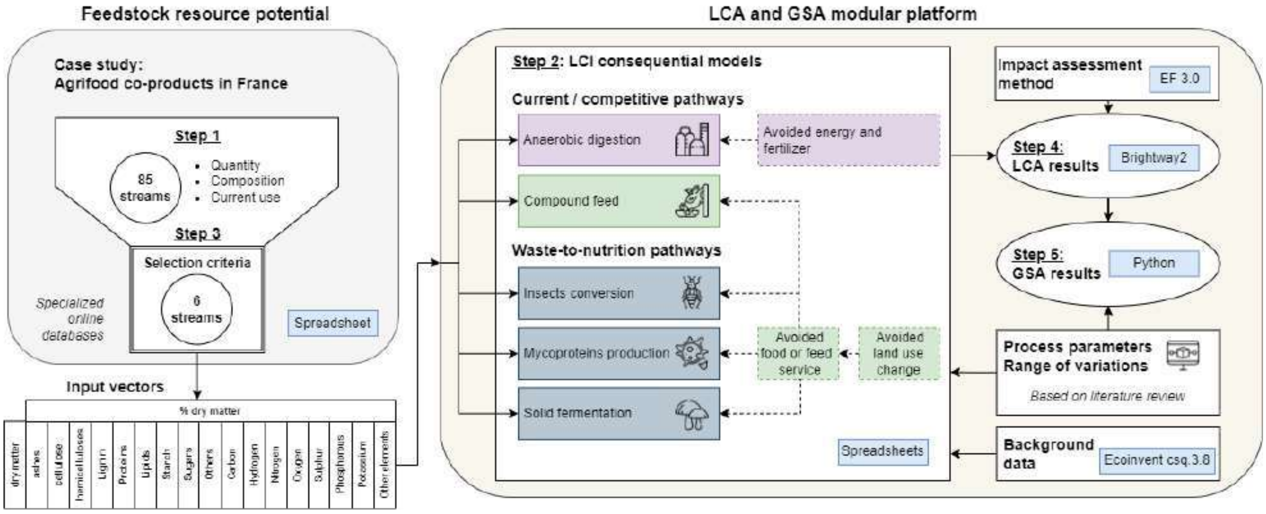
When it comes to control its current environmental impacts or to guarantee its functions in the future, the global food system is facing important challenges (Searchinger et al., 2018). These include population growth, shifting diets and exceeding planetary boundaries such as climate change, land availability or nutrients cycles. To alleviate these impacts and strengthen food system's resilience, the implementation of waste-to-nutrition pathways is increasingly promoted (Javourez et al., 2021). Yet, the environmental implications of such strategies, aiming to transform residual biomasses into edible ingredients, remain unclear. Indeed, residual biomass, while being a constrained resource, is nevertheless increasingly demanded by emerging bioeconomies (Fritsche et al., 2021). This is especially true for agrifood co-products, which encompass a broad panel of side streams generated from the processing of crops into food and beverage products. Such quality feedstocks, while already sustaining food systems through their agronomic valorization or direct use as feed ingredients, are also prospected by biorefineries platforms (Garcia-Bernet et al., 2020) and in the pipeline to formulate novel food and feed through a variety of conversion pathways involving e.g. insects, solid fermentation, protein extraction or even cellulosic sugars recovery. In front of the multiple management possibilities, it remains uncertain whether and to which extent transforming agrifood co-products into novel ingredients really improve environmental performances in comparison to current (or forecasted) practices. Therefore, this study proposes the development of a parametric life cycle assessment (LCA) platform to explore the conditions under which agrifood co-products can sustainably be used to supply emerging waste-to-nutrition value chains (**Figure 1**). Despite the necessity to quantify environmental pros and cons before binding investments are made in the bioeconomy sector, such assessment has not been developed yet.

Material and methods

In an endeavor to fill this gap, we built a five-steps assessment framework that we applied to the case of France (**Figure 1**). First, France's agrifood co-products resource potential (quantity, composition, current use) was estimated by combining feed databases and specialized reports datamining. This resulted in a dataset of 85 streams. Second, a parametric life cycle inventory (LCI) model was developed and harmonized for each of the five studied valorization strategies: three emerging waste-to-nutrition pathways (solid fermentation with *Pleurotus Ostreatus* fungi; SSF, insects farming with *Hermetia Illucens* larvae; BSF, mycoproteins production with *Fusarium Venenatum* fungi; MP) and two representing current valorization (direct inclusion in compound feed; CF, anaerobic digestion; AD). The modular LCI of AD, CF and SSF were directly retrieved from (Javourez et al., 2022). BSF's LCI was modeled using the standardization framework of (Spykman et al., 2021). Finally, MP's LCI was built on the set-up proposed by (Upcraft et al., 2021). It consists in a lignocellulose (or starch depending on the case) hydrolysis stage followed by the aerobic fermentation of the hydrolysates. BSF and MP ingredients were considered suitable to supply both food and feed markets (see Supplementing information; **SI**). For all feed ingredients, their nutritional value was estimated following the digestibility-based approach detailed in

(Javourez et al., 2022). Accordingly, case-specific substitution of a mix of soybean meal, maize and palm oil were calculated. BSF and MP entering food markets were assumed to substitute marginal meat (for France, a mix of swine and poultry), while SSF was considered to replace wheat flour (justifications in **SI**). In the third step, selection criteria were defined to limit the number of case studies. It included, among others, considerations about feedstocks' suitability for the targeted valorization pathway, waste hierarchy management compliance (Teigiserova et al., 2020), available volumes and amounts of crops potentially avoided, while ensuring to represent the main agrifood subsectors and biomass characteristics. Six streams were retained (see **Figure 2**).

Figure 1 – a harmonized platform for parametric LCA of waste-to-nutrition pathways



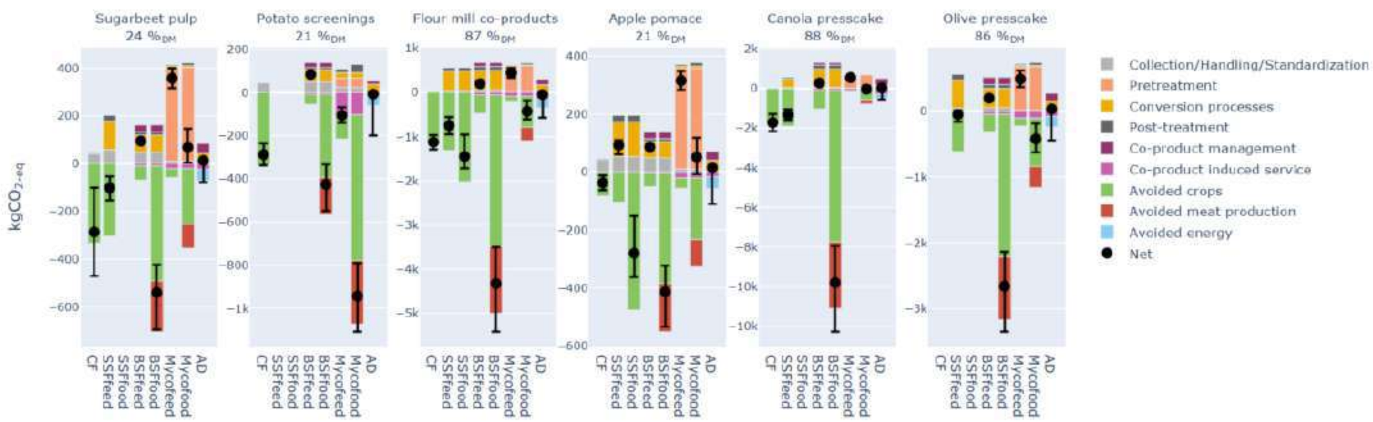
The fourth step consisted in implementing the consequential LCA, following applicable standards and the EF 3.0 impacts assessment method. Background data were derived from the Ecoinvent 3.8 consequential database, and specific processes (e.g. energy, transportation, etc.) were harmonized between all LCI modules, considering France as the geographical scope. The final (fifth) step consisted in a global sensitivity analysis (GSA) to (i) quantify uncertainties intrinsic to prospective assessments of low-TRL technologies and (ii) estimate results reliability and parameters' influence. Variation ranges of the results were estimated through analytical uncertainty propagation as detailed in (Bisinella et al., 2016). While all impacts categories were calculated, only the five usually related to food systems were analyzed (**SI**), and only climate change results are displayed here.

Results

Identified agrifood co-products constitutes a bioresource of around 18.3 $Mt_{DM}.y^{-1}$ in France, of which ca. 3.8 $Mt_{DM}.y^{-1}$ already supplies high value valorization markets (e.g. petfood, cosmetics). The majority (ca. 11.5 $Mt_{DM}.y^{-1}$) are already used as animal feed, and estimated to avoid the production of 3.2 $Mt_{ww}.y^{-1}$ soybean meal, 5.6 $Mt_{ww}.y^{-1}$ maize and 0.2 $Mt_{ww}.y^{-1}$ palm oil. Therefore, transforming such feed-grade co-products into novel feed ingredients mostly induces a net additional demand for feed crops (e.g. ranging between 5.9–7.3 $Mt_{ww}.y^{-1}$ if formulating BSF or mycoproteins). Despite the enhanced nutritional functions of novel ingredients (higher digestibility, proteins content, etc.) compared to the raw co-products; studied waste-to-nutrition pathways display limited conversion yields (on a DM basis: 19% ± 13% for BSF, 3% ± 2% for mycoproteins and 79% ± 7% for SSF enrichment). Even in scenarios allowing to avoid more feed crops in comparison to CF (e.g. SSF case), the resulting environmental benefits are offset by the additional processes involved (Javourez et al., 2022). For all case studies, CF remains the best option to target feed markets for climate change, marine eutrophication and water depletion impacts categories (**Figure**

2; SI). Yet, BSF and SSF pathways reduce impacts on freshwater eutrophication as these respectively create and concentrate lipids, hence leading to more palm oil avoided. Similarly, MP generates advantages over CF for land use as the side-generated lignin can replace wood pellets. In the light of these mixed performances, upgrading end-markets alongside the waste management hierarchy appears necessary to improve current management practices of agrifood co-products. The first upgrading option is to provide feed markets access to low quality streams (case of low-digestible apple pomace and olive presscake. Yet, this is not enough. As displayed in **Figure 2**, forecasted climate change performances of AD pathways position their energy valorization preferable to novel feed formulation. Therefore, even if upgrading low-quality streams towards feed markets results in net benefits for the other impact categories assessed (see **SI**), providing bioenergy and biofertilizer remains preferable in a context of urgently required climate change mitigation. The second upgrading option consists in targeting food markets. The environmental relevance of such approach was found to be case- and impact category-dependent, as primarily conditional to (i) the displaced ingredients in consumer's food basket and (ii) the pathway-specific conversion yield. Nevertheless, novel food production generally performed better than feed valorization (**Figure 2; SI**) except for cellulosic-based mycoproteins, due to its low yield (ca. 2%). For low proteins streams (e.g. apple pomace), SSF used for food (substituting wheat flour) achieves overall better environmental benefits than meat substitution by BSF. For the other cases, the valorization of BSF as meat-alternative is shown as the best option for all the impact categories assessed. In terms of $CO_{2\text{-eq}}$ emissions, diverting 1 $Mt_{DM}.y^{-1}$ flour mill co-products from CF towards BSF meat-analogues could save as much as 2.4 – 4.8 $MtCO_{2\text{-eq}}.y^{-1}$ (while it would be 0 – 1 $MtCO_{2\text{-eq}}$ if directly valorized as flour). As an exception, the production of mycoproteins based on starch-rich co-products (here potato screenings) outperformed the other novel food pathways. Indeed, (i) starch saccharification is less process-intensive (e.g. in terms of pretreatment) than cellulosic sugars production, (ii) it achieves greater conversion yields (ca. 5% compared to 2% for cellulosic routes), (iii) it generates co-products of feed-grade quality (while only energy valorization is possible in the cellulosic pathway) and (iv), the lack of proteins in starch-rich co-products limits BSF yield (7% here). Therefore, shifting the 0.1 $Mt_{DM}.y^{-1}$ potato screenings available in France from CF towards mycoproteins production could also achieve 2.4 – 4.8 $MtCO_{2\text{-eq}}.y^{-1}$ savings.

Figure 2 – LCA breakdown and GSA results of agrifood co-products valorization pathways applied to the selected case studies (1 Mg_{ww} input), illustrated for climate change. k:10^3



Discussion

As, expected, meat substitution is the best possible valorization case, and marketing strategies of BSF and MP should point to that direction. If these instead integrate food markets as snacks, or substitute other "meat alternatives" (e.g. plant-based), then food substitution would mostly be similar (in terms of impacts) to feed substitution, which is worse than current valorization strategies. Interestingly, the LCA modules' sensitivity and uncertainty were mostly found to rely on relatively small (less than 10) sets of key shaping parameters whose influence (direction, magnitude) on the results were mostly invariant to the input feedstock. This could further guide data refinement efforts and reduce the modular LCI complexity. Yet, the interactions between parameters should be characterized first (not done here). Finally, the scarcity and opacity of published consequential LCAs of novel food and feed prevented to confront our results with those of previous studies.

Conclusion

This work proposes a parametric LCA platform allowing to comprehensively assess the relevance of insect farming, mycoprotein production and SSF as alternative management for agrifood co-products. Building on the analysis of six case studies, we show that the only way such waste-to-nutrition pathways can mitigate food system's impacts is by phasing out burden-rich food commodities (e.g. meat). Else, direct animal feeding remains preferable, or energy valorization when not suitable. As designed, the platform is not only expandable to a wider span of residual biomasses and waste-to-nutrition pathways, but also to the broader bioeconomies' value chains, and can provide quantitative arguments to support biomass allocation decision-making even under high system uncertainty.

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Data availability statement

The **SI** and datasets generated and analyzed in this study are available in the dataverse repository: https://doi.org/10.48531/JBRU.CALMIP/ZFUYPD

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Reducing livestock methane emissions with *Asparagopsis taxiformis* feed supplement – comparison of climate metrics

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Keywords: *Aquaculture; Climate action; Greenhouse gas emissions; GWP*; Macroalgae; Radiative forcing footprint*

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Livestock account for an estimated 15% of total anthropogenic greenhouse gas (GHG) emissions and global demand for livestock products continues to increase. As such, the livestock industries have become one of the focal areas for emissions reduction. In the case of beef and dairy production systems, strategies are being pursued to lower enteric methane emissions. These strategies include improved herd management, the breeding of lower methane-emitting cattle, the development of vaccines that inhibit methane production, as well as novel feed ingredients. In regard to the latter, ingredients based on the red macroalgae *Asparagopsis taxiformis* are under development in Australia. These seaweeds accumulate the bioactive compound bromoform that inhibits methanogenesis and impressive results have been obtained in both *in vitro* and small-scale *in vivo* studies where up to 98% reduction in methane production has been reported (Roque et al., 2021; Kinley et al., 2020). This presentation, based on a recent study (Ridoutt et al., 2022), examines the potential climate benefits of widespread deployment of these feed ingredients in Australian beef cattle feedlots. Beef cattle production systems in Australia are predominantly pasture and rangeland based. However, the inclusion of a feedlot finishing stage is becoming increasingly common.

The study was undertaken in four steps. Firstly, a baseline emissions inventory for the Australian beef cattle sector was developed using data primarily sourced from the Australian Government's national greenhouse gas inventory that is used to support reporting under the Paris Agreement. The included gases were CO_2, CH_4 and N_2O. This baseline emissions inventory, covering the period 1990 to 2018, was extrapolated to 2030. Secondly, the life cycle greenhouse gas emissions of a macroalgal feed ingredient of defined bromoform concentration were estimated. As the *Asparagopsis taxiformis* cultivation and processing industries are under development in Australia, this assessment was based on data taken from literature for large-scale offshore cultivation of macroalgae and subsequent freeze drying and milling. As the commercial adoption of the new feed additive is uncertain as well as the level of methane reduction achieved in practice, seven supplementation scenarios were developed in a third step. These scenarios differed in rate of adoption, level of methane reduction, along with potential impacts on dry matter intake and average daily liveweight gain. Finally, climate impacts were assessed relative to the baseline using the IPCC 5th Assessment Report's 100-year global warming potentials, the GWP* climate metric (Smith et al., 2021) and the radiative forcing (RF) footprint (Ridoutt, 2020).

Under the baseline projection, GHG emissions in the Australian beef cattle sector increase from 49.22 Mt CO_2e in 2018 to 53.44 Mt CO_2e in 2030. The feedlot sub-sector represents a small but important share of these emissions (8.6% in 2018, rising to 9.4% in 2030). The use of *Asparagopsis taxiformis* in feedlots was found to have the potential to reduce feedlot sub-sector emissions by 12 to 40% by 2030, and overall sector emissions by 1 to 4%. While this is an important emissions reduction, it is modest in relation to the sector's ambition of achieving carbon neutrality by 2030. When emissions were assessed using alternative climate metrics that are more sensitive to changes in the rate of methane emission than the GWP100 climate metric, larger potential benefits were found. When using the GWP* climate metric, Australian beef cattle sector emissions were projected to increase from 34.98 to 39.51 Mt CO_2e over the period 2018 to 2030. With *Asparagopsis taxiformis* feed supplementation, these emissions could potentially be reduced by up to 13%. RF footprints are another way of assessing the impact of emissions over time. In 2018, the sector's RF footprint was 3.73 mW/m^2, with an annual increase that year of 45 μW/m^2. Under the baseline scenario the RF footprint increases by 38 μW/m^2 in 2030, reaching 4.26 mW/m^2. With *Asparagopsis taxiformis* feed supplementation, this could potentially be reduced to between 28 and 32 μW/m^2, a reduction of 15 to 27%. For the feedlot sub-sector alone, most feed supplementation scenarios achieved a net negative contribution to RF in 2030.

In conclusion, feed supplementation with *Asparagopsis taxiformis* is a promising approach to reducing livestock GHG emissions. The choice of climate metric impacts the assessment of benefits. The GWP100 metric may not always provide optimal guidance towards reducing climate impacts.

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Tailor made solutions for regenerative agriculture in the Netherlands: a diversity of solutions

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Introduction

Agricultural land which is managed in a specific way can provide ecosystem services and contribute positively to the environment. Regenerative agriculture (RA) is a mode of agriculture that uses soil conservation as the entry point to regenerate and contribute to multiple ecosystem services, with the aspiration that this will enhance not only environmental, but also social and economic objectives of sustainable food production (Schreefel et al., 2020). The objectives for RA described by Schreefel et al. (2020) are, however, broad. The extent to which these objectives can be achieved, depends on their local context (e.g. management and pedoclimatic conditions). Moreover, RA practices are not equally relevant, applicable or effective for all farming systems. To help farmers in the transition towards RA, tools are needed that can give more specific insight in the objectives of RA and efficacy of RA practices in delivering on multiple RA objectives at the local context.

The assessment of regenerative objectives requires a modelling framework that links regenerative farm management practices at field-scale to environmental and socio-economic outcomes at farm-scale. In agricultural systems research, Life Cycle Assessment (LCA) is often used for ex-ante design and assessment of farm practices to meet specific objectives. Despite their proven usefulness, many of these models do not address the full complexity of farming systems. The main objective of this paper is, therefore, to create a modelling framework which allows for the assessment of RA objectives and ex-ante design of diverse farming systems considering their local context.

Methods

For the ex-ante design and assessment of farming systems towards RA we used a combination of models that together use the soil as the basis to optimize and explore overall farm sustainability (Schreefel et al., 2022). The modelling framework takes a systems approach and makes use of Soil Navigator a decision support tool to assess and optimize five soil functions at the field-level and FarmDESIGN a farm-level bio-economic exploration model to optimize multiple farm sustainability objectives. Using three typical Dutch case-study farms (i.e. a dairy farm on peat soil, an arable farm on clay soil and a mixed farm on sandy soil) we demonstrated that these models can be used together to not only indicate the most relevant soil functions for improvement, but also to explore which RA practices contribute to RA objectives.

The exploration starts by using Soil Navigator to indicate which soil functions perform suboptimal.

This assessment is done by using input data which include data on the environment (i.e. average air temperature and precipitation), farm management (i.e. tillage and the amount of N fertilizer applied to the field) and the soil (i.e. clay content and soil organic matter). This data is used in integrated hierarchical decision-support models to determine the capacity of the soil to deliver the five soil functions using qualitative scores. Then, we used Soil Navigators optimization function, based on user-set objectives (e.g. medium or high scores for any of the functions), to shows if the objectives can be achieved; it proposes directions for change and farming practices needed to meet the objectives.

The suggested practices and directions for change were incorporated into FarmDESIGN to find-out in what extent the practices could contribute towards other regenerative objectives. FarmDESIGN, therefore, quantifies farm-level resource flows such as annual balances for materials, animal feeds, economics and labor. The resource flows are grouped into modules and are used as proxy indicators to assess both the environmental and socio-economic performance of a farm. Besides the quantification of flows, FarmDESIGN enables the exploration of optimized farm configurations, which are generated by a Pareto multi-objective optimization, based on two or more user-defined objectives (e.g. minimize GHG emissions and maximize farm profitability), a set of decision variables (e.g. upper and lower limits on animal numbers or crop areas) and preset constraints (e.g. lower and upper limits on animal feed requirements). The new farm configurations are new land-use and resource allocation configurations that result in optimized performance indicators (e.g. reduced GHG emissions). These new configurations have, for example, new crop or animal products being introduced on the farm, different crop areas and allocation of crop products, and changes in herd size

Results and discussion

Our approach allowed to upscale soil functions from field to farm-level and show the consequences of improving soil functions to other farm-level sustainability indicators (e.g. greenhouse gas emissions, farm profitability and labor). We identified 4000 optimized farm configurations towards RA for each of the case-study farms. Some of these configurations showed synergies between RA objectives, while others resulted in trade-offs. A synergy was found for our dairy case-study farm, in which the objective to increase the area of species-rich grassland also contributed to our objective to reduce the demand for imported fertilizers. Consequently, by increasing the area of species-rich grassland with its associated atmospheric nitrogen (N) fixation, the dairy farm could completely rely on solid manure without any import of N fertilizers. Moreover, incorporating RA practices (e.g. solid manure and species-rich grassland) resulted in improved scores for four out of five soil functions (e.g. water purification and regulation and nutrient cycling) at the expense of primary productivity (i.e. crops, milk and meat) and farm profitability. The objective to increase farm profitability and reduce greenhouse gas emissions resulted in a trade-off, showing lower greenhouse gas emissions (from 30 to 28 Mg CO_2 eq. ha^{-1}), and reduced farm profitability (from 62876 to 30022 € yr^{-1}) due to lower animal numbers. Reduced farm profitability in combination with the improvement of other RA objectives was seen for all case-study farms, when transitioning towards RA management. Reduced farm profitability is a hinder for farmers aiming to transition towards RA. In order to support a wider transition towards RA, business models have to not only value primary production, but also other regenerative objectives.

Conclusion

Combining Soil Navigator with FarmDESIGN indicated which soil functions could be improved at a local context. It also enabled the ex-ante design of farming systems towards RA, by evaluating RA practices as the basis for exploring the overall socio-economic and environmental sustainability. For the case-study farms, we modelled a set of RA practices that showed multiple improved soil functions, however, at the expense of primary productivity and farm profitability. To support a wider transition towards RA the benefits of other RA objectives, besides primary productivity, should be remunerated in farm business models.

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Assessing the eco-efficiency of irrigation scenarios using Territorial Life Cycle Assessment: Water, energy and infrastructure nexus of agricultural areas

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Keywords: *Eco-efficiency; Decision-making; Life Cycle Assessment; irrigation; Agricultural reservoir; Water transfer.*

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Introduction

Irrigation is one of the main strategies for adapting agriculture to climate change (El Chami & Daccache, 2015) as it allows sustaining yields in the face of drought and increasing temperature (Mbow et al., 2019). Large-scale planning projects can be implemented to secure agricultural area water supply such as Inter-Bassin Water Transfers (IBWT), based on imported water resources, or Agricultural Reservoirs (AR) that harvest local run-off water. These hydraulic infrastructures have a long lifetime, therefore an ex-ante environmental assessment is required to support local decision-making and support territorial planners for the selection of the least impactful alternative on the environment.

Several studies have used Life Cycle Assessment (LCA) to compare the environmental impact of hydraulic structures (Byrne et al., 2017). However, the boundaries stop at the water supply gate. Therefore, they do not grasp the entire range of services provided by irrigation, such as the territorial socio-economic benefits resulting from agricultural yield conservation. These limitations are inherent of the LCA framework which is a product-oriented method at a "microscale" and do not allow for the full integration of the territorial context, and multifunctionality (Loiseau et al., 2018).

These limitations can be overcome by using Territorial LCA (T-LCA), an adaptation of the conventional LCA framework, to assess the performance of a territory and an associated land planning scenario while considering its multifunctionality (e.g. economic, social or environmental land use functions) (Loiseau et al., 2013). The T-LCA outputs are eco-efficiency ratios, i.e. the ratios between services provided by the territory and its environmental impacts (Seppälä et al., 2005). This study aims at using the T-LCA framework to compare the eco-efficiency of land planning scenarios with or without hydraulic project implementation. In addition, trade-offs in the Water-Energy-Infrastructure nexus between projects were identified, and the design conditions under which one project performs better environmentally than another are discussed. Generic conclusions are drawn from a theoretical case study of an agricultural area occupying 700 ha located in a water-stressed area in the South of France.

Materials and methods

As shown in Figure 1, three land planning scenarios will be compared, i.e. one rainfed scenario (Scenario 0) and two irrigated scenarios (Scenario 1 – IBWT and Scenario 2 – AR). Since Scenario 0 does not have any irrigation infrastructure, the crops are rainfed. Three types of crops have been selected to be consistent with Mediterranean agriculture and to reflect a diversity of production both in terms of type of plants (perennial or not, cultivated or not), and in terms of valorization (food security or added value creation). Both scenarios 1 and 2 have the same crop occupation. Indeed, non-irrigated crops still occupy the cultivated area while irrigated crops occupy the remaining surface. With access to irrigation, it is assumed that yields could be increased and vines would no longer be

registered as Controlled Designation of Origin (CDO) (yield limits) but would rather be classified within Protected Geographical Indications (PGI).
The IBWT imports water from an unstressed area whereas the AR uses water near the agricultural perimeter, in the same water stressed area. Unlike the AR, the IBWT allows for the irrigation of a large area, for which the studied territory only represents a small share (impact allocation based on a ratio between the annual quantity of irrigation water needed by the territory and the annual quantity of water circulating in the IBWT). The system boundaries rely on a cradle to territorial gate perspective, encompassing all upstream processes related to the water supply, the energy use, the irrigation infrastructure as well as all the inputs necessary to produce crops. To deal with multifunctionality, different territorial services are quantified, i.e. land management (ha) and food production (kg). Data collection is based on water and energy balances, and using existing processes in databases such as Agribalyse and World Food LCA Database. Environmental impacts are quantified at both the midpoint and the endpoint level with the Life Cycle Impact Assessment method IMPACT World+ (Bulle et al., 2019). Then according to T-LCA framework, eco-efficiency indicators are computed.

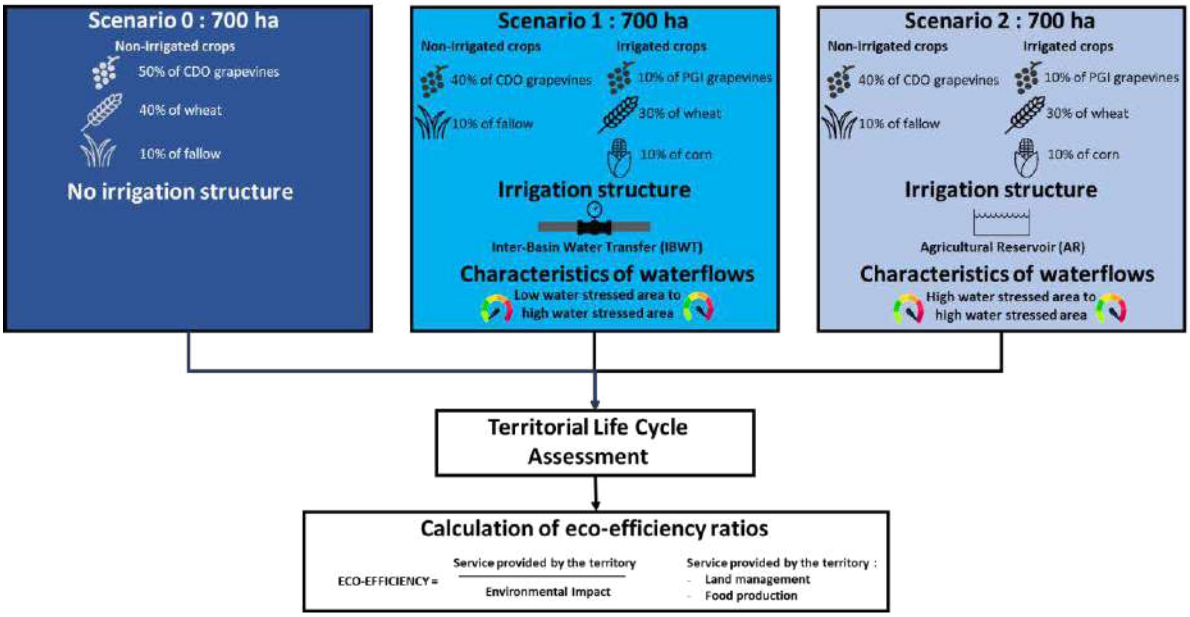
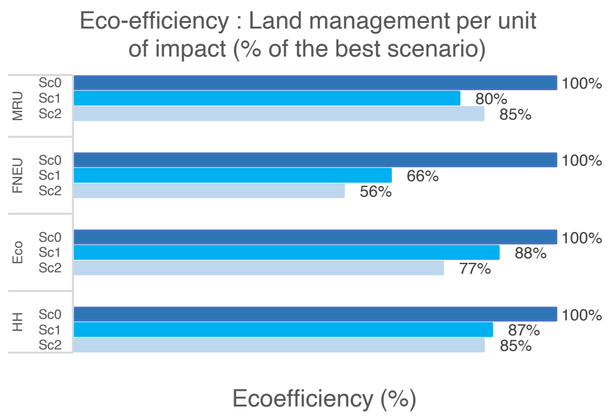


Figure 1 Description of the three land planning scenarios studied with the T-LCA framework

Results and discussion

The eco-efficiency ratios showed that the results for the environmental performance of a scenario depend on the investigated territorial function.



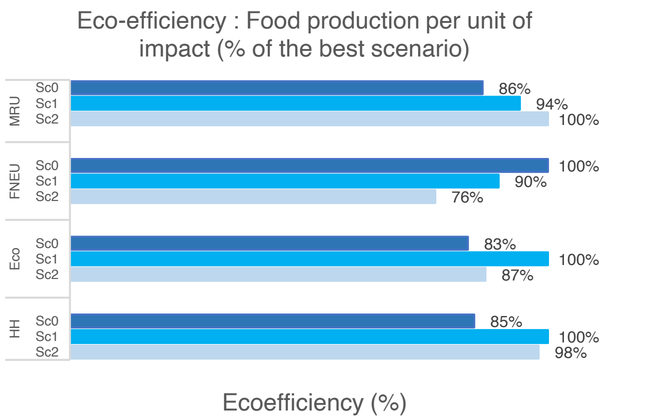


Figure 3 Eco-efficiency calculated for the agricultural area management HH: "Human Health"; Eco: "Ecosystems"; FNEU: "Fossil and Nuclear Energy Use"; MRU: "Mineral

Figure 2 Eco-efficiency calculated for the biomass production

For example, in Figure 2, when looking at "Land management", Scenario 0 (rainfed) is more performant than scenarios 1 and 2 (irrigated) for all impact categories. The results are more contrasted when looking at "Food Production", on Figure 3, where both irrigated scenarios perform worse than the rainfed scenario only on Fossil and Nuclear Energy Use (FNEU), because they both use the French electricity mix for irrigation, mainly based on nuclear energy.
Scenario 1 and Scenario 2 have the same crop occupation. Therefore, the difference of their eco-efficiencies resides in the impacts of water supply. The latter is presented in Figure 4.

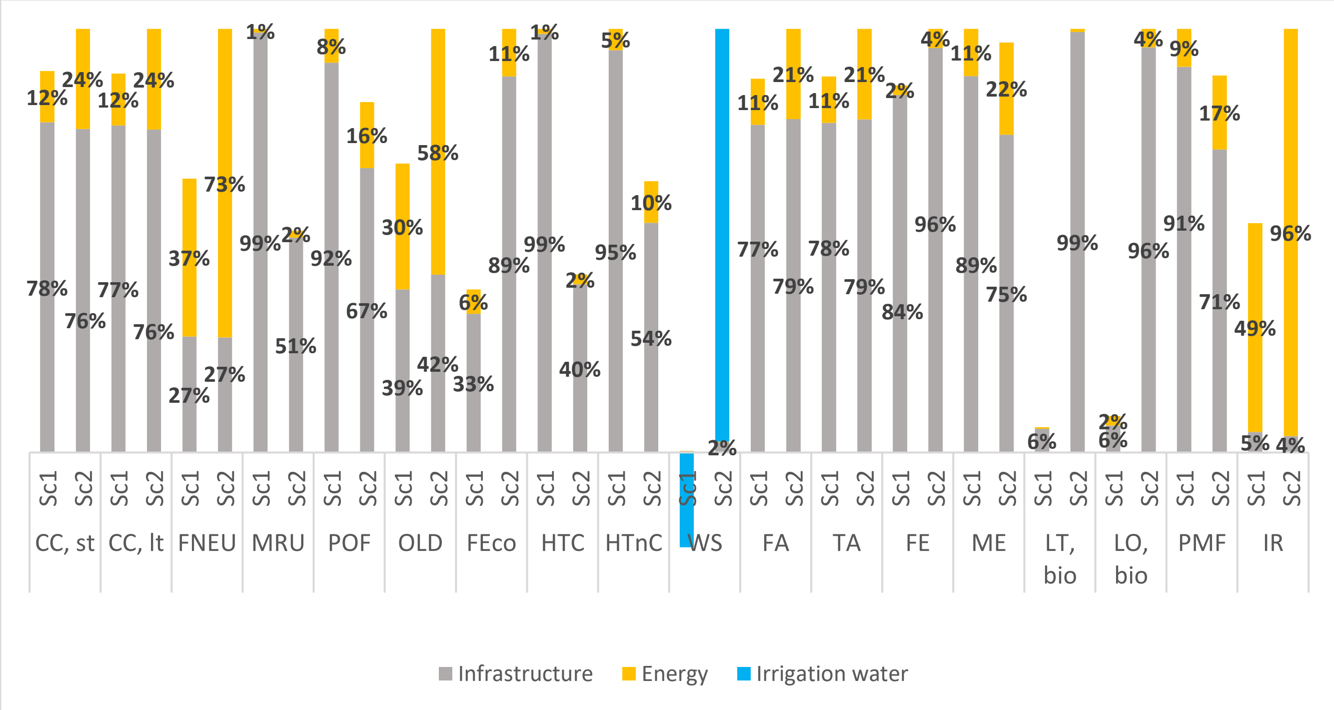


Figure 4 Environmental impacts at midpoint for Scenario 1 and 2 water supplies
CC, st: "Climate Change, short term"; CC, lt: "Climate Change, long term"; POF: "Photochemical Oxidant Formation"; OLD: "Ozone Layer Depletion"; FEco: "Freshwater Ecotoxicity"; HTc: "Human Toxicity cancer"; HTnc: "Human Toxicity non cancer"; WS: "Water scarcity"; FA: " Freshwater Acidification"; TA: "Terrestrial Acidification"; FE: "Freshwater Eutrophication"; ME: "Marine Eutrophication"; LT, bio: "Land Transformation, biodiversity"; LO, bio: "Land Occupation, biodiversity"; PMF: "Particular Matter Formation"; IR: "Ionizing Radiation"; PII: "Primary Irrigation Infrastructure"; SII: "Secondary Irrigation Infrastructure"; TII: "Tertiary Irrigation Infrastructure"

Scenario 2 performs worst that Scenario 1 on 12 of 18 impacts categories because of its Water-Energy-Infrastructure nexus. Concerning impacts due to water consumption, unlike the AR, the IBWT supplies water from a low water stress area with a low AWARE characterization factor (CF). Thus, for water scarcity (WS), this leads to an avoided impact for the Scenario 1. Concerning the energy use, the impacts of scenario 2 are about two-fold higher than scenario 1, because the energy use of the IBWT is approximately half that of the AR. For the "Infrastructure" part of the nexus, results are more mixed. For some of the midpoint indicators, the IBWT performs worse than the AR because of the high amount of cast-iron necessary in its infrastructure. On Freshwater Ecotoxicity (FEco) and Freshwater Eutrophication (FE), AR performs worse than IBWT because the amount of bronze and copper necessary for equipping the AR pumping station is fully allocated to the studied territory. The same applies to Land Transformation, biodiversity (LT, bio) and Land Occupation, biodiversity (LO, bio) because of the high amount of land occupied by AR, unlike the IBWT, which involves a buried pipeline. These results highlight the water, energy and infrastructure nexus induced by the two hydraulic projects. This nexus is determined by two main design parameters, i.e. i) the length of the IBWT pipeline (L_{IBWT}) and ii) the amount of water withdrawn at source for IBWT allocated to the agricultural area ($\%allocation_{IBWT}$).
Figure 5 presents the environmental break-even areas between the IBWT and AR bordered by tipping

lines according to different impact categories. The Ecosystems break-even area can only be achieved with unrealistic values of (L_{IBWT}, $\%allocation_{IBWT}$). Hence, IBWT always performs better than AR on Ecosystems damages as well as for water resources as it imports water from an unstressed area, to a water-stressed area. A project based on imported resources can perform better on all the endpoint indicators, if the parameters are located in Zone 5 (e.g. L_{IBWT} = 50 km and $\%allocation_{IBWT}$ = 1.0%). For other values of (L_{IBWT},$\%allocation_{IBWT}$), there is no better scenario for all the endpoint indicators.

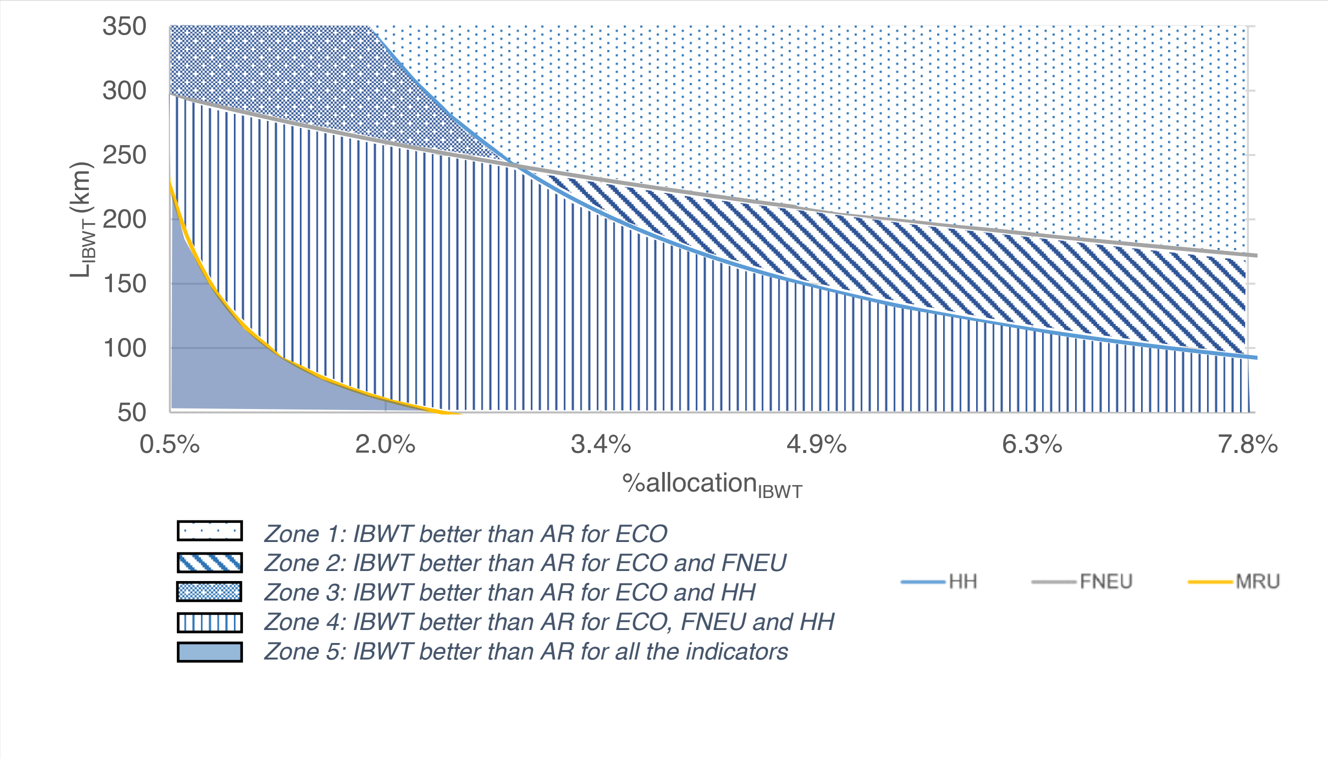


Figure 5 Environmental break-even area for which IBWT water supply is better than AR

Conclusion and perspectives

T-LCA was applied to a theoretical agricultural area to compare the eco-efficiency of three land planning scenarios with or without the implementation of hydraulic projects. These metrics provide exhaustive information about the environmental performance of land planning scenarios considering territorial multifunctionality. The environmental performance of the three land planning scenarios can vary depending on the selected territorial function. These outputs allow the identification of scenarios that limit trade-offs between different functions and impacts. T-LCA results also highlight trade-offs in the water-energy-infrastructure of hydraulic projects. These trade-offs depend on design parameters such as the size of the water pipeline or the water flow. One limitation of this study is the use of a static approach without considering prospective elements (e.g., climate, hydrology and soil) which are expected to further intensify during the lifespan of the hydraulic infrastructure, and affect their long-term environmental performance.

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Consistent modelling of heavy metal balances in LCA on field and farm level

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Keywords: *heavy metal balance, farm, field, life cycle inventory, ecotoxicity*

Introduction

The ecotoxicity impacts of agricultural systems are driven by pesticides and heavy metals. We often see a dominance of heavy metals in the impact assessment. In the last years, the modelling of pesticide emissions has been revised in the frame of the pesticide consensus process (Nemecek *et al*., 2022). Among others, a tool to estimate emission fractions to the different compartments after application together with default factors are provided, so that we now have a more solid basis for the assessment. Heavy metals however, although highly relevant for the ecotoxicity impacts, are not well represented in many agricultural LCAs. Emissions and flows of heavy metals were included in the SALCA (Swiss Agricultural Life Cycle Assessment) method since many years (Freiermuth, 2006). In the course of the new implementation in SALCAfuture, the model for the heavy metal balance and emission has been completely revised. A particular challenge was to represent the flows at crop, livestock and farm level to cover different application cases. Furthermore, the implications for the modelling of emissions and assessment of impacts over the whole value chain need to be considered.

Methods

Two separate versions are implemented in Freiermuth (2006): heavy metal balance at the farm level (used for farms and livestock production) and a balance at crop level (to calculate crop LCAs). The model has now been revised to cover all application cases in the same system in order to avoid redundancy (Fig. 1). As in the previous version, the model covers the elements Cadmium (Cd), Chromium (Cr), copper (Cu), mercury (Hg), nickel (Ni), lead (Pb), and zinc (Zn). Because the relevant emissions take place at crop and field level, it is not necessary to model the farm as a whole. First, the balance is calculated for the animal system, which includes the herd, housing and yard, and the manure management. Feed intake (purchased or produced on farm), animals and manure imported to the farm are counted as inputs, while animal products (milk, eggs, wool, etc.), live animals, and manure exports are counted as outputs. The balance follows the same principles as the nutrient balances of N, P, and K. The resulting balance represents the heavy metals contained in farmyard manure, which is used as an input for the crop system.

$$M_{excr\ i} = \sum_j(M_{feed\ j} * c_{feed\ j,i}) + \sum_j(M_{animin\ j} * c_{animin\ j,i}) - \sum_j(M_{animout\ j} * c_{animout\ j,i}) - \sum_j(M_{animgr\ j} * c_{animgr\ j,i}) + \sum_j(M_{manin\ j} * c_{manin\ j,i}) - \sum_j(M_{manout\ j} * c_{manout\ j,i}) - \sum_j(M_{anpr\ j} * C_{anpr\ j,i}) \quad \text{(eq. 1)}$$

where $M_{excr\ i}$ [kg] are amounts of metal i excreted, $M_{feed\ j}$, $M_{animin\ j}$, $M_{animout\ j}$, $M_{animgr\ j}$, $M_{manin\ j}$, $M_{manout\ j}$, $M_{anpr\ j}$ are the amounts in kg of feed intake, animals purchased, animals sold, animal growth (change of live weight of the herd), manure imports, manure exports, and animal products; $c_{feed\ j,i}$, $c_{animin\ j,i}$, $c_{animout\ j,i}$, $c_{animgr\ j,i}$, $c_{manin\ j,i}$, $c_{manout\ j,i}$, $c_{anpr\ j,i}$ are the respective metal concentrations [kg/kg]. Feed intake and excrement deposition during grazing are not counted, assuming that the corresponding heavy metal flows are of similar size. The metal excreted are partitioned between

solid and liquid manure and divided by the amounts of both manure types to derive the metal concentrations in solid and liquid manure.
The agricultural inputs $M_{agro\ i}$ [kg] of metal i to the field are

$$M_{agro\ i} = \sum_j(M_{seed\ j} * c_{seed\ j,i}) + \sum_j(M_{pesti\ j} * c_{pesti\ j,i}) * (1 - f_{air} - f_{OFS}) + \sum_j(M_{ferti\ j} * c_{ferti\ j,i}) + \sum_j(M_{man\ j} * c_{man\ j,i}) \quad \text{(eq. 2)}$$

where $M_{seed\ j}$, $M_{pesti\ j}$, $M_{ferti\ j}$, $M_{man\ j}$ are the amounts in kg of seed, metal-containing pesticides (e.g. copper fungicides), mineral and purchased organic fertilisers, and farmyard manure (calculated by eq. 1), $c_{seed\ j,i}$, $c_{pesti\ j,i}$, $c_{ferti\ j,i}$, and $c_{man\ j,i}$ are the respective concentrations of metal i in input j. f_{air} and f_{OFS} are the fractions of pesticide emitted after application to the air and off-field surfaces, respectively. The emissions to the off-field surfaces have to be split between agricultural soil, natural soil and water according to the share and land cover in the region. f_{air} and f_{OFS} can be calculated with the PestLCI Consensus model or taken from the default values (crop and target group specific) provided by Nemecek *et al.* (2022). For the concentrations values of the different inputs, we use several sources, mainly Desaules & Studer (1993, mineral fertilisers), Menzi & Kessler (1998) and Gross *et al.* (2021) for farmyard manure, and for biomass Koch & Salou (2015), Freiermuth (2006) and www.feedbase.ch.
A further input to the system is the metal deposition, however, it is not caused by agricultural management, rather it stems from non-agricultural sources like industry or transports. To take this into account, an allocation factor A_i [-] is calculated as

$$A_i = M_{agro\ i} / (M_{agro\ i} + m_{depos\ i}) \quad \text{(eq. 3)}$$

where $m_{depos\ i}$ is the total input of heavy metal from atmospheric deposition [kg]. The values for average deposition in Swiss agricultural areas are taken from BAFU & Empa (2015) for Cd, Cu, Zn, Pb, and Ni, and Thöni *et al.* (2008) for Cr, and Hg. Since deposition is caused by non-agricultural sources, the heavy metal flows due to exports with the harvest (eq. 4), to leaching (eq. 5), and erosion (eq. 6) are multiplied by the allocation factor $M_{agro\ i}$. The outputs with the harvest $M_{harv\ i}$ [kg] are calculated as

$$M_{harv\ i} = \sum_j(M_{mainpr\ j} * c_{mainpr\ j,i}) * A_i + \sum_j(M_{copr\ j} * c_{copr\ j,i}) * A_i + \sum_j(M_{pesti\ j} * c_{pesti\ j,i}) * (1 - f_{air} - f_{OFS}) * A_p \quad \text{(eq. 4)}$$

where $M_{mainpr\ j}$, $M_{copr\ j}$, and $M_{pesti\ j}$ are the amounts in kg of harvested main products, harvested co-products and amount of pesticides applied, and $c_{mainpr\ j,i}$, $c_{copr\ j,i}$, $c_{pesti\ j,i}$ the respective concentrations. A_p is the fraction of metals in pesticides exported with the harvest, which is set to 0.05 according to Audsley *et al.* (1997). In cases, where $M_{agro\ i} = 0$, i.e. no agricultural inputs to the soil occur, A_i also becomes 0. Heavy metal leaching to groundwater ($M_{leach\ i}$ [kg]) caused by agricultural management are calculated as

$$M_{leach\ i} = m_{leach\ i} * A_i \quad \text{(eq. 5)}$$

Where $m_{leach\ i}$ is the average amount of metal leaching according to Wolfensberger & Dinkel (1997) [kg ha^{-1} a^{-1}]. Heavy metal emissions through erosion of metal i [$M_{eros\ i}$, kg ha^{-1} a^{-1}] are calculated as:

$$M_{eros\ i} = M_{eros} * c_{soil\ i} * a * f_{eros} * A_i \quad \text{(eq. 6)}$$

where $M_{eros\ i}$ is the amount of eroded soil [kg ha^{-1} a^{-1}], $c_{soil\ i}$ is the heavy metal concentration in the soil ([kg/kg], values from Gubler *et al.*, 2015 for three types of crops: arable land, horticultural crops, grassland), a is the accumulation factor 1.86 (according to Wilke & Schaub (1986) for P) [-], f_{eros} is the erosion factor considering the distance to river or lakes with an average value of 0.2 (considers only the fraction of the soil that reaches the water body, the rest is deposited in the field) [-].
The resulting balance is counted as an emission to agricultural soil ($M_{soil\ i}$ [kg]):

$$M_{soil\ i} = M_{agro\ i} - M_{harv\ i} - M_{leach\ i} - M_{eros\ i} \quad \text{(eq. 7)}$$

Results
The model allows calculating the relevant emission flows in agricultural LCA, namely leaching to ground water, erosion to surface water, and emissions to agricultural soil (Fig. 1). It can be used for the assessment of whole farms, for animal sources products like milk and meat as well as for crop LCAs in the same system. Note that the emissions to the agricultural soil, resulting from the balance at crop level can become negative. This means that the sum of outputs for a given metal exceeds the inputs. This is particularly the case, when fertiliser inputs are low and the harvested biomass is high. Often this is balanced out, when the calculation is done for a whole farm or a crop rotation.

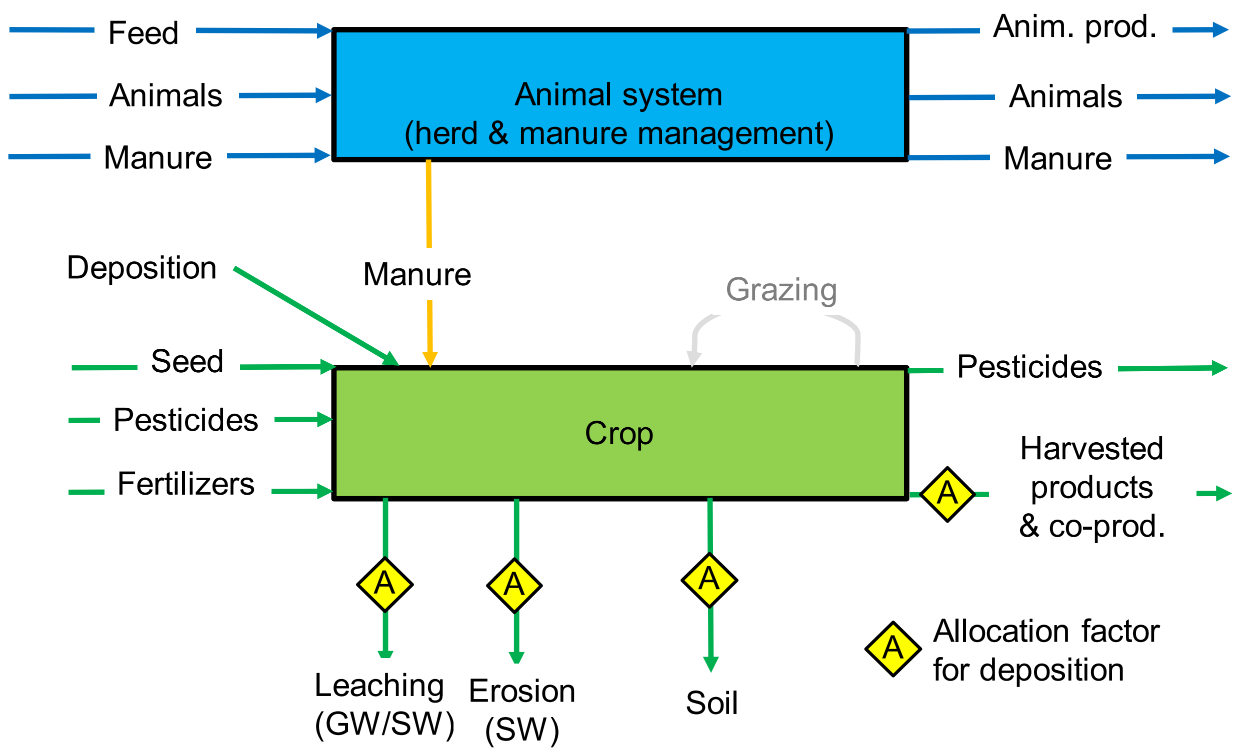

Fig. 1: Heavy metal flows considered in the SALCAheavymetal model. GW = ground water, SW = surface water.

Discussion
It is often argued that heavy metal uptakes by the biomass should not be included in the balance. An alternative model would be to ignore the uptake by the plants and on the other hand to exclude animal manure and seed from the calculation, where most – but not all – of the heavy metals stem from previous agricultural plant uptake. This calculation would be simpler and negative values would not occur in most cases. We argue that the model proposed here is more accurate and allows flexible use. All heavy metal flows are accounted for, irrespective of the source, e.g. by treating mineral and organic fertilisers equally. Furthermore, ignoring plant uptake implicitly assumes that the final destination of the metals is in the agricultural soil. However, the biomass has different uses and leads to different final environmental compartments, as illustrated in Fig. 2. The pathways differ according to the use of the harvested goods as food, as animal feed, or as raw material for production of biofuels. The final destination can be agricultural soil, but also water, landfill or natural or forest soil (e.g. biomass deposited in a forest). According to the system, these paths need to be properly modelled and we cannot simply assume that the metals will be returned to the agricultural soil in the end. When the assessment is done over a whole supply chain, the fate of the heavy metals contained in the harvested products, needs to be properly accounted for, by considering the different pathways.

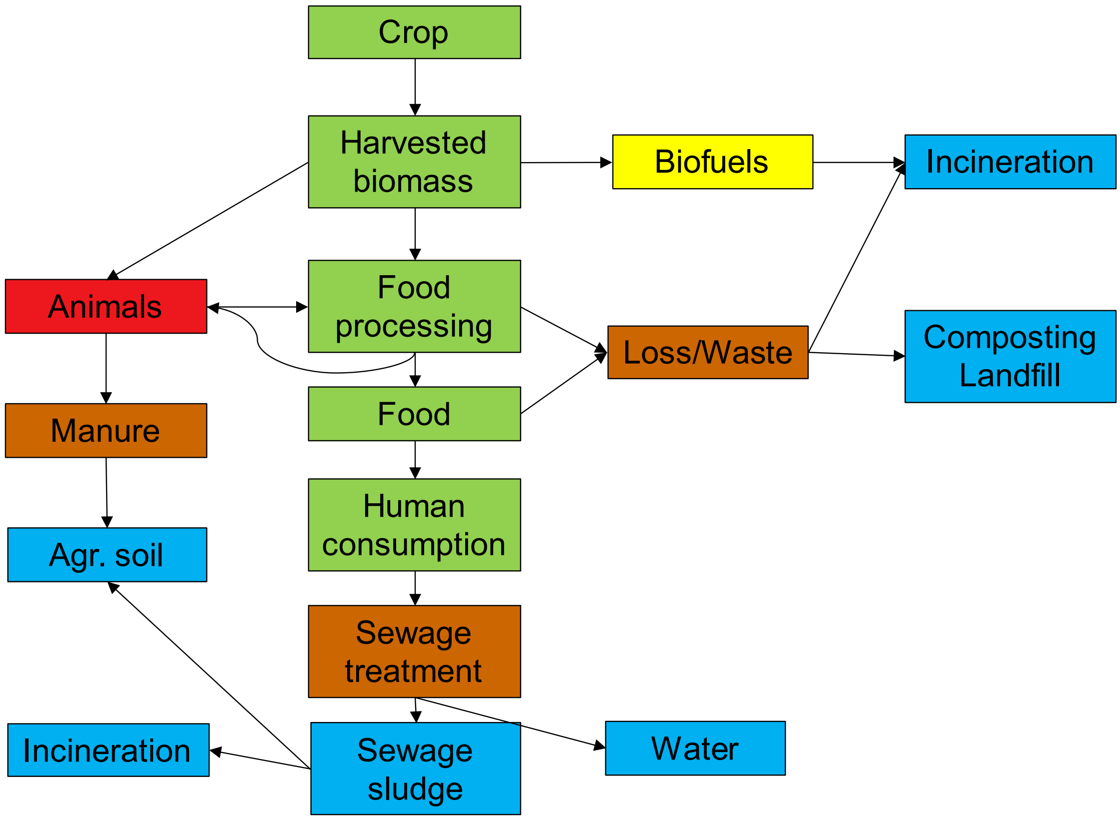

Fig. 2: Heavy metal flows in the post-agricultural phases.

Modelling heavy metals emissions from pesticides needs to be consistent with pesticide emission modelling on the one hand (see Nemecek *et al.*, 2022), and to heavy metal balancing on the other hand. The approach proposed here fulfils the requirements of both models by linking the pesticide inputs to the default emission fractions (eq. 4).

Despite the progress made, the model has a number of limitations. In the SALCA heavy metal model, the metal concentrations in harvested goods and emissions by leaching are not dependent on the metal concentrations in the soil. At least for some metals, the concentration in the soil can influence heavy metal uptake and leaching. However, the relationships are highly non-linear and complex. They depend on the metal considered, chemical and physical properties of the soil (soil organic matter content, pH, etc.), and the crop species. We recommend to do sensitivity analyses to assess the sensitivity of toxicity impacts to the variation on leaching and concentrations in the harvested biomass. Another limitation of the method is that the speciation of the metals (i.e. its oxidation form) could not be considered due to a lack of data. However, it can play a major role for toxicity, as e.g. for Cr(III) and Cr(VI), with Cr(VI) showing considerably higher toxicity impacts. This results in a need for further development.

Conclusions

The revised SALCAheavymetal model, as implemented in SALCAfuture, enables a consistent modelling of heavy metal emissions to groundwater, surface water, and agricultural soil and calculates the metals contained in the harvested products. Their fate needs to be taken into account in the further modelling of the supply chain.

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03 Oral Session Day 3

LCA of Ecuadorian cocoa and chocolate: is the cocoa sector environmentally sustainable?

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Keywords: agroforestry; Cacao Fino y de Aroma; Chakra; CCN-51; semi-processed cocoa products.

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Cocoa is one of the main crops in Ecuador. The agricultural area dedicated to cocoa (601 954 ha in 2019) represents the largest area dedicated to a permanent crop in Ecuador: 38% in the period 2014-2019, followed by oil palm and banana with 18% and 12% respectively. The area dedicated to cocoa represents 4% of total land use. Dry bean production, which reached 283 680 t in 2019, has grown at an average annual rate of 15% since 2014. Several varieties of cocoa are grown in Ecuador, but production is dominated by two main varieties: "national" or Cacao Fino y de Aroma (CFA, 43% of area and 28% of production in 2017) and the clone named CCN-51 (57% of area and 72% of production in 2017). Cocoa is mainly produced on the Ecuadorian coast and its value chain is highly complex. A thorough mapping of the value chain was performed (Figure 1) to better organise the LCA work, e.g. regarding typologies, following (Acosta-Alba et al., 2022).

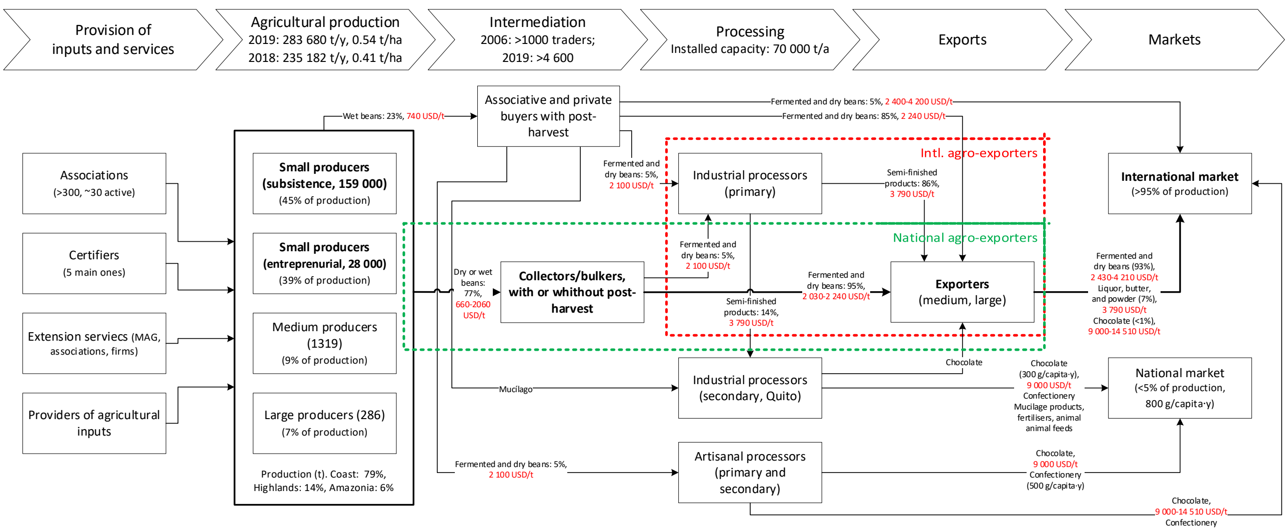

Figure 1. Ecuadorian cocoa value chain flow diagram

The LCA-based environmental assessment of the cocoa value chain and sub-chains in Ecuador aims at comparing the potential impacts of different types of actors and sub-chains (i.e. specific interlinkages of different types of actors across the value chain). The most important sub-chains, in terms of volume and potential, are:

- An agro-industrial "Volume" sub-chain that seeks economies of scale on volumes: It is structured around collection centres of collectors/brokers (practicing thermal drying) supplied by small producers, focuses on large volumes of commodity cocoa (with industrial quality), makes blends, and supplies national agro-exporters and transnationals. Transnationals seek to integrate the supply of raw materials with their international links (value addition outside Ecuador), and in principle seek traceability.
- A "Quality" sub-chain based on CFA: It is structured around private or corporate collection

centres, mostly provided by large producers who carry out fermentation in crates; it focuses on moderate volumes of CFA, for export in grain (national agro-exporters). Produces smaller quantities of semi-processed products.

- A "Semi-processed" production sub-chain: It is structured around a small group of primary, industrial processors, which use cocoa blends to produce semi-processed products (i.e. liquor, butter, powder) mainly for the international market. They are mainly sourced from small producers.

To estimate these impacts, LCIs representing the various types of systems in each link of the value chain (i.e. the various types of farming systems, artisanal and industrial processing and distribution), were constructed in terms of representative production units. To do so, primary and secondary data were collected for the most representative system types, as defined by the constructed actor typologies. Primary data were obtained via field visits and surveys. The life cycle impact assessment methods recommended by the European Community's Product Environmental Footprint (PEF) initiative (Zampori & Pant, 2019) were applied, complemented with complemented with ReCiPe endpoint indicators (2.2 Endpoint World H/A (Hierarchy/Average)).

The identified sub-chains have different impact intensities (Figure 2), due to differences in yields between the different types of cocoa producers and varieties that feed the sub-chains. Transport contributes marginally to the impacts, as does primary processing in the case of the Semi-processed products sub-chain.

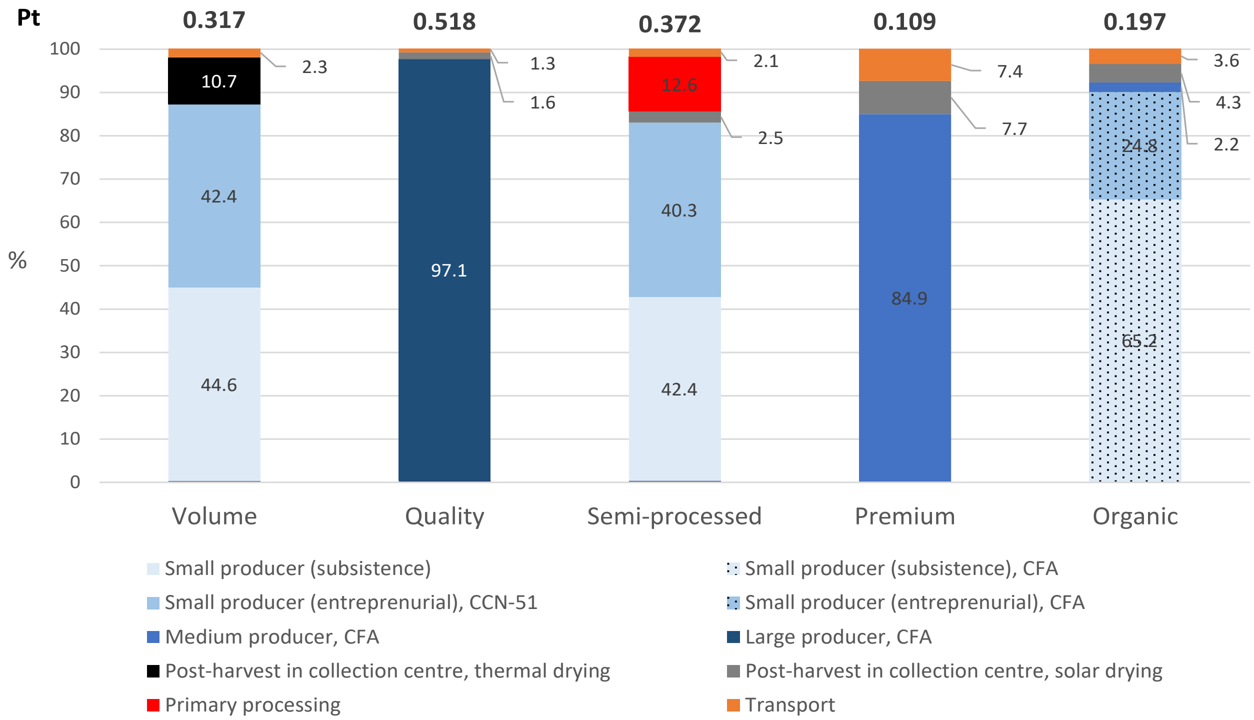

Figure 2. Cumulative sub-chain impacts (Pt/t) and contribution analysis (%), for cocoa products exported from the port of Guayaquil [EF 3.0 single score]

The value chain is generally sustainable, as (except for large intensified producers, especially CCN-51) it generally exhibits low input pressure, contributes to climate change mitigation through high C sequestration in biomass that exceeds C losses due to land use change (e.g. deforestation), and does not pose an immediate threat to biodiversity. For instance, a recent estimate of the impact of land-use change associated with cocoa in Ecuador indicates that deforestation is minimal in the cocoa context compared to other countries (Table 1). In the Amazon, there are already areas of overlap between different types of cocoa systems and protected areas. Nevertheless, native communities that produce via agro-forestry systems (e.g. Chakra) are key actors for the preservation of natural and cultivated biodiversity.

Table 1. Estimated comparative midpoint impact on climate change (kg CO2/ha) of land use change related to cocoa cultivation, for Ecuador and other countries [EF 3.0 (Zampori & Pant, 2019), data from World Food LCA Database]

Impact of land use change (e.g. deforestation)	Brazil	Côte d'Ivoire	Cameroon	Ecuador	Ghana	Indonesia
GWP associated with LUC annualised over 20 years	23 486	35 473	20 636	83.4	15 786	28 781

The impacts of Ecuadorian cocoa products (beans, semi-processed, chocolate) are considerably lower than those of products from other international cocoa value chains, as demonstrated by a comparison of the climate change impacts of cocoa beans and chocolate from different exporting countries (Avadí et al., 2021).

A manuscript presenting this case study has been submitted to the International Journal of Life Cycle Assessment Special Issue associated with LCA Foods 2022 (https://www.springer.com/journal/11367/updates/20266956).

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Comparative early-stage life cycle assessment of two starch films based on food crop and agri-food waste sources

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Keywords: Early R&D stages; Scale-up; Biopolymer; Waste valorization; Ex-ante LCA; Bio-based products

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Several biopolymer films have been developed at experimental scale, aiming at finding sustainable alternatives to fossil-based plastic films, especially for applications in food packaging. Examples are starch films based on the valorization of agri-food wastes, which besides being compostable, also avoid food waste treatment (Álvarez-Castillo et al., 2021). Mangoes are the world's most dominant tropical fruits and have been increasingly industrialized in Brazil to produce frozen pulp, where around 45% of mango biomass is discarded, i.e., peels and seeds (Pereira da Silva et al., 2021). Oliveira et al. (2018) obtained starch films at the laboratory from mango seed kernels and a conventional starch source (maize). The aim of this paper is twofold: a) to identify opportunities for environmental performance improvement of a mango kernel starch (MKS) film, and b) to compare the future environmental impacts of producing two novel starch films based on MKS and maize starch (MzS).

This article presents an ex-ante LCA implemented to the two starch films (from maize starch or MKS), from cradle-to-gate with 1 kg of film as functional unit. Mango kernels were modeled as wastes (burden-free approach) since they do not have economic value. Film formulation was modeled by mass balance using information from Oliveira et al. (2018). LCI data for MKS production (isolated starch extraction route) was retrieved from a previous simulation (from TRL 4, lab-scale) performed by Pereira da Silva et al. (2021). Sixteen LCIA categories recommended in the Product Environmental Footprint guidelines (Fazio et al., 2018) were analyzed. Four scenarios were assessed for the MKS film: i) Increasing starch extraction yield (assuming maximum literature value, 58%, instead of 38% in Oliveira's experiment); ii) Using seed shells (outer part of the seed, rich in lignocellulosics) to produce steam in boilers; iii) Considering avoided emissions from landfilling the kernels; iv) Combining all previous scenarios.

The results show that most impacts of the MKS film occurred at starch production, primarily due to steam for drying processes. Comparative results (Fig.1) show that the MzS film has lower environmental impacts than the MKS film baseline in 12 (out of 16) impact categories, including climate change with about half of the impact. The MKS performed better in 4 categories: land use, marine and terrestrial eutrophication, and resource use– minerals and metals. Scenario i (MKS yield increase) shows reductions in all categories (9-29%), and the MKS film performs better than the MzS film in two additional categories: particulate matter and acidification. Scenario ii (steam from shells) shows reductions in 6 categories, particularly noticeable for fossil (56%) and ozone (57%) depletion; however, particulate matter emissions are four times higher. Scenario iii accounted for the avoided burdens of not sending seeds to final disposal, resulting in substantial reductions in climate change (86%) and marine eutrophication impacts (103%) and minor decreases in most categories (1-6%). This scenario only changed the ranking in climate change, with emissions of 0.55 kg CO_2-eq/kg, around four times lower than the MzS film production emissions. All impacts decreased in scenario iv (combined changes i-iii), except particulate matter (which increased considerably by producing steam from biomass, scenario ii). In this scenario, MKS performs better than the MzS film in 7 categories (including climate change, land use, and all forms of eutrophication) and worse in 7 (including all toxicity categories and health-related categories - ozone formation, particulate matter, ionizing radiation). In two categories, the impacts of MKS and maize starch films were approximately the same (fossil resource and ozone depletion).

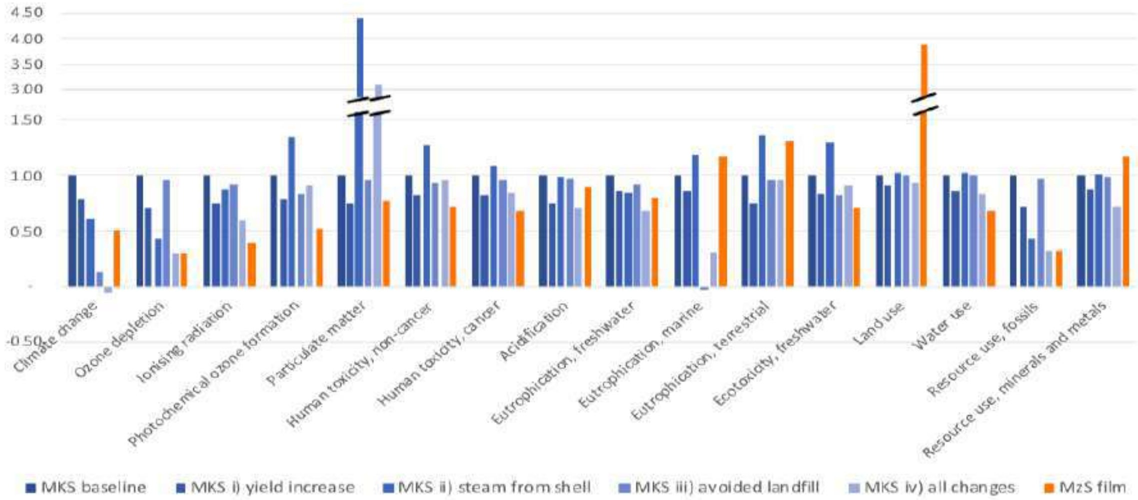

Fig. 1. LCIA results for MKS (baseline and scenarios) and MzS (normalized for MKS baseline)

It should be noted that the MKS model is based on simulation data from TRL 4, and this data do not necessarily capture all the improvements and optimization of a mature technology such as maize starch. Maize starch (TRL 9) is usually produced by wet milling, generating bran, gluten, and germ (Erickson et al., 2006); thus, burdens are divided between these co-products. The MKS film model considered that starch was produced by an isolated starch extraction (A) process instead of integrated extraction (B) – another process modeled by Pereira da Silva et al. (2021) which also yields fat and polyphenols. Process A was chosen due to its lower impacts and higher starch yield (producing around four times more starch). Nevertheless, it should be noted that yield and material efficiency could be optimized in Process B, reducing starch impacts, although this was not explored by Pereira da Silva et al. (2021). Furthermore, no solvent recovery and little heat integration were considered, which are widely used in the industry to reduce costs.

Our analysis shows that only in the best-case scenario the MKS film has a similar environmental performance to the maize starch film. However, the mango waste-based film shows higher toxicity and human health-related impacts. Furthermore, since MKS is at a low TRL, the MKS film has more room for environmental improvement than the maize starch film. Ex-ante LCA has proven useful to assess and compare novel starch films and may be applied to other biopolymers to select and promote the most sustainable alternatives from the early research and development stages.

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ENVIRONMENTAL IMPACT ASSESSMENT IN THE UEB ÁLVARO BARBA, COMPANY LOS ATREVIDOS

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Keywords: Life cycle analysis, Food

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In Cuba, policies are applied to meet economic needs with the efficient use of natural resources and the lower emission of waste to the environment. In the work, the environmental impact assessment of the production of tomato puree, guava jam and cabbage pickle in the UEB Álvaro Barba is carried out, using the Life Cycle Analysis (LCA), from the inventories they are qualitatively identified the main impacts that are generated, conclusions are reached and measures are proposed. The application of the LCA methodology is carried out on the basis of NC ISO 14040: 2006 and Sima Pro 9.1 software, ReCiPe method is used. The study showed that the greatest contributions to the total impact, for the three processes studied, correspond to the product system and the type of packaging, the categories of greatest impact are global warming and formation of particulate material.
For the development of the work, descriptive research is used, based on the analysis of normative documents, review of the state of the art on the subject of research, previous studies on the subject of Life Cycle Analysis carried out in Cuba (Rosa D, E (2018) and Rosa et al, 2019) combined with the application of scientific methods of analysis such as mass and energy balances, and other techniques and tools necessary for the study. The SimaPro software (Goedkoop, M, 2004) was used through which the environmental profiles of each of the analyzed products were obtained considering different impact categories with a cradle-to-gate approach, which is limited by not considering of the agricultural stage of the products. One (1) ton of each analyzed product was considered as a functional unit. The data were collected in the entity, from the literature and from similar studies. For the impact evaluation, the ReCiPe end point and mid point methodology was used. With the ReCiPe mid point, the results of the impact of each category are obtained in kg of the corresponding reference substance and the characterization profile of the process that allows visualizing the contribution of each input and/or output to each of the impact categories. With the end point method it is possible to make comparisons between the categories and highlight the greatest impacts. For the conformation of the inventory it is necessary to express all the entrances and exits based on the functional unit. (NC ISO 14040:2009, NC ISO 14044:2009).
Using the Recipe mid point method to compare the case studies (Figure 1) by category, it can be concluded that, in the categories of global warming, ionizing radiation, ozone formation, particulate matter formation, terrestrial acidification, ecotoxicity, carcinogenic toxicity and non-carcinogenic and scarcity of resources tomato puree has the greatest contribution, the reason being that during this process the highest consumption of electricity and fuel is reached. This leads to higher gas emissions. Although electricity apparently seems more friendly to the environment, it is not, because throughout the process of producing electricity, five of the greenhouse gases regulated in the Kyoto Protocol are emitted: methane, carbon dioxide, nitrous oxide, hydrofluorocarbons and sulfur hexafluoride (Garcia, 2007).

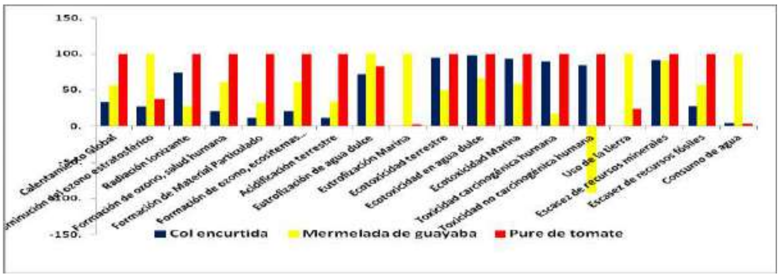

Figure 1 Comparison of the three production processes. Method: ReCiPe 2016 Endpoint (H) V1.03 / World (2010) H/A / Single score.

Figure 2 shows the results obtained when analyzing the category of single score or greatest contribution by the End point method, from which it can be concluded that the production process of tomato puree is the greatest contaminant of the three analyzed, which It leads to a gradual and silent deterioration of both the ecosystem and human life. Although guava jam is not the greatest contaminant, it is important to highlight the fact that it contaminates, only that compared to tomato puree it is not as significant.

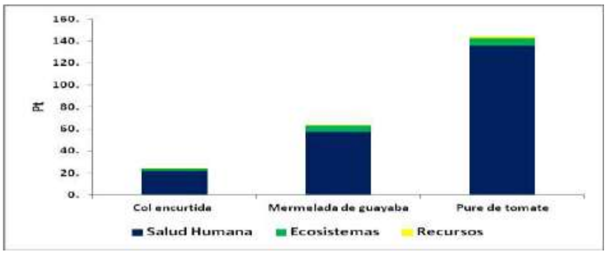

Figure 2 Comparison of the three production processes. Method: ReCiPe 2016 Endpoint (H) V1.03 / World (2010) H/A / Single score.

A set of measures aimed at solving the problems detected are proposed, which are proposed to be implemented in the short, medium and long term and are oriented based on recommendations for the efficient use of: water, energy and raw materials and supplies and for the reduction of waste and emissions in the production process of fruits and vegetables. The tomato puree production process is shown as an example, where very positive results are obtained, managing to reduce the environmental impact by 75% (Figure 3).

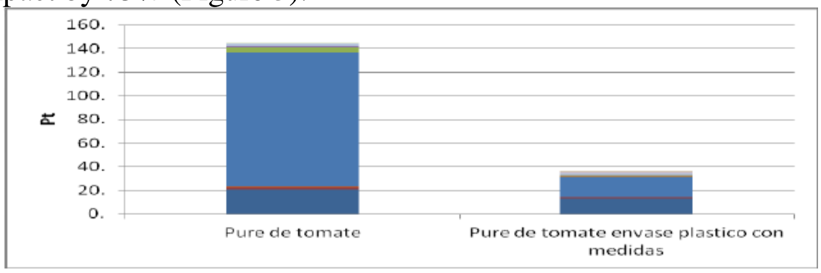

Figure 3 Comparison of the production process of tomato puree production before and after implementing CP measures. Method: ReCiPe 2016 Endpoint (H) V1.03 / World (2010) H/A / Single score.

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Assessing the contribution of lemon crops to climate change and blue water scarcity in Uruguay

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Rationale and objective

In Uruguay, citrus fruit is the most important horticultural commodity in terms of production, area, labour demand and economic contribution. At the same time, the use of ecolabels is on the rise worldwide, intending to promote products with higher environmental performance. In fact, initiatives to measure the environmental performance of products and organisations are emerging, such as Environmental Product Declarations-EPDs (EPD, 2022), and Product Environmental Footprint-PEF (EC, 2021). Despite the importance of Uruguayan citrus fruits and the increasing environmental awareness of both distributors and consumers (not only in international markets but also in local ones), a scientific analysis of its environmental impacts is lacking. Taking also into consideration the interest shown by Uruguayan companies in differentiating their products to underpin the access to new markets and maintain the existing ones, this study aims to assess the contribution to climate change (CC) and blue water scarcity (BWS) of lemon crops in Uruguay by applying a cradle-to-farm gate approach. The results of the study will help to identify the most relevant sources of impact (hotspots). In addition, temporal representativeness of the data, a critical aspect when quantifying the environmental impacts of agricultural products, is analysed by using data from four harvesting seasons.

Approach and methodology

Primary data corresponding to the seasons 2016 to 2020 was collected from a 6.26 ha lemon orchard whose production is aimed at fresh consumption. The orchard is located in the south of Uruguay and the farming practices followed are representative of the citriculture in the region. The orchard management was similar in the studied years, only changing the irrigation dose as it depends on climate conditions. Fertilisation was carried out from September to December with a total application of 203.10 kg $N \cdot ha^{-1}$ and 8.46 kg $P_2O_5 \cdot ha^{-1}$. Fertiliser supply is mainly done by fertigation although some of them are sprayed (foliar application). Watering is performed from October to March by drip irrigation using an electric pump fed from an underground well at 30 meters depth. Yields ranged from 47 tonnes $\cdot ha^{-1}$ in 2016-2017 to 66 tonnes$\cdot ha^{-1}$ in 2019-2020. Two functional units were used, namely 1 tonne of lemons and 1 ha$\cdot$season^{-1}. The system boundaries included all the relevant activities involved in the agricultural stage, namely the production of agricultural inputs (fertilisers and pesticides), their transport to the orchard, their application, the use of agricultural machinery (including fuel production), and the irrigation (including electricity production).

To estimate N_2O emissions from fertilisers application, Tier 1 IPCC Guidelines (IPCC, 2006) and the subsequent update (IPCC, 2019) were followed. In this update, the climate in the region and the type of fertiliser are considered which, in this case study, correspond to wet climate and synthetic fertiliser, respectively. Modelling indirect N_2O emissions requires modelling NH_3, NO_x and NO_3^- emissions. For the first two, Tier 2 and Tier 1emissions factors from the EMEP/EEA guidebook (EEA, 2019) were considered. NO3- leaching was estimated following the Tier 2 SQCB-NO3 model (Emmenegger

et al., 2009), which considers multiple parameters. Namely, the clay content of the soil, which was estimated taking into account that it is a Vertisoil based on the USDA classification, and using the table from Emmenegger et al. (2009). In addition, to estimate the N content in soil organic matter, the equation and standard values proposed by the SQCB-NO_3 model were used. The depth of the roots was retrieved from Goñi and Otero (2009). As to the absorption of nitrogen by the crop, values from Gambetta et al. (2021) for Uruguayan citrus fruits were used.
Water consumption from irrigation was calculated according to Pfister et al. (2011), considering the effective precipitation and the crop evapotranspiration. Precipitation values were obtained from the nearest meteorological station, INIA Las Brujas, located in Canelones department (INIA-GRAS, 2022). Crop evapotranspiration was estimated by following FAO guidelines (Allen et al., 1998). For this, climate data from INIA Las Brujas meteorological station (INIA-GRAS, 2022) was used as an input for the Penman-Monteith equation (Allen et al., 1998) to obtain the daily reference evapotranspiration (ETo). In addition, values of monthly crop coefficient (Kc) for Uruguayan citrus fruits were obtained from García Petillo and Castel (2007). Those authors performed a water balance considering the irrigation, effective precipitation, and parameters related to the soil (drainage and variation in the soil water storage during the crop season) for a citrus orchard located at Kiyú, Uruguay. Datasets on relevant background processes, namely input production, transportation and machinery use, were taken from Ecoinvent 3.8 (Moreno Ruiz et al., 2021; Wernet et al., 2016) and Gabi v.10 (Sphera, 2021) databases. Specifically, fertilisers not found in the databases were modelled as generic N, P and K fertiliser production, by considering the corresponding fertiliser units as N, P_2O_5 and K_2O. The production of a corrective foliar fertiliser and of gibberellic acid could not be modelled due to a lack of data.

For the quantification of the impacts in the category of climate change, recommendations of the EPDs (EPD, 2022) were followed, which suggest the use of the EN 15804+A2 method. This method is based on the IPCC (2013), which in turn coincides with the characterisation factors proposed by the PEF (EC, 2021). AWARE method (Boulay et al., 2018) was applied to quantify the BWS impact, as it is the methodology recommended by both PEF and EPDs. Specific monthly characterisation factors (CF) from WULCA (2022) for the corresponding Uruguayan basin (Río de la Plata) were used to quantify the direct BWS impact on the field, whereas the world average CF for non-agricultural activities (20.30 m^3eq./m^3) was used for that of the background processes.

Main results and discussion
The average climate change impact in the studied season was $4.98 \cdot 10^3 \pm 7.29 \cdot 10^1$ kg CO_2 eq·ha^{-1} and 93.25 ± 13.12 kg CO_2 eq·$tonne^{-1}$, as shown in Table 1. For both functional units, on-field emissions from fertilisers application were the dominant contributor (55-56% of the total impact, depending on the harvest season), followed by fertilisers production (24% of the total impact). As to the results obtained per hectare, considering that the impacts from the production of fertilisers are the same in each season since the same amount of fertilisers was applied, special attention must be paid to on-field emissions. These present a maximum value in 2018-2019 and a minimum in 2016-2017, with N_2O emissions dominating the CC impact category. As explained above, these emissions comprise direct N_2O, volatilised indirect N_2O and leached indirect N_2O. The first two are constant regardless of the season analysed because there are no variations in the dose of N applied. The third, however, presents an inter-season variation because it also depends on parameters that do vary, such as the 'irrigation dose + rainfall', which is maximum in 2018-2019 and minimum in 2016-2017. Thus, when expressing the results per hectare, the CC largely depends on the total amount of water added to the crop, which in turn is influenced by climate conditions. As can be seen in Table 2, the coefficient of variation (CV) of N_2O emissions, calculated as the standard deviation of the four seasons divided by their average, is 3%, due to the 6% CV associated with the indirect N_2O leached, as a consequence of the 7% CV of the sum of irrigation plus precipitation.

When expressing the results per tonne of product, they are strongly dominated by the yield. The maximum CC corresponds to 2016-2017, with a yield of 47 tonnes $\cdot ha^{-1}$, and the minimum to 2019-2020, with a yield of 66 tonnes$\cdot ha^{-1}$. The coefficients of variation of the on-field emissions rise to 14-15 % (Table 2), evidencing the strong influence of the yield in the final results, which has an inter-season variability of 16%. This variability can be explained by the high variability of climatic variables (precipitations, temperature-freeze damage, irradiance, relative humidity), in addition to other agricultural practices or decisions (pruning, alternance management, harvest date).

Table 1. Results of climate change (CC) and blue water scarcity (BWS) impacts

	CC (CO_2 eq.)		BWS (m^3 eq.)	
	UF = 1 tonne	UF = 1 ha	UF = 1 tonne	UF = 1 ha
2016-2017	103.62	$4.87\cdot10^3$	267.98	$1.26\cdot10^4$
2017-2018	91.09	$5.01\cdot10^3$	255.62	$1.41\cdot10^4$
2018-2019	102.76	$5.04\cdot10^3$	234.75	$1.15\cdot10^4$
2019-2020	75.54	$4.99\cdot10^3$	218.27	$1.44\cdot10^4$
Average	93.25	$4.98\cdot10^3$	244.15	$1.31\cdot10^4$
Standard deviation	13.12	$7.29\cdot10^1$	22.04	$1.34\cdot10^3$
Coefficient of variation (%)	14	1	9	10

The average BWS in the studied seasons was $1.31\cdot10^4 \pm 1.34\cdot10^3$ m^3 eq$\cdot ha^{-1}$ and 244.15 ± 22.04 m^3 eq$\cdot tonne^{-1}$ (Table 1), and the irrigation requirements are the major contributor (88-90% of the total impact depending on the assessed season), followed by fertilisers' production (9-11% of the total impact depending on the season). Taking these relative contributions into account, it is interesting to analyse the water consumed by the crop. When 1 hectare is selected as FU, the highest blue water consumption corresponds to the seasons 2017-2018 and 2019-2020 (see Table 2), which implies that, in turn, the BWS values are also maximum. When observing in detail the monthly water consumption, the highest values of the above-mentioned seasons (approx. 70% of the total for 2017-2018 and 2019-2020) correspond to November, December, January, February, and March, which are the months with the highest CFs, making the BWS impact greater. These higher values are consistent with the fact that the mentioned months are the driest months of the season, when there is less precipitation, since they correspond to the summer months. The lowest BWS is that for 2018-2019, when the total water consumption is the lowest, especially in the above-mentioned months (46% of the total). When the chosen functional unit is 1 tonne, again the yield dominates the BWS results. The maximum BWS value is observed in 2016-2017, when the lowest yield is obtained, whereas the lowest BWS value corresponds to 2019-2020, the season with the highest yield, showing the high influence of yield on the final results. It should not be overlooked that for 2017-2018 and 2018-2019, this yield relationship does not hold. This can be explained by the fact that, for those seasons, water consumption has more weight in the final results than the yield, since the water consumption in 2017-2018 was greater than in 2018-2019, making the total BWS value higher, despite the higher yield obtained in the former. For this category, a variation coefficient of 11% and 9% are obtained per hectare and per tonne, respectively (Table 2). This variability can be explained, as observed in the "approach and methodology" section, by the dependency of water consumption on climatic variables (mostly precipitations, relative humidity, wind, and temperature). In turn, the BWS impact also depends on the monthly scarcity CF of the basin, also influencing the variability of the results.

Table 2. Values of fertiliser on-field emissions, and blue water scarcity in the field stage and their respective coefficient of variation.

	FU = 1 $ha\cdot season^{-1}$					FU = 1 tonne				
	2016/17	2017/18	2018/19	2019/20	CV (%)	2016/17	2017/18	2018/19	2019/20	CV (%)
N_2O direct (kg)	5.11	5.11	5.11	5.11	0	0.11	0.09	0.10	0.08	15
N_2O indirect, leached (kg)	3.49	3.95	4.04	3.84	6	0.07	0.07	0.08	0.06	14
N_2O indirect, volatilized (kg)	0.30	0.30	0.30	0.30	0	0.01	0.01	0.01	0.00	15
N_2O total (kg)	8.90	9.36	9.45	9.24	3	0.19	0.17	0.19	0.14	14
NH_3 (kg)	13.61	13.61	13.61	13.61	0	0.29	0.25	0.28	0.21	15
NO_2 (kg)	8.12	8.12	8.12	8.12	0	0.17	0.15	0.17	0.12	15
NO_3^- (kg)	894.73	1011.94	1035.71	982.60	6	19.04	18.40	21.14	14.89	14
BWS (m^3 eq.)	$1.19\cdot10^4$	$1.33\cdot10^4$	$1.08\cdot10^4$	$1.37\cdot10^4$	11	252.40	242.30	219.80	207.16	9

Conclusions

The results of Uruguayan lemons' impact at the farm level show the great influence of fertilisation on climate change impact and that of irrigation requirements in terms of blue water scarcity. As regards the inter-season variability, when expressing the results per-area basis, CVs have lower values. This is due to the fact that results are mainly dependent on the irrigation dose and climatic parameters, namely the precipitation. When expressing the results per mass basis, there is a high yield dependency (which in turn depends on climatic conditions but also on management practices) and the variability tends to be greater. Therefore, a multi-year analysis is encouraged especially in the study of crop production under variable weather, since an environmental assessment based on only one season may not be representative of the environmental impacts, even when following the same practices.

Improving the management practices of lemon crops is crucial for lowering CC and BWS impacts. Actions to reduce the impact on CC should include the optimization of the dose of N fertilisers, as well as the selection of more environmentally friendly alternatives during their manufacturing. The optimization of crop nutrition management, which is mainly based on fitting the N supply to the plant demand, is critical. To this end, tools such as the Normalized Difference Vegetative Index (Pettorelli, 2013) or the Site-Specific Nutrient Management (Buresh and Witt, 2007) are recommended. The selection of the type of fertiliser is also relevant in terms of mitigating nitrogen emissions; the use of slow-release fertilisers should be encouraged.

Although Uruguay is a country with a baseline water stress of less than 10% (World Resources Institute, 2019), which means that, for now, there is enough water available to supply the crops, reducing water consumption can always benefit the environmental profile of Uruguayan lemons against similar products from other countries. Thus, the study and optimization of the ratio "irrigation dose/crop yield" in the months of greatest water scarcity is encouraged. As well, technological optimization of irrigation is a very important strategy to reduce the BWS. Using up-to-date techniques can reduce unproductive soil evaporation thus reducing the consumption of water. Other strategies, such as advanced irrigation scheduling and deficit irrigation, can also be useful to decrease the irrigation dose. At the same time, fitting the irrigation dose also contributes to reducing nitrate leaching, thus lowering the impact on CC.

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Sustainable Consumption and Production in the Food and Beverage sector of Argentina: Hotspots Analysis

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Rationale and objective

The 12 SDG is to ensure sustainable consumption and production (SCP) patterns by decoupling economic growth from environmental degradation, increasing resource efficiency and promoting sustainable lifestyles (UNEP, 2015). In order to help countries to identify hotspot areas and to set policies for achieving that goal, the Life Cycle Initiative commissioned the Hotspots Analysis Tool for Sustainable Consumption and Production (SCP-HAT), together with the One Planet Network and the International Resource Panel. The pilot analysis held in Argentina delivered that one of the most vulnerable sectors related to SCP is the Food and Beverage (F&B), which plays a key role in the economic development of the country, through the generation of added value, tax recovery, employment and foreign trade. This prompted the development of an in-depth study to find the critical aspects where Life Cycle Assessment (LCA) could help to improve the consumption and production pattern of this particular sector. The project's aim was to identify: 1) what are the main hotspots in the different productive chains of the F&B sector in Argentina; 2) what are the best options for improving the environmental impacts detected; and 3) which factors may hinder the implementation of the identified improvement measures.

Approach and methodology

To find the answers to these questions, information about 27 productive chains was used, in addition to the main packaging materials used. Since primary products from the agricultural, and livestock sectors are transformed through industrial processes into food and beverages, all stages of the life cycle of the production chains involved must be considered.

The methodology was structured as follows: 1) Compilation of LCA studies in the Argentinian F&B sector; 2) Identification of an initial set of hotspots: the dominant impact categories, the most significant life cycle stages, and the sources of impacts processes and/or substances were identified; 3) Validation of the initial set of identified Hotspots through consultations with stakeholders; 4) Refining the LCA information by deepening some existing LCA studies, and developing new ones; 5) Identification of Hotspots, improvement opportunities, barriers, and policy recommendations in the broad set of F&B datasets; 6) Final stakeholder validation: six sector-specific workshops were held, presenting the enhanced results, and collecting their opinions and suggestions.

For the LCA calculations, whenever possible, direct information from producers was considered, complemented with secondary data obtained from life cycle databases, mainly Ecoinvent 3.5 and World Food LCA Database 3.5. Data gaps were filled relying on peer-reviewed publications, commercial catalogs, and reports from government agencies and private sector. SimaPro® was used for LCA calculations. All the impact categories in the CML-baseline methodology were analyzed with an emphasis on Global Warming Potential (GWP).

Main results and discussion

34 F&B products and packaging materials were assessed thanks to the generous participation of professionals from different institutions. Also, dozens of commonly used inputs to the F&B sector were re-contextualized to fit Argentinian conditions. Considering the GWP contribution of the analyzed product chains, including both the impact produced per unit of product and their total annual production, the main contributors are beef, pork, vegetable oils, dairy products, wine, and sugar.

The most recurrent hotspots identified are:

- primary production: production and application of fertilizers (except for meat production),
- processing and manufacture: use of fossil energy/electricity,
- distribution: internal transportation using fossil fuels,
- consumption: waste and food losses,
- end of life: logistics and poorly recycled materials.

Some of the most recurrent policy recommendations derived from the study are: to promote soft loans, credit lines or tax incentives for the incorporation of precision agriculture technologies; to support capacity building actions to reduce the consumption of traditional fertilizers; to continue with the promotion of biofuel production and use; to foster the implementation of sectoral energy-efficiency programs; to promote public campaigns to encourage change in consumption habits; to stimulate the adoption of circular economy strategies in the sectors involved. Also, a first estimation of food loss and waste (FL&W) and its related climate change potential is performed for the considered products, using waste loss percentages estimated for Argentina (León *et al*., 2014). Results show that meat, vegetable oils and dairy products are the biggest contributors in terms of GWP in Argentina.

Conclusion

The identification of hotspots in the F&B sector in Argentina was performed during a highly data-intensive short-term project. This constitutes the most extensive compilation and analysis that has been carried out in the country to date for hotspots identification, which may trigger new studies that could improve the results obtained and expand the list of products analyzed. More research is needed, covering other regions and production systems, in order to obtain a more representative picture of the impact associated with the Argentinian F&B sector. The results presented in this study can be helpful for the definition of policies by government bodies and for establishing priorities on research activities by scientific and technological institutions.

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Environmental burdens of fishing and aquaculture trade between Spain and South America: a bottom-up approach

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Globalization and the worldwide need to nourish human communities have led to increasing trading flows of natural resources among nations in recent decades. Thus, when countries cannot supply their demand for certain foods, they import from others with higher production levels, becoming trade a fundamental piece in the global food supply and security systems (Dalin and Rodríguez-Iturbe, 2016; Gephart and Pace, 2015). Considering that food production and consumption are linked to environmental impacts and high reliance on biodiversity and ecosystem services (Crenna et al., 2019; Cucurachi et al., 2019), international food trade may generate serious environmental repercussions outside the countries' borders (Khan et al., 2020).

In this context, the European Union (EU) has traditionally been a net importer of multiple food products, especially fishing and aquaculture products, due to the incapability of European waters to provide sufficient seafood for the local demand. Thus, 64% of European demand for fishing and aquaculture products was covered by imports in 2018, mainly from developing countries as Morocco, China, India, Vietnam, Ecuador, and Argentina (EUMOFA, 2019; FAO, 2020; Guillen et al., 2019). Interestingly, Spain is the main importer of these products (EUMOFA, 2019). Therefore, the environmental sustainability of this sector depends, to a great extent, on the production beyond continental boundaries (Guillen et al., 2019).

The environmental burdens linked to international trade and consumption of diverse products and services has been extensively assessed using bottom-up and top-down approach (Heinonen et al., 2020; Marques et al., 2017; Notarnicola et al., 2017; Sala and Castellani, 2019). The top-down approach is based in Environmentally Extended Input-Output (EEIO) Tables and statistical data of households' expenditure (Sala et al., 2020, 2019b, 2019a). This approach allows assessing the environmental burdens related to a wide range of economic sectors at a macro scale (Beylot et al., 2019; Castellani et al., 2019; Heinonen et al., 2020; Sala et al., 2020). On the other hand, bottom-up approaches consider Life Cycle Assessment (LCA) studies of specific products, prioritizing those that are considered relevant based on their mass and economic value (Notarnicola et al., 2017; Sala et al., 2020, 2019b, 2019a).

In this sense, the present study aims to estimate the greenhouse gas (GHG) emissions linked to the trade of aquaculture and fishery products between Spain, the main producer and consumer of seafood in the EU, and South America, using a bottom-up approach. This approach was adopted due to the limitation of top-down approach linked with the high aggregation level by sectors (Beylot et al., 2019; Castellani et al., 2019; Heinonen et al., 2020; Sala et al., 2020). Meanwhile process based-LCA allows analyzing the environmental impacts of products and services with higher level of granularity (i.e., high level of detail)) (Beylot et al., 2020; Corrado et al., 2020; Huysman et al., 2016; Sala and Castellani, 2019). As far as we were able to ascertain, this study is the first attempt to estimate the global warming potential (GWP) of trade of aquaculture and fishery products between Spain and South America.

The estimation of the environmental burdens of the different products from fisheries and aquaculture was carried out in three main steps. Firstly, the data of imports and exports (2019) of aquaculture and fishery products were gathered from the European Market Observatory for Fishery and Aquaculture Products-EUMOFA (European Commission (EC), 2022a). This database contains detailed information on aquaculture and fishery products imported and exported between the EU and the rest of the world, from 2004 to 2021, with amounts expressed in weight (kg) and economic revenue (€), and classified according to species, commodity group, type of presentation and conservation (South American countries were considered based on the grouping proposed by FAO). Thereafter, the transport mode (by sea and/or air) of seafood products was obtained from the database of the statistical office of the European Union-EUROSTAT (European Commission (EC), 2022b). Finally, the GWP values of the products assessed were obtained from LCA studies in the scientific literature, considering the origin of each product and excluding studies from grey literature.

A total of 50 scientific papers were used, containing data of 163 aquaculture and fishery products. Thus, when data from LCA studies were not found for a product according to its geographical area, studies from closer regions or with a similar production system were used. In addition, for the case of products in which it was not possible to obtain reliable GWP values, the global mean values reported by Gephart et al. (2021) were used. However, due the differences linked to system boundaries across LCA studies, and in order to standardize the different results used, this study only considered the GWP contributions of aquafeed and electricity for aquaculture products, whereas diesel production and combustion contributions were considered for fishery products, as recommended by Gephart et al. (2021). In parallel, the GWP values linked to the processing phases of aquaculture and fisheries products were obtained from recent review papers about the environment performance of processing and packaging of seafood (Almeida et al., 2021; Avadí and Vázquez-Rowe, 2019; Ruiz-Salmón et al., 2021).

Preliminary results reveal that Ecuador is the main exporter of aquaculture and fishery products from South America to Spain, followed by Peru and the Falklands Islands, with exports in terms of mass of 114, 88 and 86 thousand metric tons, respectively. These represent roughly 63% of all Spanish seafood imports from South America. The main commodities exported from South America include cephalopods (37%), crustaceans (25%), and tuna and tuna-like species (19%). These products are mainly traded as frozen (72%) and prepared/preserved (21%). In contrast, Spain mainly exports to Chile, which represents 83% of all Spanish exports to South America, followed by exports to Brazil and Peru: 68.3, 3.8 and 3.6 thousand metric tons, respectively. Regarding the main commodities exported from Spain, tuna and tuna-like species represented 91% of all exports (96% as frozen products). Previous studies have highlighted that the EU is the main importer of raw material and intermediate products, and exporter of products with high value-added (Corrado et al., 2020). However, according to these results, Spain exports high amounts of raw and intermediate aquaculture and fishery products (frozen products), and imports large amounts of both raw (frozen) and manufactured products (prepared/preserved).

On-going activities of this study include the quantification of GHG linked with the international trade, which will be obtained in the upcoming months, after the collection of the Life Cycle Inventory (LCI) data from LCA studies through email requests to authors who have not reported contributions from aquafeed, electricity, and fuel.

In this sense, considering that changes toward more responsible patterns of production and consumption are needed, as established within the Sustainability Development Goals (SDG 12) (UN, 2015), and taking into account that projections for the next decade predict growth in global fishing and aquaculture production, consumption and trade (FAO, 2020), the sustainability assessment and better production practices of this sector are pertinent and urgent. Therefore, according to the preliminary results of this study, we conclude that there is a relevant flow of seafood trade between South America and Spain, a key seafood producer and consumer in the EU, that could contribute significantly to the GWP of this sector. Thus, more efficient practices should be adopted in all phases of production chain, in order to reduce emissions from international trade of aquaculture and fishery species.

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Introducing "An operational guide to LCA of agri-food systems within developing and emerging economies"

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The application of LCA for environmental assessment in the context of developing and emerging economies (i.e. countries, regions and economies that are not fully industrialized, generally showing an average low to middle income and high inequality of income distribution) is still very limited (Hou et al., 2015), especially in Africa (Karkour et al., 2021). The scarce existing studies were generally commissioned by international or developed country-based institutions, or were carried out in the context of research activities financed from abroad. Political and social conditions influence the capacity of agri-food stakeholders –i.e. in agriculture (including livestock), aquaculture, fisheries and food processing– to adopt new social or technical innovations. Such conditions may affect both the implementation of LCA and the use of final LCA results. Developing and emerging contexts feature some specificities, embedding potential consequences on LCA implementation and uptake: land tenure issues, prioritisation of development concerns, tropical conditions complexifying the modelling of direct emissions, efficiency issues, and research and development priorities and capacities (Basset-Mens et al., 2021). The practice of agri-food LCA under these conditions faces additional challenges than in developed countries. Reasons for this include the greater diversity of agri-food systems (e.g. due to specific natural conditions and combined socio-economic constraints), the paucity of data to inform LCIs, and even the varying awareness, capacities and priorities of stakeholders.

Based on the cumulated scientific and field experience of a dozen researchers over more than 10 years, we proposed recommendations to overcoming the challenges for robust agri-food LCA in developing and emerging economies, in the recently released book **"An operational guide to LCA of agri-food systems within developing and emerging economies"** (Basset-Mens et al., 2021). The e-book version is freely available at https://www.quae.com/produit/1734/9782759234677/life-cycle-assessment-of-agri-food-systems. We provide advice on co-designing the study with the stakeholders making up the "community" of the study, building LCIs (including foreground and background data collection, direct field emissions modelling, and quality management), performing LCIA, and interpreting the results for each stakeholder category. We propose, moreover, best practices for agri-food LCAs, at the system level (e.g. Table 1).

The most important recommendations of the guide are summarised below:

- Design and validate the goal and scope of the study with the commissioner; clarify the study purpose and constraints; never accept a poorly designed or under-resourced study.
- Co-design and perform the study with all associated stakeholders, and present the results adapting the message to the target public.
- Analyse the community of the study as well as each stakeholder's expectations and potential

fears; take time to explain, build trust, protect interests, and always give something back!
- Work on the field as a team with local experts and partners, other experts, and producers.
- Take care when developing typology, the sampling strategy and the survey of data providers since this constitutes the foundation for the quality of your results.

Table 1. Best practices for agricultural LCAs

<table>
<tr><th colspan="2">Challenges</th><th>Best practices</th></tr>
<tr><td rowspan="3">Inclusion of management-related indicators</td><td>Land use change</td><td>Model land use change associated with the studied system, as carbon losses and impact on biodiversity could be significant</td></tr>
<tr><td>Changes in soil quality</td><td>Consider at least changes in soil organic carbon associated with land use change and management changes</td></tr>
<tr><td>Effect of the crop rotation on emissions</td><td>Consider the whole crop rotation (or at least the previous and next crops) regarding the allocation of direct emissions</td></tr>
<tr><td rowspan="5">Methodological LCA challenges in the agriculture context</td><td>Selection of functional units</td><td>Contrast mass- and area-based functional units, especially in cases where the multifunctionality of complex agroecosystems cannot be properly accounted for with LCA</td></tr>
<tr><td>Delimitation of system boundaries</td><td>• Include key agricultural infrastructure and equipment (e.g. irrigation), and their maintenance
• Include on-farm manure management and organic fertiliser storage
• Include ad minima inventories: fertilisers and phytosanitary inputs, irrigation, soil work, energy carriers, equipment and infrastructure, direct field emissions, yields of products and co-products.</td></tr>
<tr><td>Allocation strategy</td><td>Contrast mass-, economic- and some density-based (e.g. nutrients, digestible energy) allocation</td></tr>
<tr><td>Selection of impact categories</td><td>• Select ad minima lists of impact categories: climate change, eutrophication, acidification, etc.
• Include an assessment of impacts on biodiversity
• Include water footprints</td></tr>
<tr><td>Direct emissions</td><td>Use models adapted to the specificities of the agricultural situation under study (pedoclimatic conditions, type of crop, fertilisation strategies)</td></tr>
<tr><td rowspan="2">Data availability and data management</td><td>Data gaps</td><td>Use data from reports, technical institutes, statistics, etc.</td></tr>
<tr><td>Uncertainty management</td><td>• Data variability: create a typology of systems
• Data uncertainty: Horizontal averaging of unit process data including estimates for uncertainty
• For comparative purposes, perform dependent sampling and pair-wise comparisons</td></tr>
</table>

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Exploring the carbon footprint of different vegetable choices in Aruba, a food import dependent island

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Rationale and objective

Aruba is an island in the Dutch Caribbean that is nearly import-dependent for their food supply. We aim to give insight into low-carbon vegetable import strategies for Aruba by modelling the carbon footprint of a selection of vegetables imported to Aruba. As islands are not situated on main maritime transport routes, we calculated the maritime transport phase with a high level of detail. We first made an overview of the carbon footprint of a selection of vegetables imported to Aruba. Then, we explored the carbon footprint of one package of tomatoes from Mexico more in-depth. We aim to give insight into the contribution of different life cycle stages, and the changes in the carbon footprint of Mexican tomatoes when more accurate data is used.

Approach and methodology

Selection of vegetables. Vegetables were selected by their weight contribution to the total vegetable category in Trademap import statistics from 2017 – 2019 (International Trade Center, 2020). Countries of origin were determined via Trademap and by visiting two large supermarkets in Aruba.

LCA methodology. The functional unit is one kg product at the supermarket in Aruba. The system boundaries are from farm in country of origin until arrival at the supermarket in Aruba. This includes agriculture (incl. land use change), processing, packaging, losses (post-harvest and distribution) and chilled road/sea/air transport. Greenhouse gas emissions (GHGs) were calculated using the characterization method IPCC 2013 (100a). We used three different LCA databases: the meta-analysis "LCA of food & drink products" from Poore (2018) as the basis, Agri-footprint version 4.0 for data on sea transport, and Ecoinvent version 3 for data on cooling during transport.

Agriculture. When data from a specific country of origin was not available in Poore (2018), all neighboring or the most nearby countries were selected as a proxy. For example, there was no data on tomatoes from Mexico and we selected the United States as a proxy. We did not consider differences in climate or agricultural practices. We used the proxy to calculate agriculture, processing, and packaging. Losses and transport were determined based on the country of origin.

Road transport. Road transport in the countries of origin was determined for each combination of vegetable and country of origin. The locations were determined by the geographic locations mentioned in Poore (2018). When no geographic location was mentioned, we assumed the location of other studies of the same product and country combination. When this was not possible, we assumed that the geographic location was similar to that of all other vegetables from the country of origin. Upon lack of data, we calculated the distance from the center of the country. Distances for road transport were determined with Google Maps, based on the fastest route. We assumed that all countries used cooled road transport. We multiplied the time needed for cooling with two to account for the driver's rest periods. Cooled road transport in Aruba was assumed to be 15 km.

Sea transport. Sea transport was mostly determined via the schedule of CMA CGM, one of the largest container shipping companies (AXSMarine, 2022). Their schedule shows duration, place(s) of transshipment, shipping lines, and vessel names (CMA CGM, 2022b). Data on distances between ports was obtained via the CMA CGM Eco Calculator (CMA CGM, 2022a). Data on the size of the ships was obtained via www.marinetraffic.com, expressed as summer deadweight tonnage (DWT). Often at least one transshipment was required to import products to Aruba. We assumed that larger container ships (> 13,000 DWT) were sailing at a load factor of 100% and smaller container ships used for the last transshipment to Aruba at a load factor of 80%. For these smaller ships we also assumed 'empty return', as Aruba has limited exports. The transport routes from Cartagena and Barranquilla in Colombia were based on a schedule from Caribbean Feeder Services (2022). GHGs were determined based on the DWT, load factor, distance sailed, and possible empty return.

Air transport. Distances were determined with www.airmilescalculator.com. No distinction was made between freight airplanes and freight transported by passenger airplanes. We assumed that no cooling was needed, according to the methodology of Poore (2018).

Losses. We assumed losses for post-harvest handling and for distribution. We assumed that post-harvest losses occurred at the farm, and that products were packaged afterwards. To determine the quantity of post-harvest losses we used an average of 2009-2011 from FAOSTAT, as provided in Poore (2018). For losses during distribution we used data from Gustavsson et al. (2013), as provided in (Poore, 2018). This data was based on FAO's Food Balance Sheets from 2007. We assumed that half of the losses during distribution occurred during road transport and half of the losses during sea or air transport. We accounted for the weight of the losses and of the packaging of the losses. We did not include the end-of-life treatment of losses.

In-depth analysis of Grape tomatoes from Mexico. During one of the supermarket visits we observed a package of Mexican Grape tomatoes from a brand from the United States, from now on referred to as brand A. The traceability code and information on the package allowed us to calculate the carbon footprint of this package in more detail, compared to the overview of the different vegetables. We will now describe how we adjusted the data from the overview. Proxies: In the overview we selected six data points from Poore (2018) for tomatoes grown in the United States. Now we only selected data points that reflected the production characteristics of these specific tomatoes: non-organic and open field. We also only used data points from California, as this state is situated adjacent to Mexico. We used two data points, from Brodt et al. (2013) and Nemecek et al. (2011). Road transport: We based the road transport on specific addresses. The tomatoes came from a farm in Sinaloa (Mexico) and were transported uncooled to the packaging facility in Sinaloa. At the packaging facility they were sorted, cleaned, packaged, and cooled. One or two days later the tomatoes were transported to the distribution center in Arizona (United States), this takes a bit less than one day (brand A, personal communication, June 7, 2022). The traceability code showed that the tomatoes were transported to the distribution center in a container, by a company from the United States. Therefore we assumed that the truck complied with fuel emission standards EURO6 of the United States (TransportPolicy.net, n.d.). Then, the tomatoes were transported for about three days to a consolidator in Florida (Consolidator, personal communication, June 7, 2022), and finally shipped to Aruba. Storage: The traceability code showed that the tomatoes were available to consumers in Aruba five weeks after packaging. We estimated that all cooled road transport took about one week. Sea transport also took approximately one week. Therefore, the tomatoes were stored in distribution centra in the United States for a duration of three weeks. We used the methodology as described in Asselin-Balençon et al. (2020) to take this into account.

Results and discussion

Selection of vegetables. We selected the following vegetables: potatoes (18% weight contribution), lettuce (10%), onions (10%), and tomatoes (8%). This is ~47 wt% of all vegetable imports to Aruba in 2017-2019. We also selected green beans as an interesting case study, as we noticed that they can be flown in from Kenya via the Netherlands or shipped to Aruba by sea from the United States. We identified 12 different countries of origins for all vegetables. Origins of selected products, proxies used, and carbon footprints are shown in Figure 1. We used proxies for eight out of 22 product-country combinations. Mostly, we used proxies for countries in Latin America. Although proxies were also used for green beans from the United States and onions from Canada.

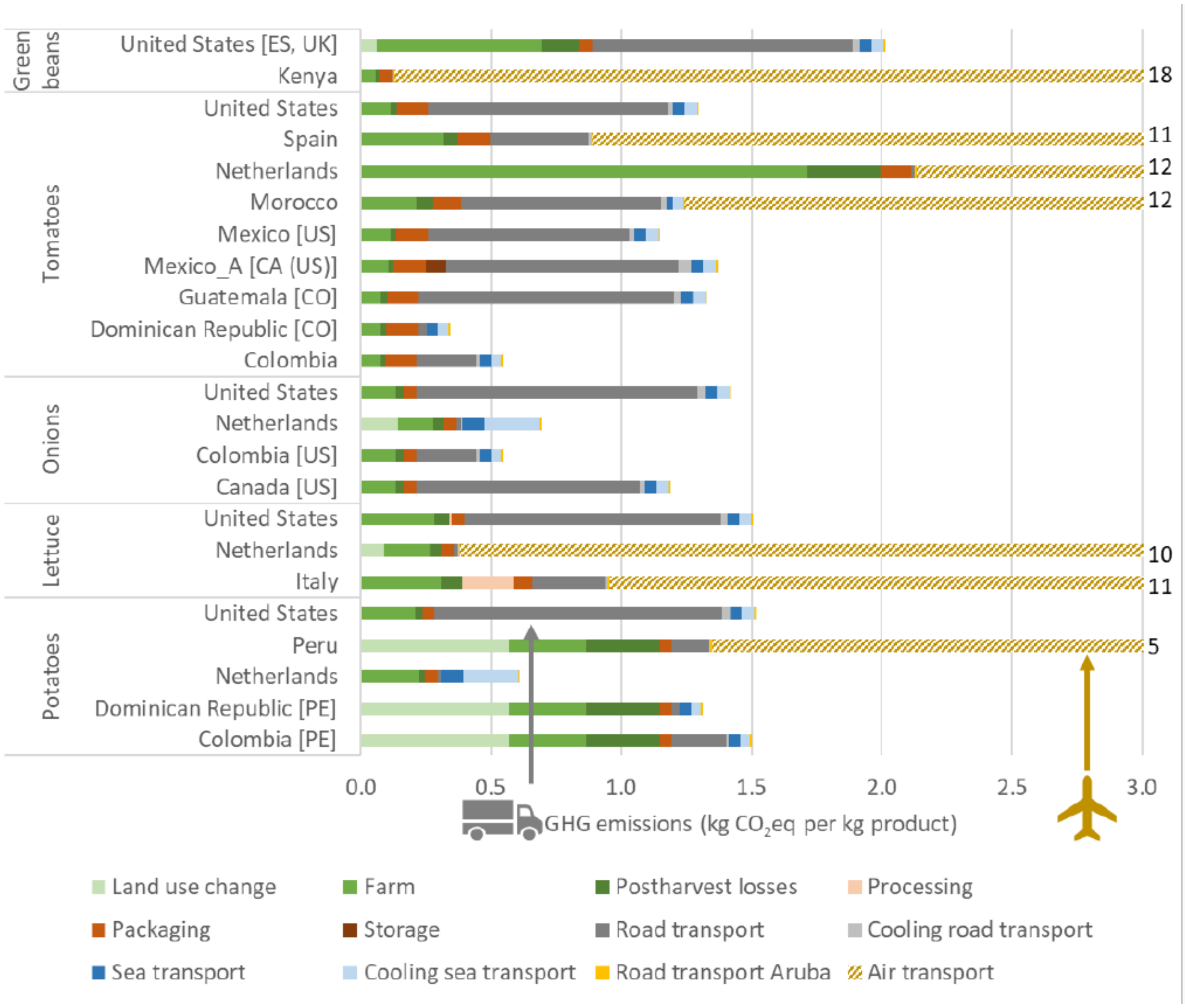

Figure 1 Greenhouse gas emissions of products from different countries of origin imported to Aruba. Losses during distribution and packaging of losses are included in the respective life cycle phases. All results from flown-in products did not fit on the y-axis and are depicted by a number. Mexico_A depicts results from the in-depth analysis of Mexican tomatoes from brand A. The 2 letter codes represent the proxies: California [CA, (US)], Colombia [CO], Spain [ES], Peru [PE], United Kingdom [UK], and the United States [US].

GHGs. Products imported by air transport had significantly higher GHGs (4.8 – 18.1 kg CO_2eq per kg) than products imported by sea (0.3 – 2.0 kg CO_2eq per kg), due to the relatively high GHGs emitted during airfreight. This was also found by Frankowska et al. (2019) who conducted an LCA on imported vegetables to the United Kingdom. Sim et al. (2007) found that air transport contributed for 89% to the carbon footprint of importing French beans from Kenya to England. In our study the air transport of green beans from Kenya contributed for 99% to the total GHGs. Although sea transport was calculated with detailed information on maritime transport routes and ship characteristics, it usually was not one of the life cycle stages that contributed most to the overall GHGs. Except for onions and potatoes from the Netherlands, which were shipped in chilled reefer containers for about one month. For most products that were not flown in, the road transport contributed mostly to the GHGs. Except when GHGs from agriculture were relatively high, such as for potatoes from Peru, the Dominican Republic, and Colombia. GHGs due to road transport were especially high for products from the United States, Morocco, Mexico, Guatemala, and Canada. For vegetables from these countries the fastest shipping route to Aruba was via Port Everglades in Miami, which resulted in a long road transport.

Lessons learned from the in-depth analysis of Grape tomatoes from Mexico. We drafted three lessons learned from the in-depth analysis of Grape tomatoes from Mexico. First, calculating actual road transport routes did not significantly increase the carbon footprint due to road transport for these tomatoes, even when the road transport increased with about 1400 km. However, it is still important to calculate road transport as accurately as possible for vegetable imports to Aruba, as this life cycle stage contributes a lot to the carbon footprint. Globally, transport was estimated to contribute for 9% to the carbon footprint of tomatoes (Poore & Nemecek, 2018). While for Mexican tomatoes from brand A transport contributed for 78%. Second, it is important to consider cooled storage, even when storage contributed only for 6% to the carbon footprint of Mexican tomatoes from brand A, which were stored for about three weeks. GHGs due to storage can increase a lot for products which are stored for a longer time, such as potatoes and onions. This might be even more important for cooled storage in Latin American countries due to the warmer outside temperature. Finally, for the tomatoes from brand A, the GHGs in the agricultural phase did not change a lot upon more accurate information. However, we need to see how this would affect the in-depth analysis of other product and country combinations to know how significant this step is.

Planning future research. To give insight into low-carbon vegetable import strategies for Aruba we have the following recommendation in terms of scope and methodology. We recommend broadening the scope by assessing several impact indicators and by extending the countries of origin included in the research, if applicable. We expect that by visiting more supermarkets more frequently, more countries of origin can be observed. Pictures of products should be taken to gain more information about production methods, brands and related locations, and possible traceability codes. We envisage to improve the methodology by including the following aspects: 1. Make a distinction between the use of passenger airplanes and freight airplanes. As nearly all foods imported to Aruba are imported by passenger airplanes. 2. Gaining more insight into GHGs emitted in the agricultural stage by finding more recent articles and by gaining insight in land use change per country and when possible, per region. Current articles used in this analysis ranged from 2006 – 2015. These also did not include the seasonality of the carbon footprint which is especially important for products produced in heated greenhouses. 3. Introduce Data Quality Indicators to compare the reliability of different results. 4. Add cooled storage for all products.

Conclusion

Vegetables that were imported to Aruba by sea rather than air have the lowest carbon footprint, due to the relatively high GHGs of airfreight. The carbon footprint was even lower when significantly less road transport was required. To give insight into low-carbon vegetable import strategies for Aruba we plan to further expand the scope and methodology of this research.

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Are Nutritionally-Balanced and Low-Carbon Diets Affordable for Low-Income Households in Ontario, Canada?

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Keywords: *Affordability; Global Warming Potential; Low-Income; Dietary Pattern; Life Cycle Assessment; Canada*

Introduction and Rationale

Dietary choices have important implications for both human and planetary health (Garnett, 2011). While multiple dietary patterns may equally meet nutrition requirements, their environmental impacts may differ substantially. Specifically, animal-based diets tend to have higher environmental impacts compared to that of plant-based diets (Veeramani *et al.*, 2017). In particular, among animal-based foods, beef has the highest carbon-intensity of any food (Poore and Nemecek, 2018). However, to ensure dietary shifts to sustainable consumption are successful, one important consideration is that they be affordable for all consumers (Barosh *et al.*, 2014). Although many studies have looked at the environmental impacts of actual and hypothetical diets, few have considered affordability of more sustainable dietary patterns, particularly for low-income households.

Objective

The objectives of this study are: to evaluate the cost and Global Warming Potential (GWP) of a range of dietary patterns (omnivorous, vegetarian, no red meat and pescetarian), based on Representative food consumption from 2015, in the province of Ontario, Canada; and to compare the affordability of dietary patterns that were modified to be nutritionally-balanced and have lower life cycle carbon emissions.

Methodology

GWP of dietary patterns: We quantified global warming potential (GWP100, IPCC 2007 method) of the dietary patterns by life cycle assessment (LCA) following ISO standards (ISO 14040, 2006; ISO 14044, 2006). We used a Canadianized cradle-to-consumption life cycle inventory database (Topcu *et al.*, 2022), which was based on various published LCA studies of food products Veeramani et al. (2017). The functional unit was 985,500 kcal based on a weighted average annual caloric intake for an individual in Ontario. We formulated Representative dietary patterns (DP) (Topcu *et al.*, 2022) using actual food intake data for about 4,200 Ontarian residents, provided in the Government of Canada's 2015 Canadian Community Health Survey (Health Canada, 2017). To formulate nutritionally-balanced and low-carbon (NBLC) DPs, we adjusted the amounts of foods in the Representative DPs following the 2007 Canada's Food Guide(Health Canada, 2007), to provide the ideal annual energy intake of 837,435 kcal, as described by Veeramani et al. (2016).
Affordability: We applied average food prices (in Canadian dollars (CAD)/kg) from the measurement tool developed by (Mollaei *et al.*, 2021) (based on 50 grocery stores in various regions in Ontario, representing discount (68%) and regular (32%) priced stores) to Representative and NBLC DPs to yield annual costs. To evaluate affordability, we considered two annual one-adult household income scenarios for 2015: a gross median income of CAD 40,830, and a minimum-wage income of CAD 19,288.80 (Statistics Canada, 2015). For incomes less than CAD 50,197, the Canadian tax rate is 15% (Canada Revenue Agency, 2022) leaving a disposable income of CAD

34,705 and 16,395, for median and minimum income, respectively. The affordability of the DPs was determined by calculating the percentage of income spent on food.

Results

Cost and GWP of Dietary Patterns

For the Representative DPs, the 'Pescetarian' DP has the highest cost, followed by 'No Red Meat', 'Vegetarian', and 'Omnivorous' DPs (Figure 1). For the NBLC DPs, the 'Vegetarian' DP is the most expensive, followed by 'No Red Meat', 'Pescatarian', and 'Omnivorous' DPs. The biggest change in cost is for the 'Pescatarian' DP, which decreased by about CAD 650 per year. The 'Vegetarian' DP increased by almost CAD 400 per year.

The biggest contribution to the costs in the Representative DPs are Meat and eggs / Fish, followed by Beverages, which include sodas, tea, and coffee (Figure 1). The largest contribution to the costs in the NBLC DPs are Cereals and Wheat flour products, Beverages, and Vegetables & vegetable juices. Canadians tend to have too much protein in their diets, and therefore, the Meat and eggs / Fish foods were greatly reduced in the NBLC DP. In contrast, there tends to be low intake of cereals and vegetables, so the amount of these foods increased in the NBLC DPs, increasing their total cost.

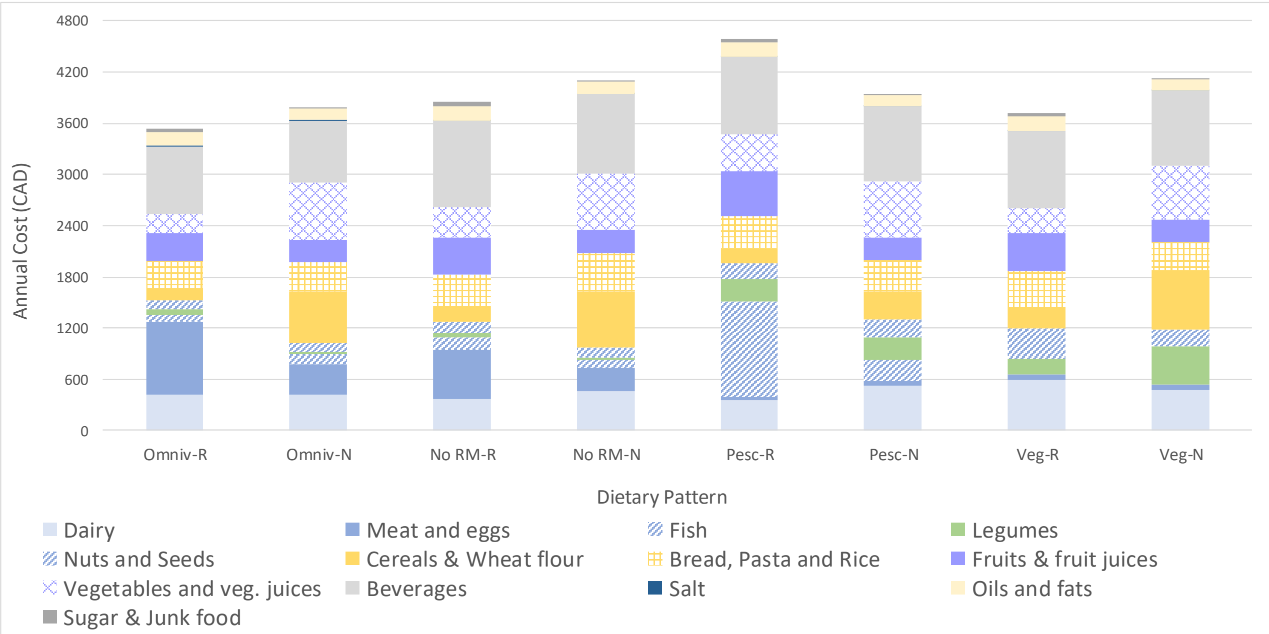

Figure 1 - Cost contributions of various food groups for DPs. R=Representative, N=NBLC

(Omniv=Omnivorous, No RM=No read meat, Pesc=Pescetarian, Veg=Vegetarian)

The GWP for each DP is presented in Figure 2. For Representative DPs, the highest GWP is associated with the 'Omnivorous' DP, followed by the 'Pescetarian', 'No Red Meat', and 'Vegetarian' DP. For the NBLC DPs, the highest GWP is associated with the 'Omnivorous', followed by the 'No Red Meat', the 'Pescetarian', and the 'Vegetarian' DP. The biggest change in GWP is observed in the 'Pescetarian' DP, which decreases by 961 kg CO_2e/FU). In contrast to the cost contributions, GWP contributions are mostly due to Meat and eggs / Fish, and Dairy (Figure 2).

A comparison between the cost of each diet and their GWP shows that for Representative food baskets, the omnivorous diet has the lowest price (CAD 3,537/year) and the highest GWP (2,203 kg CO_2e/FU). Figure 3 shows the relationship between cost and GWP for Realistic (R) and NBLC (N) DPs.

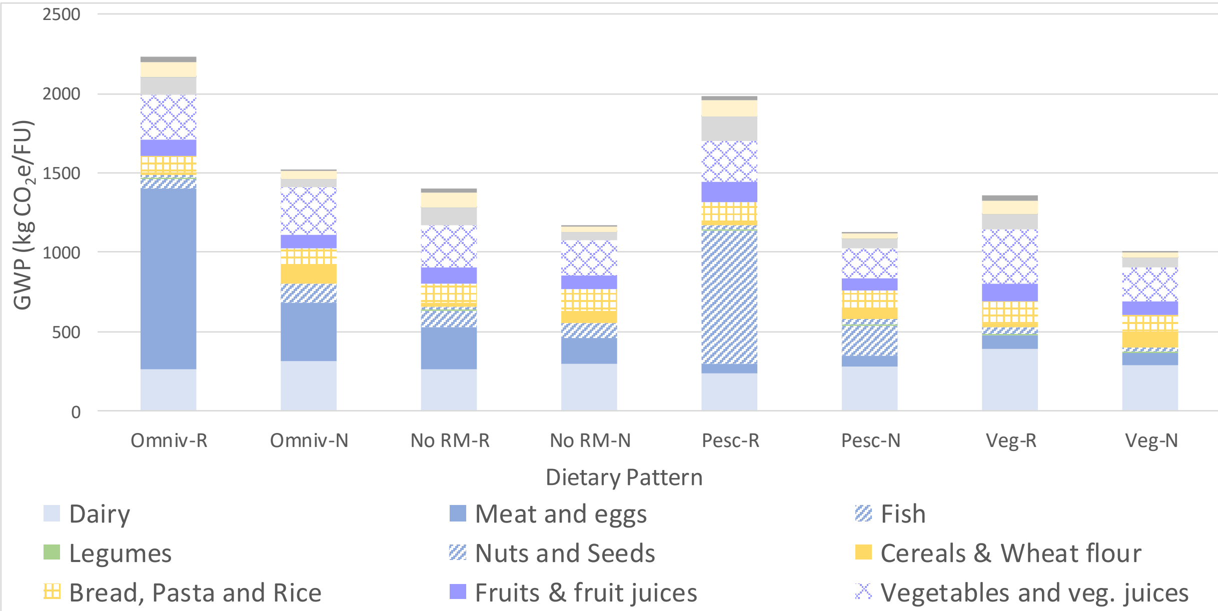

Figure 2 - GWP contributions of various food groups for DPs. R=Representative, N=NBLC

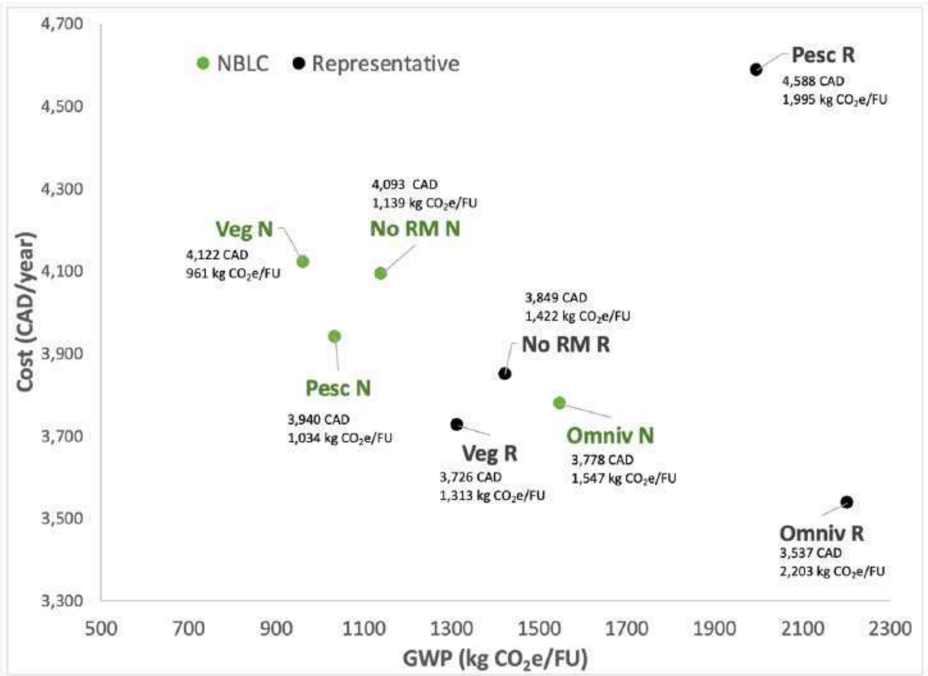

Figure 3 - Relationship between cost and GWP for Realistic (R) and NBLC (N) DPs.

<u>Affordability of Dietary Patterns</u>

On average, median-income households would spend of their 10.0 and 10.2% of disposable income for Representative and NBLC DPs, respectively. In contrast, low-income households would spend 20.4 and 20.7% of their disposable income for Representative and NBLC DPs, respectively. Nevertheless, the difference between Representative and NBLC food expenditures as a percentage of disposable income is very small, and does not affect affordability. According to Statistics Canada, the average annual food expenditure (food purchased from stores) for Canadians was CAD

6,126 in 2015 (Statistics Canada, 2022), that is 17% of income for median income and 37% for minimum wage.

Table 1 – Affordability of DPs, based on percentage of income spent on food purchases

Dietary Pattern		Food expenditures as Percentage of	
		Median Disposable Income (CAD 34,705)	**Minimum-Wage Disposable Income (CAD 16,395)**
Omnivorous	Representative	10%	18%
	NBLC	11%	20%
No Red Meat	Representative	9%	20%
	NBLC	10%	21%
Pescetarian	Representative	11%	24%
	NBLC	10%	20%
Vegetarian	Representative	9%	19%
	NBLC	10%	21%

Discussion

This study looks at the cost, GWP, and affordability of four Representative and NBLC DPs. Overall there was a general trend that the Representative DPs with the highest GWP had lower costs, except for the Pescatarian DP. For the NBLC diets, the same trend was observed, but there was a smaller difference between the lower and higher costs and GWP of various diets. Other studies also show that a healthy and nutritious DP is more expensive than the average DP and there is a need for price incentives, such as discounts and promotions, to encourage people to choose nutritious and healthy food options (Aggarwal *et al.*, 2011; Cassady *et al.*, 2007; van Dooren *et al.*, 2015; Waterlander *et al.*, 2013). However, the cost difference is not significant in all food groups (Mhurchu and Ogra, 2007; Turner-McGrievy *et al.*, 2016). Therefore, small improvements in some food groups will not necessarily increase the price but will enhance the quality of eating (Katz *et al.*, 2011).

Despite the higher costs of some of the NBLC DPs, they are still affordable for those with Median disposable income. Comparing it to the average Canadian expenditures on food, of 9.1% of disposable income for 2015 (Gray, 2016) and around 11% in 2020 (CFA, 2021), both the Representative and NBLC DPs are not much different than average expenditures. However, neither Representative or NBLC DPs are affordable for minimum-wage earners in Canada. This indicates a much larger issue regarding food affordability in general.

Conclusion

Providing affordable food choices for consumers that will meet their nutritional needs, while minimizing negative environmental impacts is significant with respect to food and nutritional security, human health, and the planet. The results provide more insights to the field of healthy and low impact diets for food security. Although no food was completely eliminated from any DP, high GWP foods were reduced by up to 75%. Further research is needed on the social acceptability of such reductions, as well as on looking at the cost and affordability of NBLC based on the updated Canada's Food Guide of 2019.

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Environmental impacts of food: future scenarios for Germany based on the planetary health diet

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Keywords: *German food consumption, biodiversity, water scarcity, planetary boundaries*

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Objective. Food consumption in Germany causes high environmental impacts (Eberle and Fels, 2016, Meier, 2014; Schmidt et al., 2019, Eberle and Mumm, 2022) as it is doing worldwide (Willet et al., 2019). Moreover, some of the planetary boundaries are already exceeded (Steffen et al., 2015; Campbell et al., 2017; Persson et al., 2022). However, a nutrition within the planetary boundaries is possible, if the recommendations of the Eat Lancet-Commission on a planetary health diet (Willett et al., 2019) will be followed.
Aim of this paper is to build scenarios for a German planetary health diet, compare it with today's intakes, and assess the related environmental impacts.
Methods. The analysis has been conducted using Life Cycle Assessment (LCA) according to ISO 14040 series (2006). The approach and underlying statistical data are described in Mumm and Eberle (2022). The following impact indicators were assessed: climate change including land use (LU) and direct land use change (dLUC), land occupation and the related terrestrial biodiversity impacts, as well as blue water consumption and water scarcity footprint. Based on the current diet ('status quo'), three scenarios for Germany were created following the recommendations for a planetary health diet for a flexitarian, a vegetarian and a vegan diet. The scenarios were kept as close as possible to the current diet in Germany, framed by a set of rules. First, the three scenarios each correspond to an intake of around 2,500 kilocalories as recommended by Willet et al. (2019). Second, for each food group (e. g. fruits) the caloric intake limits were respected. Third, the stated maximum intake was not exceeded. Fourth, for the vegetarian and vegan food basket, after distribution to the other product groups, the remaining calories were allocated to fruit and vegetables. Finally, the distribution within a food group is maintained as in the status quo whenever possible.
Results. The results show, that today, each person in Germany consumes on average about 2,650 kilocalories per day and thus six percent more than the recommended 2,500 kcal. Furthermore, the comparison shows that compared to a diet according to the recommendations of the Eat Lancet Commission in Germany today (i) too few vegetables are eaten, (ii) too many dairy products are eaten, (iii) the protein requirement is mainly met from animal sources (meat, eggs, fish) and to a significantly too low extent from vegetable protein sources such as pulses and nuts, (iv) that far too much meat is consumed, and (v) far too much added sugar is used (Table 1).
Regarding the environmental impacts, results show, that today's food consumption causes for all analyzed environmental impact categories higher impacts than the Eat Lancet-scenarios apart from water consumption and the scarcity-adjusted water footprint. Thus, following the recommendations

of a planetary health diet could significantly reduce the environmental impacts of German food consumption:

- A flexitarian diet - a diet in which no more than the amount of meat recommended by Willet et al. (2019) is consumed - could reduce land use by almost 20 percent, greenhouse gas emissions could even be reduced by more than a quarter, and biodiversity impacts by 18 percent. On the other hand, water consumption and water scarcity footprint would increase by a third and 45 percent, respectively.
- A vegetarian diet - a diet without meat and fish that follows the recommendations of the planetary health diet - could reduce land use by 45 per cent, greenhouse gas emissions by 47 per cent and biodiversity impacts by 46 per cent. However, water use and the water scarcity footprint would increase by 35 and 53 per cent, respectively.
- A vegan diet - a diet without animal products that follows the recommendations by Willet et al. (2019) - could nearly halve land use (-49%), greenhouse gas emissions (-48%) and biodiversity impacts (-49%). Water use and the water scarcity footprint, on the other hand, would increase by 55 and 78 per cent, respectively.

Figure 1 illustrates the relative differences between the status quo and the three scenarios. Table 2 shows the absolute environmental impacts for the status quo and the three scenarios for Germany.

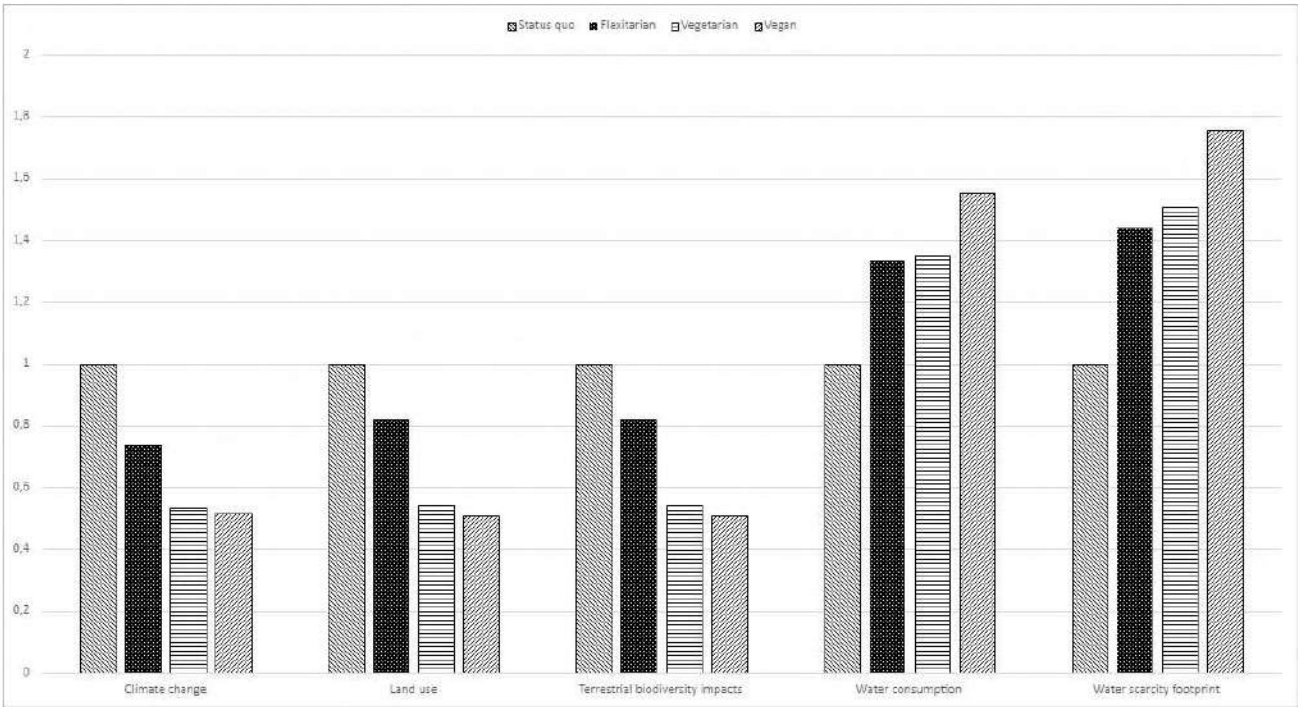

Figure 1: Relative changes of the three scenarios to the status quo for the environmental impacts of food in Germany

The results show that animal products in particular are associated with high environmental impacts:

- For instance, half (54%) of the greenhouse gas emissions from today's diet are caused by five products: sausages and cold cuts, beef, cheese, pork and poultry.
- Almost two-thirds (64%) of the land use is due to five agricultural products that are mainly produced for animal feed (wheat, soy, maize, grass, barley).
- This is even more evident in the case of biodiversity impacts. A good two thirds (69%) of the impacts are caused by the five agricultural products soy, wheat, maize, barley and rapeseed.

In terms of water consumption and water scarcity footprint, however, plant-based foods are worse. More than half of the water scarcity footprint is caused by three products: citrus fruits, almonds and peaches. Therefore, all Eat Lancet scenarios perform worse than the status quo in terms of water scarcity footprint (Figure 2).

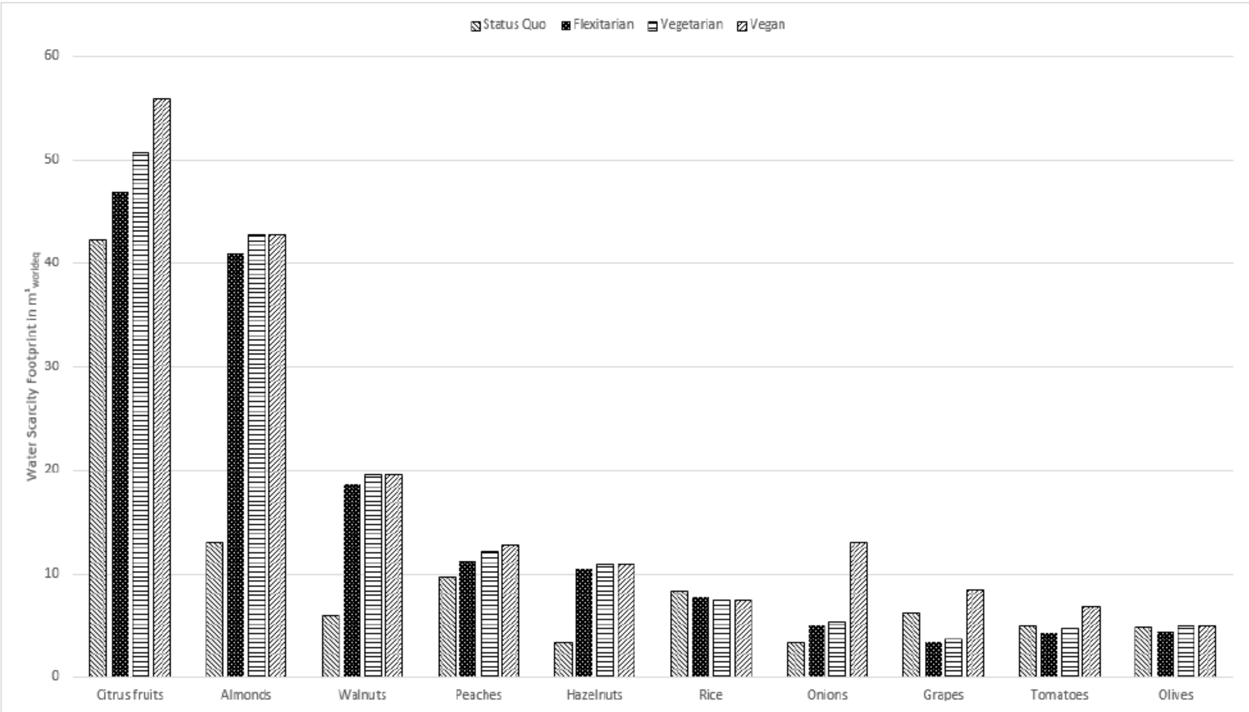

Figure 2: Water scarcity footprint for selected foods per person and year

Discussion and Conclusion. First of all, the study showed clearly that Germans in average eat too much. An average consumption of 2,650 kilocalories per day is about six percent higher than recommended in the planetary health diet. This finding correlates with the fact that over 50 % of German inhabitants are overweight and almost a fifth (18.5 %) is obese (EUROSTAT, 2019). However, this is particularly alarming in view of the fact that an average intake of 2,500 kcal for Germans can and should certainly also be discussed, since the required caloric intake depends on age, gender and activity and should thus certainly be lower on average in service societies such as the German society. For example, the German Society for Nutrition recommends consuming between 1,600 and 2,400 kcal per day and person (Breidenassel et al., 2022). If an average of 2,000 kcal is taken as the recommended amount, this means that (i) Germany consumes far too much (about one third) and that (ii) the environmental footprint of the German diet could also be reduced by about another fifth if the recommendations of the Eat Lancet Commission were combined with the daily recommended energy intakes of the German for Nutrition.
Furthermore, it could be clearly shown that with a decreasing share of animal products in the diet, the environmental impacts considered decrease, with the exception of water use and the resulting water scarcity impacts. A look at the foods that cause the high water use and the resulting water scarcity footprint shows that this could also be easily addressed if the consumption of citrus fruits and almonds were reduced and other fruits and nuts from regions less threatened by water scarcity were used instead.

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Table 1: Daily intake in Germany for the status quo and the three Eat Lancet scenarios

	Status Quo		**Scenario: flexitarian diet**		**Scenario: vegetarian diet**		**Scenario: vegan diet**	
	intake per day [g]	kcal per day	intake per day [g]	kcal per day	intake per day [g]	kcal per day	intake per day [g]	kcal per day
Cereals	**253.70**	**857.51**	**240.81**	**811.00**	**232.00**	**781.33**	**232.00**	**781.33**
rice	12.44	34.46	11.81	32.71	11.38	31.51	11.38	31.51
wheat flour	23.03	78.99	21.86	74.97	21.06	72.23	21.06	72.23
bakery products wheat	151.99	521.33	144.27	494.83	138.99	476.73	138.99	476.73
pasta from wheat	19.03	65.28	18.06	61.96	17.40	59.70	17.40	59.70
rye flour	2.91	9.41	2.76	8.93	2.66	8.61	2.66	8.61
bakery products rye	20.54	69.65	19.50	63.18	18.79	60.87	18.79	60.87
oats	7.56	25.61	7.17	24.31	6.91	23.42	6.91	23.42
maize	6.82	22.64	6.47	21.49	6.24	20.71	6.24	20.71
potato starch*	9.39	30.13	8.91	28.59	8.58	27.55	8.58	27.55
Roots or starchy vegetables	**72.44**	**52.88**	**53.42**	**39.00**	**57.72**	**42.13**	**92.90**	**67.82**
potatoes	72.44	52.88	53.42	39.00	57.72	42.13	92.90	67.82
Vegetables	**212.78**	**55.20**	**320.71**	**78.00**	**346.49**	**84.27**	**600.00**	**161.73**
green vegetables	***35.03***	***6.47***	***124.57***	***23.00***	***134.58***	***24.85***	***200.00***	***46.22***
broccoli	6.97	2.37	24.77	8.42	26.76	9.10	73.24	24.90
spinach	4.88	1.32	17.35	4.68	18.74	5.06	40.73	11.00
cucumber	23.19	2.78	82.44	9.89	89.07	10.69	86.03	10.32
red & orange vegetables	***131.08***	***33.81***	***117.76***	***30.00***	***127.22***	***32.41***	***200.00***	***51.59***
tomatoes	97.45	23.39	92.93	22.30	100.40	24.10	148.69	35.69
carots	33.63	10.42	24.83	7.70	26.82	8.31	51.31	15.91
other vegetables	***46.66***	***14.91***	***78.39***	***25.00***	***84.69***	***27.01***	***200.00***	***63.92***
cabbage	16.20	4.86	28.93	8.68	31.25	9.38	69.43	20.83
onions	30.46	10.05	49.46	16.32	53.43	17.63	130.57	43.09
Fruit	**211.45**	**136.11**	**217.71**	**126.00**	**235.20**	**136.13**	**300.00**	**193.10**
apples	67.46	35.08	77.30	40.20	83.51	43.43	95.70	49.77
peaches	13.26	6.36	16.45	7.90	17.78	8.53	18.81	9.03
grapes	18.62	13.22	15.62	11.09	16.88	11.98	26.41	18.75
banana	41.42	37.28	27.42	24.68	29.63	26.66	58.76	52.88
oranges	67.35	33.67	80.26	40.13	86.71	43.36	95.55	47.78
raisins	2.79	8.98	0.52	1.66	0.56	1.80	3.96	12.74
dates	0.57	1.52	0.13	0.34	0.14	0.37	0.81	2.16

	Status Quo		**Scenario: flexitarian diet**		**Scenario: vegetarian diet**		**Scenario: vegan diet**	
Dairy products	**294.03**	**535.04**	**192.66**	**153.00**	**208.14**	**165.30**	**0.00**	**0.00**
milk	122.57	78.45	99.66	63.78	107.67	68.91	0.00	0.00
yoghurt	71.12	33.43	78.74	37.01	85.07	39.98	0.00	0.00
cream	13.87	40.50	2.47	7.22	2.67	7.80	0.00	0.00
butter	14.13	104.86	0.99	7.35	1.07	7.94	0.00	0.00
cheese	57.65	216.75	7.98	30.00	8.62	32.41	0.00	0.00
milk powder	11.77	58.25	1.24	6.12	1.34	6.62	0.00	0.00
condensed milk	2.91	2.80	1.58	1.52	1.71	1.64	0.00	0.00
Protein sources	**173.15**	**337.79**	**281.89**	**739.95**	**236.35**	**710.63**	**247.17**	**703.14**
Meat & sausages	***116.66***	***211.97***	***66.87***	***128.00***	***0.00***	***0.00***	***0.00***	***0.00***
beef	15.84	19.81	14.00	17.50	0.00	0.00	0.00	0.00
pork	23.63	75.63	14.00	21.42	0.00	0.00	0.00	0.00
poultry	17.33	26.16	22.20	35.75	0.00	0.00	0.00	0.00
sausage (incl. lard/bacon)**	59.85	90.38	16.67	53.33	0.00	0.00	0.00	0.00
Eggs	***27.24***	***41.13***	***12.58***	***19.00***	***13.00***	***19.63***	***0.00***	***0.00***
eggs	27.24	41.13	12.58	19.00	13.00	19.63	0.00	0.00
Fish	***13.64***	***12.41***	***20.88***	***19.00***	***0.00***	***0.00***	***0.00***	***0.00***
fish	13.64	12.41	20.88	19.00	0.00	0.00	0.00	0.00
Legumes	***8.13***	***25.72***	***157.75***	***426.00***	***198.35***	***535.60***	***222.17***	***547.75***
peas	3.72	3.13	85.00	71.40	85.00	71.40	85.00	71.40
beans	0.66	0.83	15.00	19.05	15.00	19.05	15.00	19.05
tofu	0.00	0.00	0.00	0.00	25.00	19.00	50.00	38.00
peanuts	3.74	21.75	57.75	335.55	73.35	426.15	72.17	419.30
Nuts	***7.49***	***46.55***	***23.80***	***147.95***	***25.00***	***155.39***	***25.00***	***155.39***
almond	2.82	17.21	8.95	54.71	9.40	57.46	9.40	57.46
hazelnuts	1.95	12.40	6.21	39.43	6.52	41.41	6.52	41.41
cashew nuts	1.45	8.36	4.62	26.58	4.86	27.92	4.86	27.92
walnuts	1.26	8.57	4.02	27.24	4.22	28.61	4.22	28.61
Added fats	**42.96**	**385.09**	**46.12**	**414.00**	**50.13**	**450.11**	**50.13**	**450.11**
palm oil	9.48	83.76	6.80	60.11	6.80	60.11	6.80	60.11
olive oil	1.81	16.30	2.13	19.15	2.34	21.10	2.34	21.10
rape seed oil	12.33	110.96	14.48	130.31	15.96	143.61	15.96	143.61
sunflower oil	8.65	77.83	10.16	91.41	11.19	100.73	11.19	100.73
soy oil	10.69	96.24	12.56	113.02	13.84	124.55	13.84	124.55
Added sugar	**73.11**	**292.43**	**30.00**	**120.00**	**30.00**	**120.00**	**30.00**	**120.00**
sugar	73.11	292.43	30.00	120.00	30.00	120.00	30.00	120.00
Others* **	**7.06**	**23.80**	**7.06**	**23.80**	**7.06**	**23.80**	**7.06**	**23.80**
cocoa	7.06	23.80	7.06	23.80	7.06	23.80	7.06	23.80
TOTAL	**1340.69**	**2675.83**	**1390.38**	**2504.74**	**1403.10**	**2513.69**	**1559.27**	**2501.03**

* Potato starch is counted as a cereal due to its use; ** Sausage incl. bacon/lard, kcal bacon/lard in sausage also added; *** this category lists consumed foods that play a role in Germany but could not be assigned to any of the categories

Table 2: Environmental impacts of nutrition in Germany for status quo and three scenarios

	Unit	Status quo	Scenario: flexitarian diet	Scenario: vegetarian diet	Scenario: vegan diet
Climate change*	kt CO_2 eq.	2553.8	1874.5	1359.1	1314.8
Land use	Mio. ha*a	2021.5	1658.0	1098.1	1030.0
Terrestrial biodiversity impacts	BVI*Mio.ha*a	149.3	122.4	81.2	76.1
Water consumption	Mio. m^3	1443.2	2075.3	2176.2	2535.4
Water scarcity footprint	Mio. m^3 worldeq.	29.2	38.9	39.4	45.4

* incl. LULUC

Comparing apples and oysters- A review of dietary footprints

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Introduction

Over two-hundred comparisons of the environmental footprints of dietary choices have been published in peer-reviewed journals to date using results from food item specific life cycle assessments (LCAs) and related methods. The range of environmental impact estimates compiled within commodity groups across these diet studies range widely due to inconsistent data choices, models, assumptions, impact assessment methods, aggregation approaches, and other factors. To assess the extent to which factors that influence primary study LCIA outcomes have been considered, we evaluated how food-item specific studies were selected and combined among 218 dietary footprint studies.

Methods

Literature was selected based upon the search phrase: "+Diet +Food +Sustainable +"food consumption" +"Greenhouse gas emissions" +LCA" in Google Scholar, yielding 1,690 results up to 31-Dec-2019. From the search results, only peer-reviewed journal articles specifically focused on the dietary environmental impacts derived from LCA results were considered. Book chapters and reports, studies relying on I/O analysis or national IPCC inventories were excluded, as were studies that only looked at one type of food commodity. The remaining studies were screened against a set of criteria that we deemed should have been scrutinized during harmonization of individual LCAs, such as whether the results were from attributional or consequential LCA studies, co-product allocation approach used, system boundary setting, land use and land-use change considerations, weighting averages according to production volumes, and impact assessment methodology. Other notable practices that could influence conclusions were also documented.

In order to make more elaborate comparisons between the studies and our expertise, we have chosen to focus on how blue foods have been treated in the different studies. Blue foods refer to all foods that originate from aquatic environments, including finfish, crustaceans, bivalves, and aquatic plants. It is a commonly consumed food commodity group, but also a highly diverse food group with diverse environmental impacts depending on the commodity in focus (Gephart et al. 2021). More specifically, we set out to explore how apples compared to oysters in terms of global warming, as they are two food commodities with very different origins and characteristics (e.g. edible yields), and global warming being the most frequently reported impact category. We also included salmon in the comparison, as it was the most widely reported blue food commodity in the material being reviewed.

Results

Of the 1,690 results, 218 fit our criteria. These were published in 76 different journals, 39 (142 articles) with focus on environmental sciences, 15 (41 articles) on medical sciences, and 21 in more general journals. Many of the articles published in medical journals focus on relationships between nutritional and environmental aspects. Most studies (27) are published in the Journal of Cleaner Production, but articles published in Nature, Science, and PNAS are also represented.

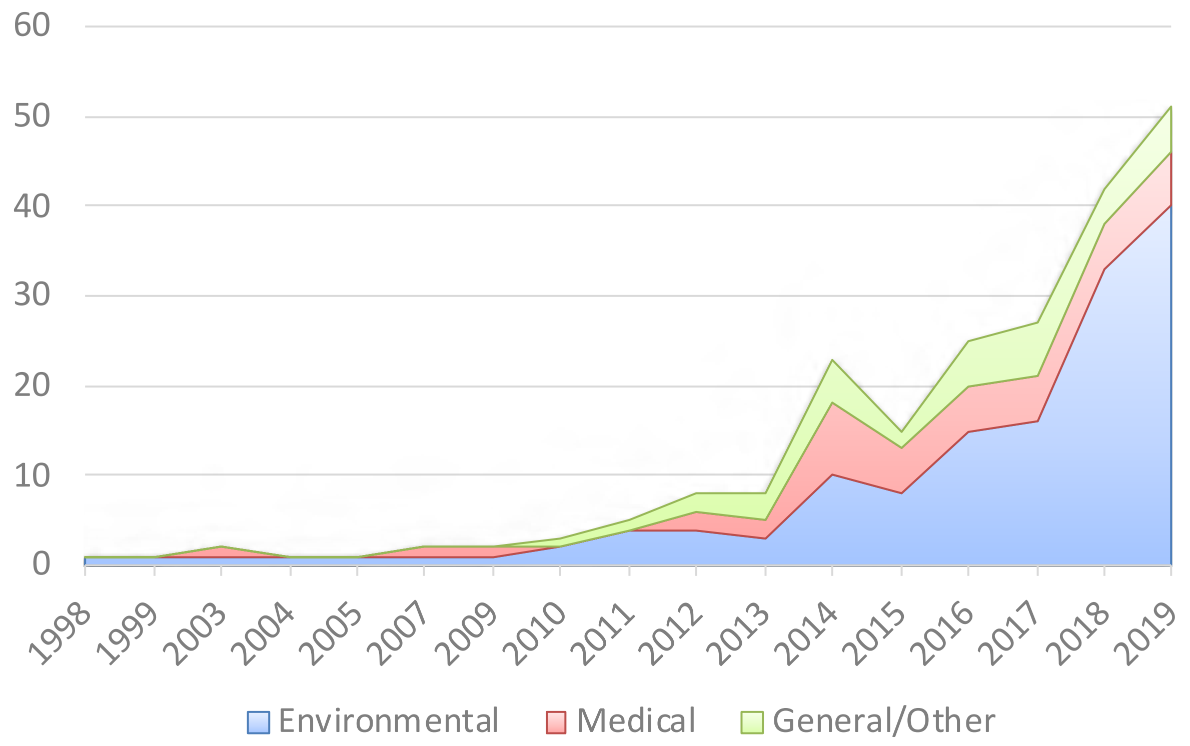

Figure 1: Number of environmental dietary studies published per year in environmental, medical, and general/other types of journals.

Extracting emission results on individual food commodities proved difficult due to poor data reporting, paywalls, different levels of aggregation of food commodities, cross-referencing across studies, confidentiality, and different reporting formats. Where underlying emissions data are reported, they are presented as different central values (e.g. mean, median, or point-value) and at different levels of aggregation (e.g. seafood, fish, herring, or oysters). We subsequently treated all central values reported and tried to avoid cross-references to make comparisons at comparable levels of aggregation (e.g. fruit vs. seafood, and apples vs. oysters). Nonetheless, across the studies we only managed to detail two unique global warming estimates for oysters, ten for shellfish, nine for salmon, and 23 for fish/seafood more generically. As for apples, 19 studies reported global warming impacts for apples and 11 for 'fruits' more generally (Figure 2a&b). The inconsistent ways of aggregation food commodities has been highlighted by Ziegler et al. (2022), but interestingly the relative discrepancies (measured as coefficients of variation; CV) among the fruits (CV=0.82), fish/seafood (C=0.65), salmon (CV=0.67), and shellfish (CV=0.95) categories remain in a similar range, while the two estimates for oysters were widely different (CV=1.36).

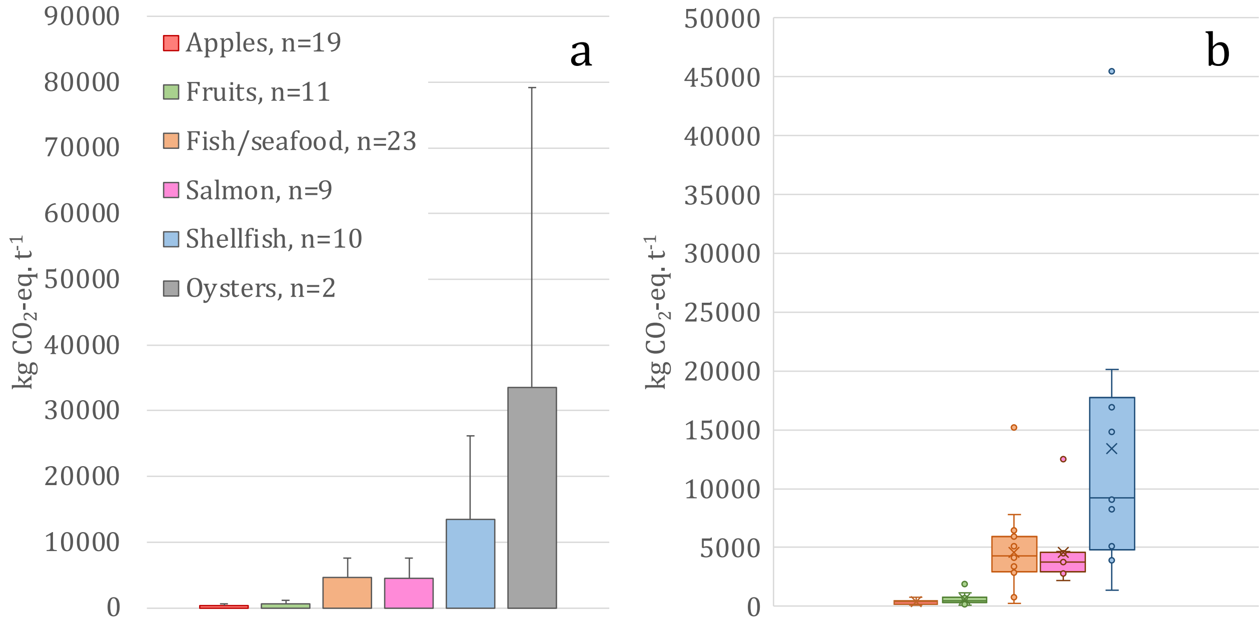

Figure 2a&b: Reported global warming impacts per tonne of apples (*n*=19), fruits (*n*=11), fish/seafood (*n*=23), salmon (*n*=9), shellfish (*n*=10) and oysters (*n*=2). Figure a presents all values as a bar chart with standard deviations, and Figure b presents the same results as a box-and-whisker plot excluding oysters, given the small sample size and higher average.

The large discrepancies could be explained by many of the diet-level studies mixing results from attributional and consequential LCAs, as well as results derived from other environmental accounting frameworks. Inconsistent considerations of whole and edible yield, as well as land use and land-use change (LULUC), also resulted in large discrepancies. Several dietary studies also included LCIA results from private or commercial databases owned by consultancy groups, which are not publicly available for scrutiny or to reproduce results.

Of the two global warming estimates for oysters, the higher one (65.8 kg CO_2-eq. t^{-1}) is from the Sharp-ID database (Mertens et al. 2019a) which is the foundation for both (Mertens et al. 2019b; Mertens et al. 2019c), and the second one is from (Esteve-Llorens et al. 2019). The Sharp-ID database, unfortunately only refers to 'Other publications' for fish and fish products, with no detail record, while (Esteve-Llorens et al. 2019) refers to a consultancy report from 2011 assessing oyster farming in Scotland (Fry 2011).

In terms of food commodities covered, inventory data and LCIA results remain fragmented or non-existent for many farming practices, which motivated many studies to use proxy impact values. For example, paddy rice, the world's third most produced crop (tied with wheat) (FAO 2018), was only represented by a handful of LCAs up to 2010. Of these, many dietary studies extrapolated impacts from trivial farming systems having trivial production volumes relative to global production volumes, such as Vercelli (risotto) rice and US rice. While progress has been made over the last decade to characterize more farming regions, many authors still fail to weight production volumes when generating global averages (Ziegler et al. 2022). There is also a persistent overrepresentation of food production in the Global North, which might compromise global dietary recommendations.

Other questionable practices include: the use of impacts of whole crop or animal at farm-gate as proxies for impacts at consumption (excluding the conversion to edible yield and processing);

disregard of uncertainty and variability; exclusive focus on global warming; and reporting too many significant digits.

Discussion and Recommendations

Large discrepancies among environmental proxies for individual food commodities and limited reporting on their origins were commonplace across the dietary footprint studies reviewed. For example, the discrepancies across global warming estimates for oysters and shellfish ranged by an order of magnitude. Shellfish also performed fairly poorly in terms of global warming compared to other blue foods, which is in contradiction to several studies with a more narrow focus on blue foods (Aubin et al. 2018; Parodi et al. 2018; Gephart et al. 2021). This could partially be explained by the scope of the limited number of available shellfish LCA studies, but also underlying modeling choices related to edible yield, transportation, processing and packaging, the inclusion of infrastructure, and carbon dioxide sequestration and emissions from shell formation (Iribarren et al. 2010; Aubin et al. 2018; Ray et al. 2018).

In many instances, none of the authors had ever published any LCA studies of their own. This could in part explain why many fundamental methodological choices of LCAs were overlooked or unexplained. Our research highlights several issues that need to be considered when comparing and potentially combining LCIA results of different food commodities in diet-level studies, including:

- The representativeness of primary LCA results, including production volumes, geographical, technological, and temporal aspects.
- Methods used by primary LCA study authors, including co-product allocation, LULUC, and system boundaries.
- Edible yields, by-product utilization, and emissions from processing and distribution.
- Defining logical bins when assigning commodities into certain food groups.

The strong influence of modeling choices on LCA results, however, challenge the usefulness of assembling LCIA datasets from independently created LCA models. Even if great efforts have been made to provide harmonized methods for LCAs, including the Product Environmental Footprint (PEF), the sheer number of case specific choices that LCA modelers are faced with suggests that LCA data should first be assembled as LCI data before being characterized. This would, in turn, require more elaborate LCA models and platforms, and motivate the full disclosure of inventory data. To support frontrunner corporations to develop such public datasets, governments should develop policies creating a level playing field for this and promote standardized reporting formats. To promote higher resolution in sustainable dietary recommendations and more consistent reporting, future efforts are conclusively better invested in supporting collective efforts to assemble unit process and LCI data, than to repeat the redundant practice of assembling LCIA datasets from individual LCA studies.

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Environmental Impact and Nutrient Adequacy of Derived Dietary Patterns in Vietnam.

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Keywords: *greenhouse gas emissions; blue water use; dietary diversity; nutrient adequacy; dietary patterns; food system.*
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Rationale and objective

Improving diet quality while decreasing environmental impacts is an important challenge for the food system (Canales Holzeis et al. 2019; Willett et al. 2019). Few studies so far have investigated diet quality in Vietnam and its potential impact on the environment (Heller et al. 2020; Trinh et al. 2021). Therefore, this study aims to analyse the most common dietary patterns of Vietnamese women and explore the diet quality and environmental impacts of these patterns.

Methodology

The nationally representative General Nutrition Survey of 2009-2010 was used to analyse the dietary patterns. Dietary patterns were derived using principal component analysis (PCA) by using 18 food groups as input variables. Nutrient adequacy and dietary diversity scores were applied to measure diet quality, and greenhouse gas emissions (GHGE) and blue water use were selected as environmental impact indicators.

Main results and discussion

With PCA, three dietary patterns were identified: An Omnivorous, Traditional, and Pescatarian pattern. All three patterns were associated with better diet quality compared to the average diet although not substantial. The average diet-related GHGE was 4.51 kg CO_2-eq. and blue water use was 0.12 m^3. The analysis revealed the consumption of rice, meat, and meat products contributed most to the GHGE in this population, and rice was the largest contributor to BW use. Environmental impact was considerably higher in all three patterns compared to the general population.

Conclusions

Despite that diet quality was slightly better in all three patterns compared to the average diet, environmental impact was also higher. It is important to explore the trade-offs between diet quality and environmental impact. Therefore, future research is needed to develop the optimal diet that considers both diet quality and environmental impact.

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Environmental consequences of reducing the share of animal proteins in a nutritionally adequate diet modeled for the French population

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Context: The actual food system is a major threat to sustainable development by driving the global earth system toward or over planetary boundaries (Willett et al., 2019). Thus, reducing animal protein in the diet is a key target of sustainable food policies to address current health and environmental issues. However, adopting a plant-based diet limits intake of important animal-driven micronutrients, especially vitamin B12, vitamin D, riboflavin, calcium, iron and zinc and may compromise diet acceptability and affordability (Fehér et al., 2020). Therefore, we conceived this study to evaluate the environmental impacts of reducing protein share contributed by animal-based foods in nutritionally adequate diets that respects consumption and cost constraints.

Methods: From observed dietary intakes in the general French population (INCA2) and a database of 207 foods compiling nutritional and cost data (Gazan et al, 2018) new diets minimizing deviation from observed diets (in term of food quantity) were modeled by mathematical optimization for 5 sub-populations: women < 50 years old, women between 50 and 64 years old, women ≥ 65 years old, men < 65 years old and men ≥ 65 years. All modeled diets met nutritional recommendations (for fiber, amino acids, fatty acids, minerals, vitamins, sugar, sodium and saturated fatty acids), eating habits and cost constraints of the sub-populations. For each subpopulation, the share of protein contributed by animal-based foods was progressively reduced by steps of 5% until constraints couldn't be no longer met. The recommended intake of total protein was estimated from the average body weight of the corresponding subpopulation observed in the general French population. For each subpopulation, the modeled diet with the lowest achievable animal-protein share, but meeting recommended total protein intake was selected. The five selected modeled diets were then aggregated applying weights of representativity of each sub-population leading to one modeled diet for the whole population (LAP diet). The LAP diet was compared to the mean observed diet in the whole population (Ref diet). Potential environmental impacts of LAP and Ref diets were estimated by Life Cycle Assessment (LCA) using eight midpoint environmental impact categories, provided by ReCiPe mid-point method (Huijbregts *et al*. 2016): climate change (CC), acidification (AC), freshwater eutrophication (FE), marine eutrophication (ME); by CML-IA method (Guinée *et al*. 2002): water use (WU), land occupation (LO); cumulative energy demand (CED – Frischknecht *et al* 2004) and biodiversity damage potential (BDP - Knudsen *et al*. 2017). The life cycle inventory data were extracted from Agribalyse© 3.0 (Asselin-Balençon et al., 2020; Koch and Salou, 2020), and adapted to allow the use of the characterization factors of the Knudsen method.

Results: The animal-protein share in the LAP diets varied depending on the subpopulation: 45 % for men < 65 years, 50 % for women between 50 and 64 years, 55 % for women < 50 and ≥ 65 years, and 60 % for men ≥ 65 years. Total protein content of the LAP diets was similar to the one in Ref

diets for women < 50 and ≥ 65 years, and decrease for other subpopulations (from -7 % for women between 50 and 64 years, to -29 % for men < 65 years). At the whole population level (weighted average of sub-populations), starting from an animal protein share of 70% in the Ref diet, it was possible to reduce that share up to 50% while still fulfilling nutritional, cost and consumption constraints (LAP diet). Compared to Ref diet, LAP diet contained (g/d) more plant-based products including fruits, vegetables, grains, potatoes and pulses (987 vs 570), less meat, fish & eggs (95 vs 156), less sweets & added fats (103 vs 146) and less mixed dishes & sandwiches (65 vs 123). Regarding dairy products, their quantity increased (350 vs 200) but the calories they provided slightly decreased due to a shift from cheese to liquid milk. Changes in environmental impacts were relatively similar across the subpopulations. Compared to the Ref diet, 5 out of 8 environmental categories were improved in the LAP diet (Fig.1): AC (-39.5 %), LO (-35.6 %), CC (-29.8 %), ME (-12.8 %), and CED (-6.5 %). Impacts related to FE, WU and BDP were increased by respectively 36.1 %, 41.2 % and 71.3 %. For all impact categories, except for AC and BDP, the food groups "Meat/Fish/Eggs" and "Fruit and vegetables" were the main contributors of the environmental impacts of the LAP diet, and were responsible together for 43.6 % (for CC) to 74.9 % (for WU) of the total environmental impact of the diet. For AC, the two main contributing food groups were "Meat/Fish/Eggs" and "Water and drinks" and for BDP, "Fruit and vegetables" and "Grains and other starchy products". The reduction of CC, AC, LO, ME and CED in the LAP diet was mainly driven by the strong decrease of red meat whose environmental impact was reduced by almost two thirds. The decrease in CED attributed to red meat (-25.8 MJ) was offset by the increase in dried fruits in the diet (+21.3 MJ), resulting in a slight overall improvement for this indicator.
Conversely freshwater eutrophication, water use and biodiversity damage potential were deteriorated. The higher environmental impact of the LAP diet on WU and FE were mostly explained by the increase of fresh fruits which includes irrigated production and fatty fish (exclusively salmon from aquaculture), respectively. Increased BDP was caused by a sharp decrease in permanent pasture acreage due to lower red meat consumption and clearing of additional land to meet the higher demand for vegetables.

Discussion: The current study highlighted that lowering animal protein share below 50% would be unlikely in the French general population without compromising nutritional adequacy and acceptability, and would have mixed effects on the environment. An important reduction of bovine meat was observed in the LAP diet, inducing a reduction in several impacts such as CC and LO, but also an increase in BDP, due to the high level of biodiversity associated to permanent pasture used by the beef sector, in opposition to the intensive crop cultures. Indeed, greenhouse gas emission and land use of cattle (corresponding to approximately 60 % of red meat in our data) are much higher than other livestock products such as dairy beef, pig and poultry (Poore and Nemecek, 2018). A large increase in WU associated with the LAP diet is due to the increase of irrigated fruit and vegetable products in the diet. The adverse effect on WU (blue water) is consistent with previous global modeling analyzing of sustainable diets that showed that increased consumption of water-intensive fruits, vegetables, and nuts was likely to overcompensate lower WU from decreased animal product consumption (Springmann et al., 2018; Willett et al., 2019). The increase in FE was mainly due to the higher emission of phosphorus to water due to the culture fertilization and to the direct emission of effluent of the aquaculture fish to water where there is no recycling possibilities. It should be noted that in the Agribalyse method (Koch and Salou, 2020), the impacts associated with the application of livestock manure on crops for fertilization are associated with crops, not with livestock.
Different points have to be kept in mind when looking at these results. They are sensitive to the database of products. Our study benefits from the use of the most exhaustive database of the French agri-food products LCIs (Agribalyse® 3.0), which allowed to consider a large set of products in the analysis while ensuring a good representativeness of environmental impacts of agricultural and food products consumed in France. However, this database is built on averages of French agriculture

practices which may induces some limitations. Here, the Agribalyse data are the main stream of French agriculture products and do not take into account particular practices (e.g. organic production). Moreover, several flows were not taken into account such as carbon sequestration in soil without land use change in France, or particulate emissions from on farm activities (Koch and Salou, 2020), which will be improved in the future versions. The results are also sensitive to the characterization methods. For instance, the biodiversity damage is only associated to specific land use whatever the practices (the differentiation of organic products was not used here). This study uses the approach proposed by Knudsen et al. (2017) that estimates the potentially disappeared fraction of species of a given land use compared to a reference ('temperate broadleaf and mixed forest' for Europe). In particular, it differentiates the major crop categories and pasture, and we added the impact of imported culture from tropical areas. Some limitations of this approach have been presented among which the non-consideration of advantages of mixed landscapes and the focus made on plant species (Kok et al., 2020). Based on the average of observed performances, this method considers the land use but not the direct relations between agriculture practices and biodiversity as proposed by other methods (Lindner et al., 2019). This method has however been judged as relevant to assess the biodiversity impacts of livestock and crop systems, and had been used in previous studies to compare organic and conventional agriculture practices (Nitschelm et al., 2021). The influence of the reduction of red meat on biodiversity observed in our study is mainly driven by the use of pasture in French dairy and beef productions, as proposed by the Agribalyse® 3.0 database, which is not the general trend at world scale. The reduction in meat consumption led to a very strong reduction in LO, but since permanent grassland is a biotope much richer in biodiversity than any other agricultural land use (including replanted forest) (Alkemade et al., 2009) the gain in LO translates into an equivalent loss on BDP.

Conclusion

The objective of this study was not to design a low environmental impact diet but rather to assess the environmental impacts of diets modeled to contain the minimum share of animal protein, compatible with the fulfilment of all nutrient-based recommendations at no cost increase. In our study, the models were unable to lower the animal-protein share below about 50 % (except for men < 65 years where a threshold of 45 % was reached) without compromising nutritional adequacy, eating habits and at no additional cost. It has already been shown that going below this 50 % threshold will not ensure protein and indispensable amino acid adequacy in the French population (de Gavelle et al., 2017). The tradeoffs between several environmental impacts highlight the importance of considering the consumption of resources and pollutant emissions as diverse as energy use, water use, air pollution, nutrient flows, and biodiversity when designing sustainable diets. Achieving a more balanced plant and animal-based diet may require major transformations in agriculture and food systems, as well as food practices, in order to meet the three major concern of the planet: climate change, water consumption and biodiversity preservation. This objective cannot be reached without taking into account the specificity of the territories and the availability of their resources, but also the food habits of the inhabitants. This will require also the evolution of evaluation methods that will have to better take into account the cause and effect relationships between practices (agricultural, food) and the environmental, economic and health consequences. In particular, specific objectives such as the protection of biodiversity will have to be studied in depth, in order to move from injunctions to practical solutions.

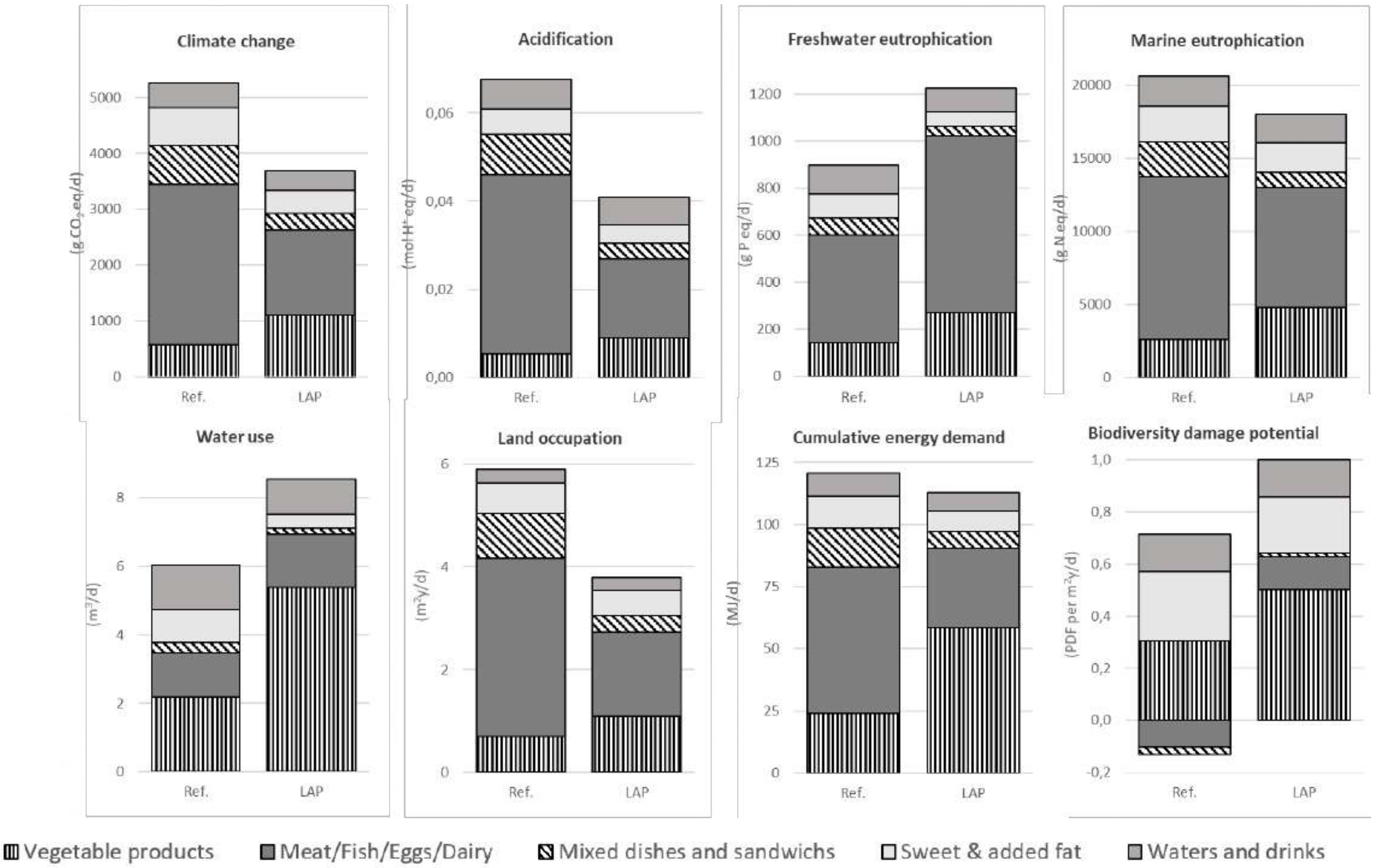

Figure 1: Environmental impacts of reference and low animal protein (LAP) diets of average French population.

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Environmental impacts of patients' dietary habits in the context of the onset of diseases of affluence

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Keywords: *LCA; environmental impacts; health; planetary boundary diet; diseases of affluence; prevention*

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The causes of a disease can be very complex. At the same time, it has been shown that dietary habits can increase the risk of the onset of a number of diseases, such as the consumption of processed red meat in connection with colorectal cancer (WCRF 2018). In times of climate change, our dietary preferences take on another dimension. Enormous environmental impacts are associated with food production, and the transition to more sustainable food systems is inevitable (Poore and Nemecek 2018).

Animal products in particular have the highest environmental impacts (Poore and Nemecek 2018). Plant-based diets are generally more environmentally friendly, especially if they consist of local and seasonal foods (Van Kernebeek, Oosting et al. 2014). From the point of view of health, the consumption of vegetables and fruits can for example reduce the risk of the onset of certain diseases, while the consumption of red meat increases the probability of the occurrence of some types of cancer (WCRF 2018). The World Health Organization (WHO 2021) and the EAT-Lancet Commission (Willett, Rockström et al. 2019) have published recommendations on healthy diets within the planetary boundaries.

This project develops the issue of diseases that are the result of lifestyle; also called diseases of affluence (Huryk, Drury et al. 2021). These first occurred mainly in developed countries (Żółtaszek and Olejnik 2018), probably due to lack of exercise, excessive consumption of food (especially of highly processed, fatty and salty foods), and exposure to stress (Sachs 2017).

Here, we studied eating habits of patients in terms of environmental impacts. Moreover, the health and environmental risks and benefits associated with the consumption of certain foods were mapped. When we juxtapose the diets of patients before diagnosis, the average diet in the country, and the nutritional plan recommended by the doctor; where do they stand in terms of environmental impacts? Throughout this project, the above-mentioned scenarios were modelled and compared based on the life cycle assessment (LCA) methodology (sphera 2020) in openLCA software using EF 3.0 characterization factors.

To the best of our knowledge, no comparison has yet been made of the environmental impacts of the diets of patients diagnosed with a disease of affluence. This is, however, not only a matter of scientific interest. At a time when sustainability becomes a hot topic, the environmental benefits of a dietary change may represent a great motivation for many while considering a switch to diets healthier for both humans and the planet; possibly leading to more effort being spent on disease prevention. At the same time, the health crisis caused by the covid-19 pandemic could lead to the promotion and development of preventive measures and increase the popularity of healthy lifestyles in general (Sabetkish and Rahmani 2021).

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Biodiversity impact of the Dutch diet: comparing two metrics

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Keywords: *Diet, Biodiversity metrics; food; life cycle assessment (LCA); mean species abundance (MSA).*

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Rationale and objective

We find ourselves in the 6th global extinction wave (Ceballos et al., 2015; Cowie et al., 2022; Ripple et al., 2017), and the global food system is a large contributor to this crisis (Benton et al., 2021). To tackle this, setting up strategies, such as the EU's biodiversity strategy for 2030 (Commission, 2020), and defining clear actions, commitments and methodologies to account biodiversity loss are needed. In this regard, biodiversity accounting in Life Cycle Assessment (LCA) is gaining attention, mainly focusing on species diversity (Marques et al., 2017). New metrics are being developed, mostly on the academic level, but the operationalization and compatibility with existing life cycle inventory (LCI) datasets is required to enable broader implementation (Sanyé-Mengual et al., 2022). The goal of this study is to operationalize and assess the results of two metrics to estimate biodiversity loss related to food consumption, using the Dutch diet as case study.

Approach and methodology

The first metric is the endpoint category of ecosystem quality from ReCiPe 2016 (Huijbregts et al., 2016) (later simply ReCiPe), which measures the species loss (potentially disappeared fraction of species; PDF) over space and time, and it differentiates damages to three different types of ecosystems: freshwater, terrestrial and marine. The second biodiversity metric, which is operationalized within the life cycle approach, is the Mean Species Abundance (MSA) loss metric (Schipper et al., 2016, 2020). The method estimates the mean abundance of original terrestrial species in disturbed conditions relative to the one occurring in an undisturbed area over space (in this case: on a country level) and time. While ReCiPe is already commonly used in LCA studies; the MSA loss method has been identified as a potential pragmatic candidate for inclusion in LCA which would add new information and is readily available for operationalization (Marques et al., 2021).

Currently, the MSA-loss factors cover terrestrial ecosystems and measure the losses in MSA driven by 5 different pressures: land use (cropland, pasture area, forest, urban, mining-energy and mining-non energy), climate change (or: global warming), fragmentation (land use and roads), disturbance (roads, mining-energy and mining non-energy) and nitrogen deposition (NH3 and NOx emissions) (Schipper et al., n.d.). Regionalized MSA-loss factors (loss per unit of pressure) were derived using GLOBIO 4 (Schipper et al., 2016) by aggregating MSA values from individual spatial cells to the country level.
The MSA loss method is operationalized for the Dutch RIVM LCI database (RIVM, 2019). This required the following actions:

1. Adapting the MSA-loss factors from GLOBIO for habitat disturbance and fragmentation of roads from 'per km road' to 'per ton-km road transport' through national total fuel use and

road length for all relevant countries.

2. Regionalization of flows in the RIVM LCI database (ammonia and NOx emissions, land use), through a code which extracts the country where the pressure takes place.
3. Creation of new flows in the RIVM LCI database related to road disturbance (measured in tkm road transport per country) and assessing magnitude of the pressure related to each transport distance. The created code recognizes the source country for each input in an inventory and splits out the total tkm transport over all intermediate countries based on transportation mode and country sizes.
4. Linking the MSA-loss factors to the regionalized (new) impact flows in a standard impact assessment method format.

A detailed hotspot analysis is made for each of the food products in the Dutch diet using both the ReCiPe and the MSA-loss impact assessment method. The original RIVM LCI database is used in combination with the ReCiPe method, the regionalized and adapted RIVM LCI database is used in combination with the MSA-loss method. Results show the impact of different lifecycle stages (cultivation of food and/or feed, animal husbandry, processing, distribution and retail and consumer), the relative contribution of different impact pathways (e.g. biodiversity loss from land use and from global warming) and for MSA-loss results are split out per continent (differentiating between biodiversity loss in the Netherlands, Europe, Asia, Africa, North America, South America, Oceania and in the world in general).
The impact of each food item is multiplied with the consumed quantity in the average Dutch daily diet, which is based on the Dutch Food Consumption Survey 2012-2016 (van Rossum et al., 2018).

Results
For both biodiversity metrics, insights are gathered on the most impactful products in the diet (based on daily consumed quantity) and the most predominant impact pathways. As the same inventory data and diet is used, this study gives insights on how the outcomes differ between both metrics. The absolute results of the two metrics represent other phenomena and are thus not directly comparable: ReCiPe results are expressed as the number of lost (extinct) species, MSA-loss represent the loss of number of animals (abundance) withing the species. For this reason, only relative contributions of product groups and impact pathways to total biodiversity impact are compared.

Based on ReCiPe, main results show that meat (especially beef, but also pork and chicken), dairy and to a lesser extend coffee and tea are main contributors to biodiversity loss of the Dutch daily diet. To be specific, beef and pork represent 32% of biodiversity impact; milk and dairy products represent 17%; non-alcoholic beverages (mainly coffee and tea) represent 8%; chicken represent 7%. In terms of impact pathways, land use (49%), global warming (excl. emissions from land use change: 20%, emissions from land use change: 3%) and acidification (16%) are main drivers of biodiversity loss of the Dutch diet.

Assessment of the Dutch diet with the MSA-loss method results in comparable conclusions: Food items in the Dutch diet contributing most to MSA-loss are beef meat, milk and milk products, chicken, cheese, pork, fats and oils and coffee. On a food group level beef and pork represent 28% of biodiversity impact; milk and dairy products represent 20%; chicken represents 9% and non-alcoholic beverages (mainly coffee and tea) represent 8%. Main drivers for biodiversity loss are identified to be land use (44%) and global warming (excl. emissions from land use change: 29%, emissions from land use change: 5%). Habitat disturbance is the cause for 12% of the MSA-loss related to the Dutch diet; nitrogen deposition for 7% and habitat fragmentation for 3%. The GLOBIO model and derived MSA-loss factors are under constant development, and this is the first implementation of these factors in an LCA context. For these reasons, the presented results should be considered as draft results, which might change with additional insights.

The relative contribution of different impact pathways to biodiversity loss found with ReCiPe and MSA-loss method are similar for overlapping indicators. Of the two main impact pathways, ReCiPe characterizes land use stronger, whereas MSA-loss characterizes global warming stronger. The different nature of the metrics (accounting for species loss and species abundance loss) makes that the metrics provide complementary information on the same pressure indicators; more research is needed to exactly identify what drives the differences. Results are in line with the current scientific findings for food consumption in the EU-28, published by Crenna et al. (Crenna et al., 2019).

Several interventions in supply chains are possible to reduce the pressures, and can in general be described as producing more *sustainable* c.q. *responsible*, more *efficient*, or consuming *differently* (Westhoek, 2019). The results suggest that to reduce the impact on biodiversity of Dutch food consumption, interventions on several levels can be effective:

1. On a diet level: replacing consumption of high-impact products such as meat, dairy, coffee and tea for low(er)-impact alternatives, while ensuring all nutritional requirements in the diet are met, is an effective and quick way to reduce the biodiversity impact of Dutch food consumption. Widespread awareness and engagement are required to realize national dietary change and consumer acceptance should be considered to facilitate the process.
2. On a product level: strategies to reduce the biodiversity impact of individual food products can be based on the hotspots in the chain (e.g., cultivation of feed, or energy use in preparation) and the key drivers of biodiversity loss (e.g., global warming, or land use). Interventions can be specific to the production chain of a certain product (e.g., more efficient cultivation), or can benefit multiple production chains (e.g., reducing the impact of electricity production).

Discussion

The operationalization of MSA-loss in LCA enables complementation of insights from existing LCIA methods (such as ReCiPe) with novel insights on biodiversity loss. ReCiPe assesses the biodiversity loss in terms of loss of species richness, whereas MSA-loss is an indicator for species abundance. This makes MSA-loss suitable to account for biodiversity impacts regarding ecosystem multifunctionality (Marques et al., 2021). A strength of the GLOBIO method to derive MSA-loss is the accounting of biodiversity losses on a country level. This provides more insight into where biodiversity is lost, and better represents the spatial distribution of species. This complements ReCiPe, which does not account for the distribution of species (Crenna et al., 2019). The ReCiPe method and the MSA-loss method both account for the impact of land use and global warming on biodiversity, although results provide different insights due to the different unit. In addition, ReCiPe considers the impact on biodiversity through a broad spectrum of midpoint indicators; however, direct factors (such as habitat disturbance) are not accounted for. The MSA-loss factors do not cover all these midpoint indicators, like acidification; however, effects of habitat fragmentation and disturbance are reflected in the MSA-loss factors. Nitrogen emissions (or leakages) are accounted for in both methods, although in MSA-loss only the effect on terrestrial ecosystems is considered and in ReCiPe only effects on freshwater and marine ecosystems are considered. The effect of land transformation is explicitly included in the ReCiPe method (and separately noted from the land use category in this study), whereas this effect is only implicitly included in the land use pressure in the MSA-loss method. Other direct effects on biodiversity such as competitive effects of invasive species, but also positive effects such as nature-inclusive agriculture or agroecology measures are not yet accounted for in either of the methods, mainly due to knowledge gasp on the exact impacts of these modes of production.

The MSA-loss factors currently only assess impacts on plants and warm-blooded vertebrates, due to limited data availability. In addition to these species groups, ReCiPe also accounts for invertebrates and fish although only a small number of species is considered for the impact pathways (Crenna et al., 2019). Accounting of biodiversity losses of marine species can be improved in both methods. The consideration of marine habitat disturbance from fishery and sea transport, and effects of ocean acidification due to global warming might improve this, although data availability remains a limitation.

Solutions to reduce biodiversity loss differ for each diet and product lifecycle, stressing the importance of more research to tailored impact calculation and solutions. Impact assessment studies are performed more and more, however, environmental improvements are currently often focused on reduction of the carbon footprint. Including a biodiversity indicator in the research and results can help to also identify specific measures and government policies that will reduce biodiversity loss. Including guidance on biodiversity accounting in leading LCA guidelines (such as the Product Environmental Footprint guidelines (Zampori and Pant, 2019)) might help to accelerate its implementation. To better understand drivers of biodiversity loss related to our diet, a wider variety of metrics should be operationalized in LCA (Marques et al., 2021; Zhongming et al., 2021). Metrics can complement each other, providing a more complete image of biodiversity impact. Discussion within the LCA community can help to identify the most suitable metrics for each study.

Despite the limitations of the used biodiversity loss method as described in the discussion, this research is a first and relevant step in identifying the biodiversity impact of our diet, and as an extension of footprint analyses on mid-point pressures like carbon emission and land-use. The presented results are sufficient to identify critical products and impact pathways of biodiversity loss and can help to effectively reduce the impact. Further development of biodiversity impact studies on food production systems, and complementary biodiversity indicators and calculation methods is required to cover all relevant aspects, but regarding the urgency of the problem at hand, it is just as important to start doing assessments with the available metrics and act accordingly.

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Consequential Life Cycle Assessment of a decrease in meat consumption based on the Planetary health diet: an application to Slovenia

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Introduction

More sustainable food systems are required in order to counter climate change while safely feeding the growing population. The EAT-Lancet commission developed a planetary health diet (PH diet) that would allow humanity to stay within planetary limits while being healthy (Willet et al., 2019). According to these guidelines, our diet should be considerably reduced in animal-based products and increased in plant-based products. This suggested change in consumption will require a profound rearrangement of our agricultural system.

Although not so commonly used, consequential LCA (C-LCA) appears to be an interesting tool to assess repercussions of a decision and help policies in making decisions. On the opposite of attributional LCA (A-LCA), which assumes a fully elastic market where goods are always available to be supplied, C-LCA is considering revenue maximization and market constraints as well as indirect effects induced by changes in consumption and production. A tool to help identifying marginal crop production is economic model (Brandao et al., 2017). Thus, C-LCA can be seen as a combination between LCA and economic methods.

This combination has been largely applied in the bioenergy sector to assess increase in production of crops intended for biogas (Roos et al., 2018). To a lesser extent in the agricultural sector, C-LCA was applied to ruminants (Salou et al., 2019) or milk production (Thomassen et al., 2008). Kløverpris et al. (2008) developed a methodology for land use, applied to an increase in wheat consumption in Denmark (Kløverpris et al., 2010) while Nguyen et al. (2013) evaluated the consequences of switching from a maize-based silage to a grass-based silage dairy system, due to an increase preference by consumers for grass-based milk in France. Although giving precious information for the C-LCA methodology, diets and consumption changes from one crop to another has not yet been studied.

Therefore, the aim of this study is to evaluate environmental impacts of a shift from meat to legumes, based on the PH diet, using a C-LCA approach. This approach was applied to Slovenia. Firstly, a partial equilibrium (PE) model was created in order to detect changes in land use for crops, based on revenue maximization. Secondly, outputs of this model were used to build the LCA model. Assessing impact categories with Environmental Footprint 3.0, results intend to deliver information regarding a shifting of diets towards less meat and more legumes. With such environmental assessment, it will be possible to analyze to which extent this scenario is feasible and frame tools for changes. We hope to bring new knowledge to take action in this challenge as well as bringing dialogues among decisions-makers and consumers.

Methodology

Goal and scope

The aim of this study is to evaluate environmental consequences of switching from animal proteins to legumes, following the PH diet recommendations. For this, a PE model was combined with LCA. Different scenarios were created such as decreasing meat consumption on one hand and increasing legume consumption on the other hand. The functional unit is the change in the Slovenian diet from 2015 to PH diet from animal proteins (beef and pork) to plant-based proteins (legumes).

The results of this study are intended to engage discussions among policymakers and governments on the possibilities that can be implemented in order to switch consumption towards more plant-based products.

Context

Slovenia was chosen as a case study as it has one of the highest consumptions of meat in Europe, according to EU Menu surveys (EFSA). The area occupied by livestock (permanent grassland and feed production) is about 80% of the utilized agricultural area. Furthermore, 64% of agricultural area was evaluated at risk of soil loss by water erosion in 2016 (agri-food data portal), while the average in Europe is 9%. The consequences for farming are loss of fertility, increased risk of flood and surface. In 2015, the consumption of all meat in Slovenia was 192.38 g/day/capita (FAOSTAT). According to the PH diet, meat should represent up to 6% of the diet or up to 86 g/day/person (Willet et al., 2009). Thus, meat consumption should be about halved. The consumption of legumes is 7.26 g/capita/day and thus should be increased by about seven.

In contrary to A-LCA, C-LCA allows to capture indirect changes caused by a change in the life cycle of the system under evaluation. This is important in order to know which suppliers or producers will be affected by a change in demand within the system and is possible thanks to economic modelling methods. Here, we use a PE model based on positive mathematical programming approach, developed by Howitt (1995), and aiming at profit maximization for farmers. The PE model is detailed in Rege et al. (2015).

Scenarios

Different scenarios were created. The first scenario assumes a decrease in the total area used for fodder crops as a result of a decrease in meat consumption. According to the PH diet, this decrease should be by 50% (scenario 1A) but a decrease by 30% was also tested (scenario 1B). The second scenario focuses on area used for legume crops. According to the PH diet, it should be increased by 14 to compensate for imports (scenario 2B), an increase by seven was also added (scenario 2A).

Table 1: description of the scenarios evaluated

Scenario	Description
Scenario 1: cut in fodder crops	
1A	Total fodder crops area reduced by 50%
1B	Total fodder crops area reduced by 30%
Scenario 2: increase in legumes	
2A	Total legume crops area increased by 7
2B	Total legume crops area increased by 14

System boundaries

The analysis is from cradle-to-gate and considers production at the country level. The processes included in LCA are those of fodder crops, permanent grassland and legumes as well as crops that are subject to change after the shock.

Material and impact assessment

GAMS software was used for the PE model and environmental analysis were performed under OpenLCA 1.10.3. The method used to assess environmental impacts is Environmental Footprint 3.0 (EF 3.0).

Results and discussion

PE model

Tables 2 shows the results from the PE model with revenue maximization for the different scenarios when simulating the respective shock.

Table 2: land use change after the shock in the PE model for the different scenarios compared to the base case

Area (ha)	Base	S1A	S1B	S2A	S2B
Barley	20110	20110	20110	20110	20110
Beans	396	409.497	409.497	2778.414	5557.897
Maize	37743	37743	37743	37743	37743
Wheat (human)	23051	47538.21	47538.21	23051	23051
Wheat (feed)	7684	7684	7684	7684	7684
Grass mixture	31031	31031	31031	31031	31031
Green maize	28734	28734	28734	28734	28734
Dry pulses	4	4.1	4.1	21.586	42.103
Fodder peas	447	447	447	447	447
Permanent grassland	278678	76464.5	157349.9	276278	273478
Total:	427878	250165.3	331050.7	427878	427878

For scenario 1, the total area for fodder crops is reduced by 50% or 30%, but for both 1A and 1B, only permanent grassland is decreased, all other crops stay the same. Beans and pulses are slightly increased, interestingly at the same area for both. It is similar for wheat for human, although the area is more than doubled. However, the total area is reduced compared to the base case, which means there will be available land potentially transformed for other use or left fallow. For scenario 2, the total area for legumes is increased by 7 or 14. It doesn't have any influence on wheat or other fodder crops, only permanent grassland is reduced accordingly, and the total area stays equal.
For all scenarios, the total profit is positive, except for the scenario 2B. When increasing area for beans and pulses, profit per hectare for these two crops becomes negative. Production costs for these two crops is raising exponentially, according to the PE model, and that's also the reason why these two crops are not increased in scenario 1.

LCA

In Figure 1, the environmental impacts for all scenarios and impact categories are shown. Climate change, ecotoxicity and land use are the categories most impacted for all the scenarios, representing between 55% and 61% of the total impact, and especially climate change from 30 to 40% of the total. If the area for fodder crop is reduced by 30% or 50%, the total environmental impact can be reduced from 15% up to 29%, respectively. On the contrary, if the area for legume crops is increased by 7 or 14, the total environmental impact is almost not changed (reduced by 0.01%).

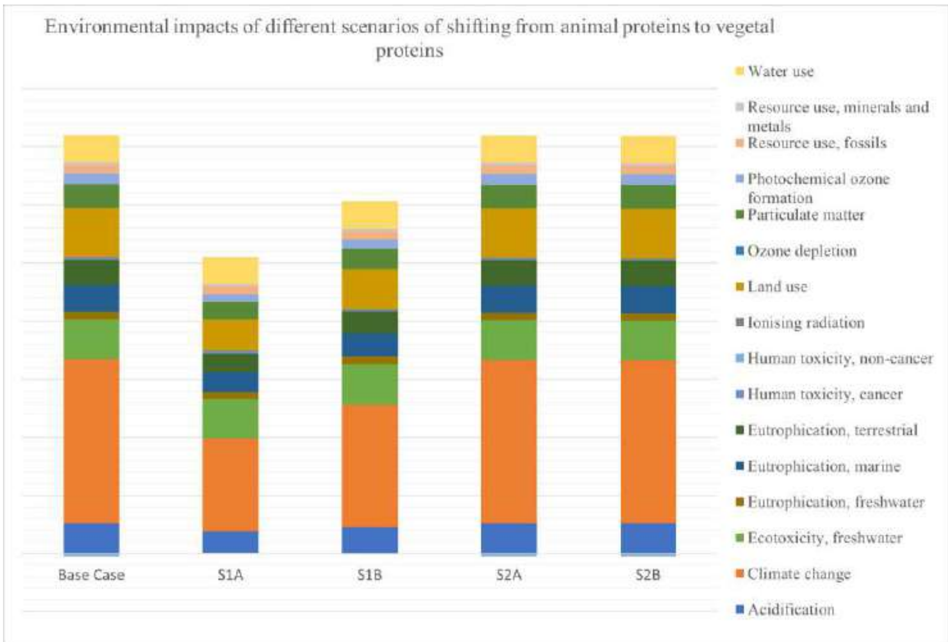
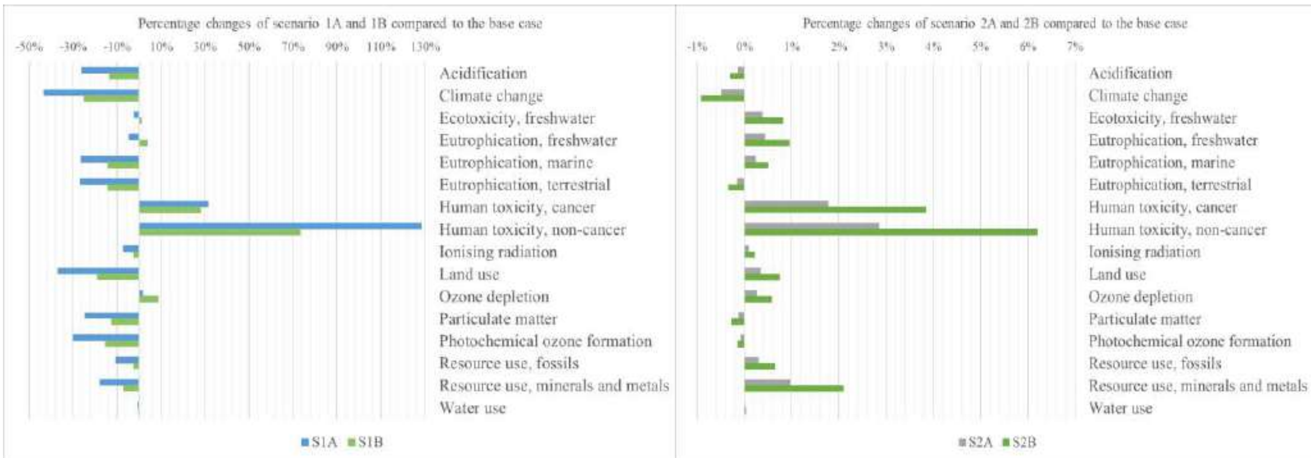


Figure 1: Environmental impacts of a switch in protein consumption following PH diet for all scenarios using EF 3.0 normalized and weighted

Regarding process contributions to the main impact categories, for all scenarios, livestock are contributing the most to greenhouse gases due to emissions from enteric fermentation and manure. Potassium chloride used as fertilizer as well as maize and green maize are the main responsible for ecotoxicity to freshwater, due to the use of herbicides and insecticides and their high land use.

Most of the impact categories are decreased up to 43% for climate change in S1A where total fodder crops area decrease is more important than in S1B. Human toxicity is increased, even though this category has only a minor contribution to the overall impact. Interestingly, we can observe that the percentage of total area decrease is not a linear function of impact categories changes. For example, no matter if the total area is reduced by 50% or 30%, human toxicity (cancer) is increase by about 30%. On the opposite, there are differences in reduction or increase for other categories.
When looking at Figure 1, we observed that the total environmental impact for S2A and S2B is similar to the one from the base case. In Figure 2b, we see nuanced changes but there are too small, just a few percentages, to be relevant. The categories the most increased are the one having only a small share in the overall impact. Beans and pulses have only a low contribution to the overall impact, even when their surface is significantly increased, their land use stays small in comparison to fodder crops.



(a) **(b)**

Figure 2: environmental consequences of a switch from animal proteins to legumes following PH diet, using EF 3.0 normalized and weighted, for: (a) scenario 1; (b) scenario 2

Conclusion

We evaluated environmental impacts of changing diets, in particular proteins from animals towards more plant-based ones. A combination of an economic model and LCA was carried out in order to capture indirect changes. Even though the displacements of crops will also be constrained by climate conditions, crop rotations schemes or soil properties, the PE model allows to take into account market conditions. On one hand, it was found that decreasing fodder crops area leads to an increase in wheat production while environmental impacts are significantly reduced and profit for all crops stays high. It also generates a relevant part of free land. The question on what type of use this land could serve has not been explored but we could imagine that it could be a way for Slovenia to become more self-sufficient by using this land for crops that are now imported. On the other hand, increasing legume crops area to meet protein intake from the PH diet doesn't change environmental impacts to a big extent. Consequently, there are positive impacts to be gained in reducing meat consumption while meeting protein intake's recommendations. Nonetheless, the profit for legumes becomes negative and this will need to be investigated further to find how it could be improved. Furthermore, decreasing or increasing demand for meat or legumes is only theoretical and will need to be translated in terms of policy decisions.

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Methods for optimizing environmental outcomes in crop and livestock systems using predictive analytics and machine learning integrated with LCA

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Keywords: *machine learning; artificial intelligence; predictive analytics; data gaps; agriculture; livestock*

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Rationale and Objective

In addition to environmental performance measurement, life cycle assessment has long been utilized as a methodology to support optimization of product supply chains for environmental outcomes. Advances in data-driven artificial intelligence (AI)/machine learning (ML), including a variety of predictive analytic approaches supported by advanced computing capabilities, are now opening up new frontiers at the intersection of optimization, life cycle assessment, and multi-criteria decision analysis in complement to traditional methods (Solano et al. 2020; Kaim et al. 2018; Utomo et al., 2019; Sharma et al. 2020; Heidari et al. 2021). This introductory talk to the special session on the use of predictive analytics and MCDA in food life cycle management will provide an overview of key techniques and emerging applications in this domain, as applied to food and agriculture, and introduce a decision tree for choice of context-appropriate techniques and associated methodological choices. Examples from on-going research of Canadian egg supply chains will be provided.

Approach and Methodology

A Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) systematic review was used to:

(1) identify and characterize trends in the integrated application of LCA and methods for optimizing environmental outcomes in agricultural crop and livestock production systems

(2) describe the strengths and limitations of existing methods based on decision-type

(3) derive a decision tree for selection of best-fit methods for different application contexts for life cycle-based optimization of environmental outcomes in agricultural crop and livestock production systems

Main Results and Discussion

The three primary decision types for environmental management of agricultural systems are strategic (usually made by governments or other national or global decision makers), tactical and operational (usually made by farmers) (Carravilla and Oliveira, 2013). Within this context, farm benchmarking, output prediction and resource use management are the three most commonly considered applications of predictive analytic methods in integrated LCA/optimization research of crop-livestock production systems. Benchmarking refers to identifying the most efficient agricultural operations within a given population as a reference point for efficiency improvements (Kahan 2013). Data envelopment analysis, which typically supports short to mid-term tactical and operational decisions (for example, the timing of farm operations such as sowing, irrigation and harvesting), is the most common benchmarking technique. It has already been applied in concert with LCA by a variety of researchers (for example, see Grados and Shrevens 2019). Neural networks are most conducive to predicting farm outputs or environmental impacts (for example, see Elahi et al. 2019). They are typically used to support strategic or tactical decision making. Mathematical programming (including linear, non-linear and mixed-integer programing) and evolutionary algorithms can be used to support all decision types, but are most commonly applied to tactical and operational decisions. Resource use management (for example, optimizing the type and amount of seed, crop protection products, fertilizers, fuel, and water use) is the most commonly reported application (for example, see Breen et al. 2019 or Pishgar-Komleh et al. 2019). A generalized decision degree for selecting best-fit methods, along with required methodological choices, for specific optimization objectives in crop-livestock systems is presented in Figure 1.

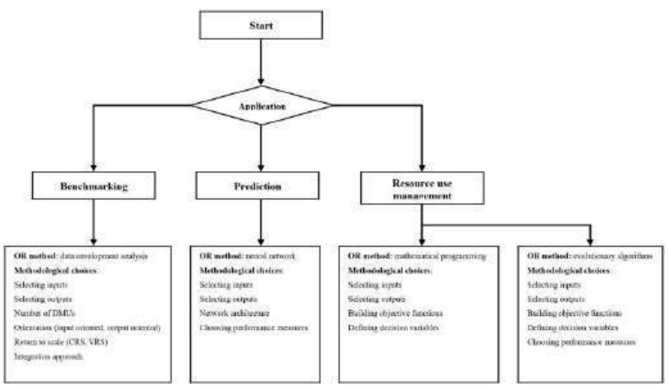

Figure 1. A generalized decision tree for selecting best methods for optimizing environmental outcomes in crop-livestock production (from Heidari et al. 2021).

Conclusion

Sustainability decision making in crop-livestock production systems can be supported through integrated application of LCA and both traditional and emerging, ML-based optimization methods. These include DEA for benchmarking; neural networks for prediction; and mathematical programming or evolutionary algorithms for resource management. Our generalized decision tree provides guidance for practitioners with respect to best-fit methods and associated methodological choices for life cycle-based agricultural sustainability research in this emergent, interdisciplinary domain.

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Multi-objective integrated decision support system of insect production

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Keywords: Life cycle assessment, Ecological-economic modelling, Decision support tool, Multi-objective optimisation

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Abstract

Purpose
Life cycle assessment (LCA) of insect production can estimate social, economic, and environmental impacts. When insects are used as feed and food, multiple sustainability facets must be considered, including food and feed production regulations, factors that affect nutrition, social acceptance, and regulation of greenhouse gases. Thus, it is challenging to consider all sustainability indicators (SI) and to select transformative factors that can improve one function without unintended consequences on other objectives. Decision systems based on multi-objective optimization (MOO) can identify trade-offs between different objectives for management. That is why the aim of this study was to develop a framework for the application of MOO algorithms in insect production chains.

Approach
The multi-objective integrated decision support system is based on (i) LCA; for which we use two impact methodologies- IMPACT 2002+ LCIA methodology (Jolliet et al., 2003) for environmental impacts and for water scarcity we use the IMPACT World+ methodology (Bulle et al., 2019); (ii) multi-objective analysis, particularly analytic hierarchy process (AHP) (Russo and Camanho, 2015); and (iii) non-dominated sorting genetic algorithm (NSGA-II) (Deb et al., 2002). LCA-based framework methodology is used to quantify the environmental, social, and economic sustainability performance. AHP is applied to evaluate and rank different alternatives based on the judgment of decision-makers. NSGA-Ⅱ multi-objective optimization technique is employed to obtain a set of Pareto-optimal solutions that cover all considered sustainability indicators.

For this framework, we consider three conflicting objectives for the optimization of sustainable insect chains; the operating profit, social and environmental impacts that should be optimized simultaneously. The equations for calculating these objectives are shown below in Eqs. (1,4,5).

Table 1: Main objectives of insect production

Objectives	Equation	
Economic aspect	$max\ f_1 = (P - EWC - R) * \sum_{fd \in FD} (FCE_{fd} * AIF_{fd})$ $-\mathrm{RW} * \mathrm{NL} * 12 - \sum_{fd \in FD} (feed_{fd} * AIF_{fd})$	(1) (Bosch et al., 2019)
Social aspect	$FWP = \frac{RW}{RWT} * \frac{CWT}{MLW} * (1 - IEF^2)$	(2) (Gurcanli et al., 2015; Neugebauer

	$LS = \sum_{(e \in E, x \in S_C)} (CPPE_{e} * Eq_e) + NL * SF_{L_S} + Sc_s$ $max\ f_2 = W * FWP + (1 - W) * LS$	et al., 2017)
Environmental aspect	$min\ f_3 = \sum_{(fd \in FD, s \in Sc)} \frac{AIF_{fd}}{FCE_{fd}} * (1 - FCE_{fd}) * FrSF_s * Sc_s$ Or f_3 calculated by IMPACT 2002+(Jolliet et al., 2003); ReCiPe 2016 ((Huijbregts et al., 2016)	(3) (Huijbregts et al., 2016; Jolliet et al., 2003)

Note: P is the price of 1 ton of insect protein (€); EWC energy and water cost necessary to produce 1 ton of insect production, FCE_{fd} feed conversion efficiency; RW real average wages; NL number of labourers; FD set of feed; R rent for 1 ton of insect production; FWP fair wage potential; RW real wages (€/month for annual period) paid to workers employed in process of insect production; RWT real working time (hours/week) of workers involving in production process AIF amount of insect feed (dry matter basis); FrSF frass scaling factor (depends on insect species, scale of production and growth conditions); E_e electrical energy; *FP* feed preparation (conditioning); RW real wages (€/month for annual period) paid to workers employed in process of insect production; RWT real working time (hours/week) of workers involving in production process; CWT contracted working time (hours/week);MLW minimum living wage; *IEF* inequality factor (express in percentage and vary by region); LS labor safety; *CPPE* cost of personal protective equipment; Eq equipment; *SF* scaling factor depend on scale of production;

The three objective functions presented above are in conflict as f_1 disfavors RW and NL and can be maximized by maximizing FWP fair wage potential and LS labor safety whereas on the other hand f_2 social aspect need maximization of RW and NL. Similarly, economic and environmental impacts are also in conflict as by increasing AIF_{fd} one can increase the profit but at the same time it can increase the environmental impacts.

To obtain pareto-optimal scenarios that consider all three objectives, the version of NSGA-II implemented in Python3 using inspyred package (Garrett, 2015) for multi-objective optimization

Results and Discussion

Insect production chains represent the food production system in miniature. Like any cultivated animals, they are characterized by high environmental impacts of feed production. The production of one metric ton of black soldier fly (BSF) larval meal to replace 0.5 metric tons of fish and soybean meal resulted in reduced land use and increased energy use, as it is similarly reported for mealworms. Another parameter in the framework is the nutrients aspect of insects. BSF larvae, for example, contain high levels of protein (37–63%) and fat (20–40%) that have well-balanced amino acid and fatty acid profiles. It is, therefore, logical to include the aspects of feed production and their nutritional suitability for insects as one of the key factors.

Furthermore, the efficiency of insect production is determined by the feed conversion efficiency and associated factors of produced biomass and insect frass. Insect production chains can vary dramatically not only due to the variations in species but also due to the "industrial setup" of companies that often rely on by-products (feed, heat, energy) from other industries. Therefore, all aspects of resource demand and emissions would integrate into a single score (using the developed systems, e.g., IMPACT2002+) applicable as an objective in MOO.

Another integrated measure reflecting the efficiency of insect production is associated with total annual costs. The cost of insect production depends on multiple factors such as capital investment, cost of raw materials, utilities and labor, and of course, the overall efficiency of production. Any losses, gains, or high costs from insect processing will be reflected in this single value.

Social factors and impacts of insect production are arguably the hardest to estimate. From one side insect production provides working places and income. On the other side it could trigger certain health issues for workers (e.g., allergies). Therefore, the developed framework included fair wage potential (FWP) developed as a characterization factor (Neugebauer et al., 2017) and labor safety, interpreted through the monetary value of personal protected means, provided to workers in the production. The developed framework will be tested on Life cycle inventory datasets and scenarios developed for various insect species currently produced for food and feed in Europe.

Conclusion

The developed framework can demonstrate its effectiveness in identifying hotspots in the insect production system that require further improvement. The framework's findings will assist decision-makers in the insect production industry in incorporating sustainability into insect production products, processes, and activities. For the concept of insect production sustainability to be implemented on a large scale, environmental accounting methods that include holistic environmental, economic, social, and technical information are required.

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Classification of Canadian egg farms according to life cycle impacts using clustering and random forest

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Keywords: *Egg; Principal component analysis; Clustering; Classification; Random forest.*

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Rationale and Objective: Food systems make large contributions to many environmental impacts (Crippa et al., 2021; Pelletier and Tyedmers, 2010). Since the mid twentieth century, improvements have been made in the environmental performance of egg production systems compared to historical levels (Pelletier, 2018). However, as egg production is one of the fastest growing livestock sectors (Govoni et al., 2021), further improvements must be realized for egg production to maintain a sustainable role in human nutrition looking forward.

Understanding the sources and differences in impacts characteristic of egg farms is important to improving sustainability outcomes. A key step towards this goal is enabling farmers to assess and benchmark their performance relative to their peers, and set sustainability goals accordingly. Farm-level decision support tools enable farmers to do this; however, only a small portion of these are based on life cycle thinking, and issues remain in regards to the rigour, consistency, and accuracy of these tools (Arulnathan et al., 2020). One potential alternative to these tools to allow farmers to estimate their performance relative to their peers is a classification model capable of classifying farms as low-, average-, or high-impact based on their total life cycle environmental impacts. Further, development of these models using non-traditional LCI data (i.e. data on farm characteristics and management practices rather than input/output data) may help simplify application and increase uptake by decreasing data requirements. The goal of this work, therefore, is to investigate differences in life cycle impacts of Canadian egg farms, identify clusters of farms with similar life cycle environmental impacts, and then develop a model capable of classifying farms into these respective clusters based on non-traditional LCI data.

Methods: In 2019, surveys were administered to Canadian egg farmers to collect data characterizing farm-level inputs and outputs, housing system characteristics, and management practices across housing systems. These data were used to develop 159 individual farm-level LCI models using similar modeling principles as those previously described (Turner et al., 2022). The models were generated automatically in OpenLCA version 1.10.3 (GreenDelta, 2020) using the python-based olca-ipc (GreenDelta, 2021). Farm-specific allocation factors for eggs and spent hens were calculated based on gross chemical energy content. These models were not regionalized, and used average Canadian electricity grid mixes, feed formulations, transportation assumptions, etc. As such, differences in farm-to-farm LCIA results are driven solely by reported differences in farm-level resource use. LCIA calculations were initiated manually using the CML 2 Baseline 2000 impact assessment methodology (Universiteit Leiden, 2016)

LCIA results for 10 impact categories for each farm were scaled using the standard scaler, and principal component analysis (PCA) was performed to reduce dimensionality prior to clustering. Three principal components were retained for clustering, cumulatively representing ~97% of the variation in the original data. Finally, the feature vectors of the retained principal components were scaled using the MinMax scaler, and k-means clustering was performed on the retained components with k = 3.

Following clustering, silhouette scores were calculated to determine how well clusters were differentiated from one another. High silhouette scores (avg: 0.74) indicated clusters were sufficiently differentiated from one another to use cluster membership as a response variable for development of classification models. Random forest was chosen as the framework to develop these models. Using this framework, 100 different classification trees are generated, each considering a number of predictor variables equal to the root of the total number of predictors. The random forest framework is particularly well suited for generation of models when predictor variables may be correlated, or when some predictor variable(s) dominate the classification decision.

Two random forest classification models were generated. The first model was developed using 16 predictor variables related to housing and manure management systems, spent hen valorization methods, mortality rates, and lay cycle lengths. The second model was developed using 12 predictor variables unrelated to housing system type. Models were developed and tested using a 75/25% train/test split, after which model performance was assessed based on misclassification rate. All processing of LCIA results and classification model generation was done using the sklearn Python package (Pedregosa et al., 2011).

Results and discussion: Farms were divided into 3 clusters. The low-impact cluster 1 contained all organic farms in the sample, while the high-impact cluster 3 contained 16 conventional farms, all with liquid manure management systems. All other farms in the sample were sorted into the average-impact cluster 2, regardless of housing system. Clustering of all organic farms together is unsurprising as previous studies indicate the environmental impacts of organic production to be much lower than those of any other housing system due to lower impact feeds (Pelletier, 2017; Turner et al., 2022). That all farms in the high-impact cluster have liquid manure management systems in similarly unsurprising, as manure management is a large contributor to many environmental impacts in egg production (Turner et al., 2022), and liquid manure management systems are generally associated with much higher levels of ammonia and methane emissions compared to solid management systems (Ershadi et al., 2020). Interestingly, however, use of a liquid manure management system does not perfectly predict cluster membership, as there are two enriched farms with these systems included in the average impact cluster 2.

Two random forest classification models were subsequently generated using cluster membership as a response variable. The first model included variables related to manure management systems, and housing system type, resulting in a model that perfectly classified the testing data. This is likely due to the clear delineation in housing systems and manure management practices between clusters. In contrast, the second model using housing-system agnostic predictor variables classified testing data with 82.5% accuracy. Overall housing and manure management systems were the most important variables for predicting cluster membership, measured by decreases in node impurity within the generated decision trees. In the absence of these variables, percentage of eggs discarded on farm, mortality rate, and lay cycle length were the most important predictor variables for predicting cluster membership.

Conclusion: This study represents the first application of random forest classification of individual farms based on life cycle impacts. Both models perform well in terms of properly classifying the training data sets, and could provide egg farmers an easy way to estimate their life cycle environmental performance relative to their peers with relative ease based on alternatives to traditional input/output LCI data. Joint application of LCA and cluster analysis, and LCA and classification modeling remains a relatively nascent field that could provide substantial value to sustainability improvement initiatives in many industries. In the future, research must continue to develop these methods to ensure the use of methodological best practices from both an LCA, and machine learning perspective. Such research may focus on topics related to dimensionality reduction, choice of ideal clustering method, and identification of best-fit classification frameworks.

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DEXi-Dairy, a multi-criteria method for assessing farm sustainability in key European dairy production areas

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Keywords: *Multicriteria assessment, sustainability tree, GHG mitigation, dairy systems.*

Context:

EU accounts for 32% of the world's milk production, thereby ranking as the largest producer among the global regions (Segerkvist et al., 2020). With annual emissions of 195 Tg CO_2-eq, the dairy sector is also the highest agricultural greenhouse gas (GHG) contributor within the EU-27 (Lesschen et al., 2011). Over the past decade, growing awareness of environmental problems associated with livestock production, volatility in farm incomes, and animal welfare concerns have reinforced the need for sustainable food production systems. In this context, European dairy production faces many challenges related to environmental, economic, and social dimensions of sustainability, with particular regard for the need to assess and eventually mitigate GHG emissions. Therefore, holistic assessment tools are required to inform how best to achieve greater sustainability across the three dimensions. To meet this requirement, the objective of the Milkey project was to develop a whole system approach to identify optimal GHG mitigation strategies in dairy production systems (DPS) based on a multi-criteria sustainability assessment (MCA).

Methods:

The MCA was conducted within the DEXi framework (Bohanec, 2020). DEXi is a software program that deals with multi-attribute decision-making. From an expert perspective, it associates a hierarchical decision model based on qualitative attributes. These attributes are organized in a tree structure allowing to build dependencies between attributes of different levels. Each decision is represented by a set of attributes, where the attributes of the first level are assessed individually and then aggregated into increasingly comprehensive levels. The attribute values are discrete and expressed with qualitative statements such as "low, medium, or high" determined through a scaling procedure (Craheix et al., 2015). The first step of the model development was to define attributes organized in principles, criteria, and indicators (PCI) for each sustainability dimension (environmental, economic, and social) in separate working groups. The choice of PCI was guided by three objectives, i.e., i) to best describe the main challenges faced by European dairy production systems (DPS), ii) to point out synergies and trade-offs across sustainability aspects, and iii) to help identify GHG mitigation strategies at the farm level. The second step was to define qualitative scales for each PCI element, as well as utility functions that aggregate each level of the tree. At each node, the upper-level score was calculated based on weighting factors attributed to each PCI element from the lower level. The weighting factors were provided as a result of a consensus between the project's partners, throughout several participative workshops. Finally, a list of data requirements was developed based on selected indicators to guide the data collection in case study farms, and, test the model with real data.

In the environmental dimension, we selected 22 indicators grouped into 4 principles: best dairy herd management practices, environmental quality, abiotic resources conservation, and biodiversity conservation. Five of the indicators were derived from LCA impact categories (i.e., climate change potential, eutrophication potential, acidification potential, heavy metal balance, and cumulative energy demand) (Figure 1). Thus, an LCA at the farm scale was performed using the Simapro 9.3.0.3 software. ILCD 2011 Midpoints indicators (for climate change and water resource depletion), CML-IA baseline v3.05 (for eutrophication and acidification), and CED 1.11 (for total energy demand) (Frischknecht et al., 2015), as implemented in Simapro software were used for the calculation of impact categories. Moreover, we used the data requirements suggested by the MEANS IN-OUT online platform to conduct the LCI of dairy production systems (Auberger et al., 2018).The functional unit was 1 kg of fat-protein-corrected milk (FPCM). The background data came from the Ecoalim database (Wilfart et al., 2016) for feed ingredients, from the Agribalyse database® for agricultural operations, machinery, and inputs, and from ecoinvent v3.8 for other background data (national energy mix and infrastructure). Emissions calculations were based on guidelines proposed by Koch and Salou (2015), with emission factors adapted for each country if relevant. The nitrates leaching were calculated according to the INDIGO® method and the RUSLE model. Then, the quantitative results obtained by the LCA were transformed into qualitative scores from "low" to "high". Such scores were determined based on reference values from the milk production-LCA literature.

Data were collected by 10 case study farms selected to represent DPS in key European regions throughout France, Germany, Greece, Ireland, Norway, and Poland. In this article, we chose to present only 3 case studies from France, Ireland, and Germany (Table 1).

Results:

Following the MCA approach, we designed an assessment tree for European DPS while considering the three sustainability dimensions. Figure 1 presents the indicators, criteria and principles of the environmental branch with the weights attributed to aggregated PCI elements. Table 2 indicates the environmental impacts of each case study expressed per kg of FPCM at the farm scale. The Irish DPS has lower environmental impacts compared to German and French DPS despite its higher number of dairy cows and its lower average milk production per cow (5362 L). While the French system had a high level of milk produced per cow (around 9567L), it had the highest impacts for all indicators under study except for climate change. In terms of environmental sustainability (figure 2a), the Irish system gets a "medium to high" score, with performance varying across PCIs. For instance, the Irish system scored very high for air quality, medium to high for energy use, climate change, water quality, and circular feed supply; and low for biodiversity and quantity of unproductive cattle. The German system also got a medium to high score for the overall environmental sustainability. It scored "medium to low" for feed efficiency, energy use, and biodiversity ("medium to low"), which constituted its lowest performance. The French system achieved an overall "medium" score since the majority of its middle scores are between medium to low and medium to high. Finally, when considering performance across the three sustainability dimension, the French and German systems showed the same level of economic sustainability ("medium to high") and scored higher than the Irish system ("medium") (figure 2b). Nevertheless, in terms of social sustainability, the Irish system achieved a high score whereas the French and German systems scored "medium" and "medium to high", respectively.

Discussion:

The DEXi approach is a semi-quantitative method combining parameters from various sources. In the environmental branch, this study notably included LCA results or LCI parameters. DEXi allows to compare environmental, social and economic issues to the same level. Specifically, it allows for the identification of a diversity of synergies and trade-offs within and across sustainability aspects on case study farms, notably when implementing GHG mitigation strategies. It has the potential to form a common basis to compare heterogeneous dairy production systems in Europe. The wide range of existing farming conditions (e.g., climate, technological advancement, farm size, economic performance, farming tradition) also influences the results and may have repercussions in the uptake and suitability of mitigation strategies. Overall, this multi-criteria sustainability assessment establishes a solid basis to use and compare data from case study farms and could increasingly inform experts and non-experts about sustainable dairy production systems.

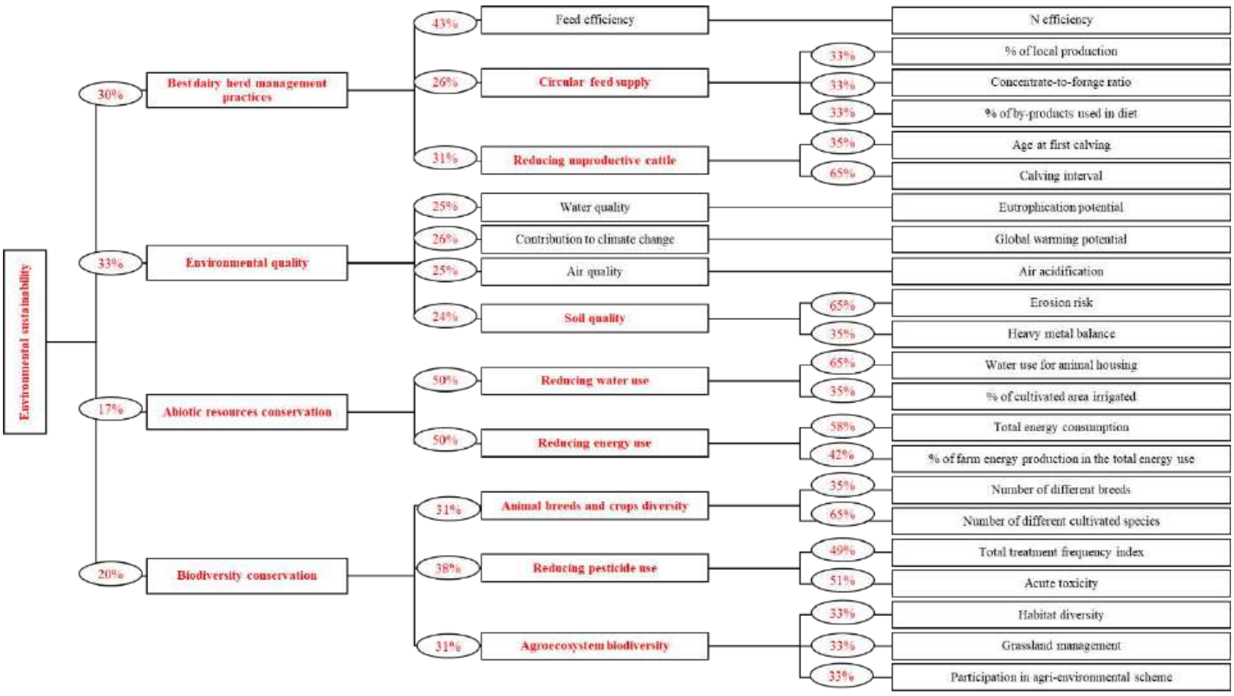

Figure 1: Weight attribution of the environmental DEXi tree. Red boxes correspond to the aggregated criteria, principles, and dimensions, while black boxes are directly dependent on corresponding indicator values.

Table 1: Characteristics of studied dairy production systems (DPS) in France, Ireland and Germany

	French DPS	Irish DPS	German DPS
Dairy herd size (cows)	75	185	110
Utilised agricultural area (UAA, ha)	103.5	87	230
Total milk production (L)	717511	991996	784000
Milk/cow (L)	9567	5362	7127
Length of grazing season (days)	168	304	214

Table 2: Environmental impacts calculated by LCA for 3 contrasted dairy production systems. The results are expressed per kg of FPCM at the farm scale

	French DPS	Irish DPS	German DPS
Climate change (kg CO_2 eq/kg)	1.35	1.14	1.46
Eutrophication (kg PO_4^{3-} eq/kg)	0.0059	0.0034	0.0046

Acidification (kg SO_2 eq/kg)	0.0126	0.0084	0.0088
Total energy use (MJ/kg)	3.84	1.87	2.40
Heavy metal balance (mg/ha)	0.0059	0.0032	-0.0032

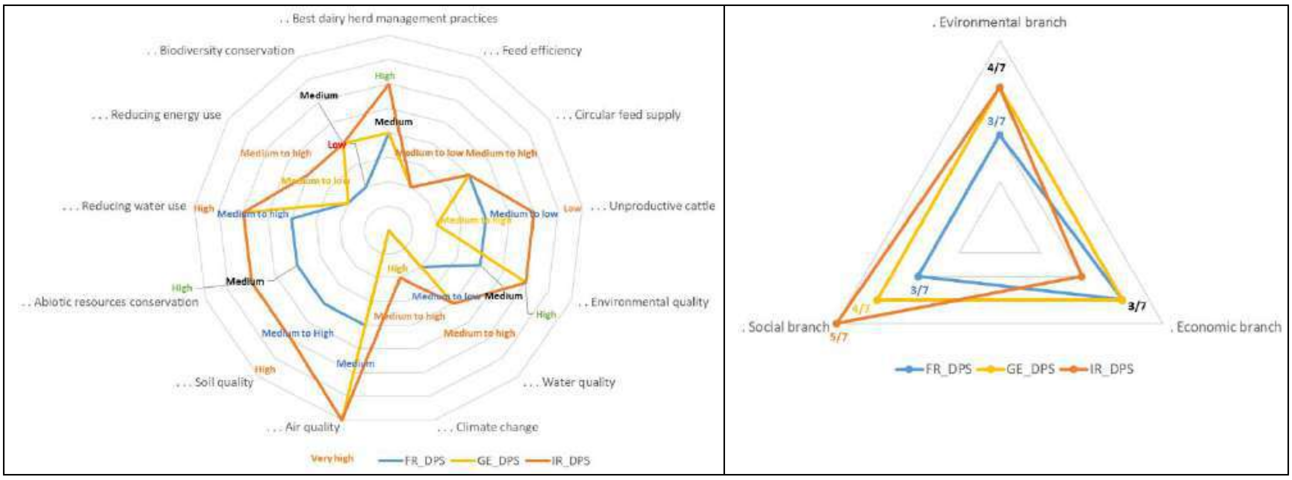

Figure 2: Sustainability scores for a) the environmental branch b) the overall sustainability score for the 3 case studies**.**

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Environmental impact of animal-based, plant-based and discretionary foods - a multicriteria assessment of Swedish self-reported diets

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Keywords: *Life cycle assessment, population-based cohort, self-reported data, food consumption, food groups, dietary patterns*

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Introduction
Food consumption and production is known to cause large environmental burdens. Environmental assessments of foods and diets are dominated by analyses of climate impact, indicating a large impact of animal-based foods and a desired transition towards more plant-based diets. However, to avoid the risk of sub-optimized dietary recommendations which may result in trade-offs between environmental effects more knowledge is needed on how the impact of different food groups varies between environmental indicators. To fill this knowledge gap, we assessed the environmental impact of Swedish self-reported diets based on six environmental indicators with the objective to estimate the contribution of animal-based, plant-based and discretionary foods to the diet´s total environmental impact.

Method
Dietary intake was based on data of 50 000 individuals within two population-based cohorts in Sweden, representative of the Swedish middle-aged and elderly population (56-95 years), who completed a food-frequency questionnaire in 2009 (Harris et al., 2013). Environmental impact was calculated for six environmental indicators: greenhouse gas (GHG) emissions (CO_2e), cropland use (m^2), nitrogen application (kg of N), phosphorus application (kg of P), consumptive water use (m^3) and extinction rate (E/MSY=extinctions per million species-years). System boundaries include the most influential steps from farm to fork, including primary production, processing, packaging, international transportation, and edible food waste along the food chain. LCA data were adapted from Moberg et al. (2020), representing the average environmental impact associated with food sold on the Swedish market between 2011 and 2015, and adjusted to account for food waste at consumer level, non-edible parts and weight changes in cooking according to the method in Hallström et al. (2021). Mean environmental impact and dietary energy in the study population were reported by the share of animal-based foods (red meat, poultry and eggs, dairy, seafood), plant-based foods (vegetables, fruits, berries, nuts, seeds, bread, grains, cereals, rice, and pasta), and discretionary foods (non-alcoholic drinks with exception of milk, alcoholic drinks, sweets and snacks, other foods).

Results
Animal-based and plant-based foods contributed the same amount of dietary energy (41%) but differed in environmental impact (Fig 1). Animal-based foods accounted for 23-83% of the diet´s total environmental impact, with the highest contribution to nitrogen application, GHG emissions and cropland use. Plant-based foods accounted for 8-40% of the diet´s total environmental impact, with the greatest contribution to consumptive water use and extinction rate. Discretionary foods

(18% of dietary energy) accounted for 9-37% of the diet´s total environmental impact, with the greatest contribution to consumptive water use, extinction rate and P application.

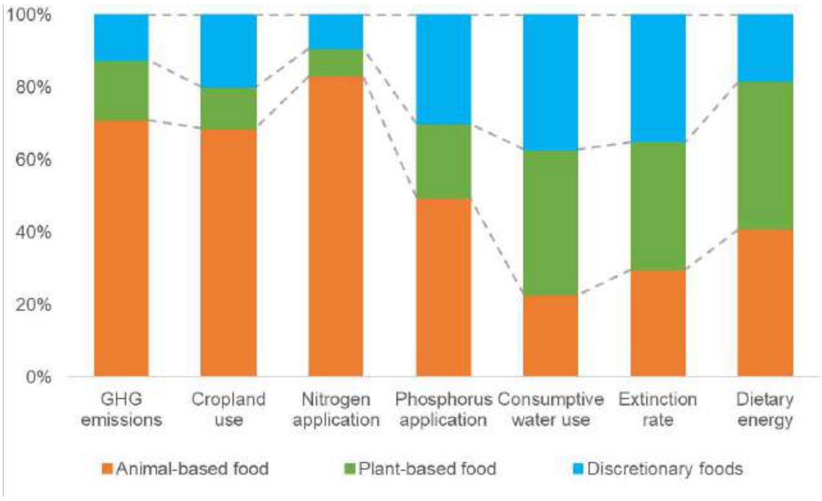

Figure 1. Contribution to mean environmental impact and dietary energy per food category for the total population

Discussion

Both animal-based, plant-based and discretionary foods contributed substantially to the diet´s total environmental impact. However, their impact varied across environmental indicators. The results suggest that measures with the greatest potential to contribute to reduced environmental impact depend on the food group and environmental impact in question. For animal-based foods measures to reduce GHG emissions, cropland use, and application of nitrogen and phosphorus are identified as critical to prioritize. For plant-based and discretionary foods, the importance of limiting negative effects on biodiversity and consumptive water use is especially highlighted. The results of this and similar research studies are greatly affected by the underlying methods and data used. Uncertainties exist both in dietary and environmental data. Data availability varies largely between environmental indicators and food group. Future studies would benefit from a greater availability of region specific LCA data for additional food items and environmental indicators. This would also facilitate assessments at a less aggregated level to clarify differences within the broader food categories assessed in this study.

Conclusion

Potential for reduced dietary environmental impact varies depending on the food category and environmental impact in question. Achieving the greatest impact reduction while avoiding environmental trade-offs may therefore require policy measures targeted for specific food groups and environmental impact categories.

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Using Multi-Criteria Decision Analysis to rank sustainability strategies and technologies for Canadian egg production

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ABSTRACT

Rationale

Decision-making is the process of determining the best alternative among all possible choices. However achieving an optimized result can be challenging for decision makers (Darko et al., 2018). Decision problems are often delicate and complex, and usually involve several criteria. In most cases, no perfect option exists to satisfy all relevant criteria. Multi-criteria decision analysis (MCDA) methods have been developed to help decision makers in their decision process to identify an appropriate compromise solution. (Ishizaka and Nemery, 2013).

Life Cycle Thinking (LCT) is a systems-based, sustainability management approach that considers all of the relevant interactions in industrial product systems (Pelletier, 2015). Decision-making for better sustainability outcomes based on the results of LCT-based methods such as Life Cycle Assessment (LCA) is often challenging due to the complexity of trade-offs between multiple impact categories. Sustainability assessment results from LCT-based methods can be translated into information that aides the decision-making process with the use of MCDA methods. The most common pathway to achieve this is by using the results from LCT-based methods as inputs to a MCDA process (Zanghelini et al., 2018).

Objective

A wide range of strategies and technologies have been identified and analysed for improving the environmental outcomes of Canadian egg production (Ershadi et al., 2021; Kanani et al., 2020; Li et al., 2021). However, identifying the mitigation option that is likely to lead to the best environmental outcomes is challenging due to the number of options available and the difficulty of interpreting the results of multiple impact categories. Hence, the objective of this paper was to use MCDA to develop a ranking of alternatives (sustainability strategies and technologies) based on their environmental mitigation potential across multiple assessment criteria.

Methods

Choice of MCDA method:

Analytical Hierarchical Process (AHP) was used to generate the ranking as it is one of the most widely used MCDA methods (Herva and Roca, 2013). Despite the availability of other MCDA methods, AHP was chosen both for its relative simplicity and because the choice of MCDA method often has limited impact in determining the alternatives that are assigned in the top positions of the rankings (Huang et al., 2011).

AHP methodology:

AHP is a full aggregation method that involves breaking down complex problems into sub-problems and solving them one at a time. The full aggregation approach assumes that scores are compensable and based on the global scores, and all options can be compared and ranked, including equal ranking among alternatives. Four steps were defined to obtain the ranking of alternatives in this study.

AHP Step 1:

The first step was the structuring of the problem. Problems in AHP need to be structured with at least three hierarchical levels – top goal, criteria, and alternatives. The top goal in this study was the ranking of all available technology or strategy options (alternatives) based on their environmental impact mitigation potential for egg production provincially. The criteria used for this AHP analysis were Life Cycle Impact Assessment (LCIA) impact categories (Bulle et al., 2019). Thirteen Impact World+ midpoint impact categories were considered. No economic or social criteria were considered in this analysis due to a lack of quality data for the alternatives considered.

Choice of alternatives:

The alternatives evaluated were obtained from three sources – Ershadi et al. (2021), Kanani et al. (2022a – in prep), and Kanani et al. (2022b – in prep). Ershadi et al. (2021) used LCA to analyse the potential impact of implementing nitrogen use efficiency strategies in Canadian egg production. Five strategies from this study were considered as alternatives here – 4Rs approach to feed crop production, biochar addition to feed crop soil, a reduced crude protein diet, addition of an ammonia scrubber to the layer barn, and biochar addition to manure storage.

Kanani et al. (2022a) studied the mitigation potential of solar and wind energy generation for Canadian egg production. This study used solar and wind speed potential in different provinces as the basis for identifying zones with renewable energy generation capacity that has environmental payback times within the lifetime of those technologies. Three different solar (1100-1200, 1200-1300 and 1300-1400 kWh/kWp solar potential) and wind (3, 4, and 5 m/s windspeeds) energy generation scenarios were considered as alternatives.

Kanani et al. (2022b) analysed two manure valorization techniques – anaerobic digestion and gasification. Impacts of gasification were modelled regionally due to electricity credits being given for the syngas produced by the process. For anerobic digestion, natural gas credits were applied and hence not regionalized. Overall, thirteen alternatives were considered in this analysis.

All three studies from which alternatives were sourced used Pelletier (2017) as the baseline LCA model for Canadian egg production. Only egg production in conventional housing was considered.

AHP Step 2:

The second step in the AHP analysis was the identification of criteria priorities. Often, this is done by generating preference information through pairwise comparisons. Due to the diverse range of stakeholders in the egg industry and lack of time and resources to conduct multiple stakeholder preference elicitation exercises, a global weighting scheme for life cycle impact categories generated by the European Commission's Joint Research Centre for product environmental footprints (Sala et al., 2018) was used to prioritize criteria. The global weighting set considered the same impact assessment method (Impact World+) as this study and aggregated the weights generated using diverse techniques such as distance-to-target (planetary boundaries), panel-based stakeholder preference elicitation, monetary valuation, and meta models from over 30 different sources. Further, Sala et al. (2018) also considers the robustness of the characterization models in generating the final weights – hence the exclusion of toxicity impact categories from the weighting set.

AHP Step 3:

The third step was generating the global alternative scores. This requires the generation of local alternative priorities for each criteria using pairwise comparisons. Pairwise comparisons were done a 9-point importance scale. The LCIA results of each alternative was converted into a % change in impacts compared to a baseline scenario. Based on the range of outcomes, thresholds were defined for a 9-point scale. For each criterion (impact category), the relative importance of an alternative was considered individually against other alternatives. Repeating this process for each criteria generated local scores which were then combined with criteria priorities to generate global scores.

AHP Step 4:

Step 4 consisted of consistency and sensitivity checks. The free online AHP tool – AHP-OS – was used in this analysis. This tool has in-built consistency checks for the pairwise comparisons.

Consistency ratios below 10% are considered acceptable in an AHP analysis. Several sensitivity checks were performed due to the methodological choices made. Sensitivity checks on prioritization of criteria was done by using an alternate Canada-specific weighting set, using equal weights for all impact categories, and using weights generated based on expert opinion. Sensitivity analysis using different assessment criteria such as considering only one impact category (Climate change) was also performed. The final check introduces two new alternatives to check the sensitivity of the alternatives considered – a combination of the five nitrogen efficiency strategies that was modelled in Ershadi et al. (2021) and a net zero energy barn alternative that was analyzed in Li et al. (2021).

Results and Discussion

Cat		Priority	Rank
1	4Rs approach	5.3%	13
2	Biochar addition to soil	9.3%	3
3	Reduced crude protein diet	7.8%	4
4	Acid scrubber	10.2%	2
5	Biochar addition to manure	6.9%	10
6	Solar energy generation - 1150 kWh	7.6%	7
7	Solar energy generation - 1250 kWh	7.6%	7
8	Solar energy generation - 1350 kWh	7.7%	6
9	Wind energy generation - 3 m/s	5.7%	12
10	Wind energy generation - 4 m/s	6.0%	11
11	Wind energy generation - 5 m/s	7.5%	9
12	Anaerobic digestion	10.6%	1
13	Gasification	7.8%	5

Cat		Priority	Rank
1	4Rs approach	3.4%	11
2	Biochar addition to soil	36.7%	1
3	Reduced crude protein diet	2.1%	13
4	Acid scrubber	3.4%	11
5	Biochar addition to manure	6.3%	5
6	Solar energy generation - 1150 kWh	6.3%	5
7	Solar energy generation - 1250 kWh	6.3%	5
8	Solar energy generation - 1350 kWh	6.6%	4
9	Wind energy generation - 3 m/s	3.5%	10
10	Wind energy generation - 4 m/s	4.5%	9
11	Wind energy generation - 5 m/s	6.3%	5
12	Anaerobic digestion	7.4%	2
13	Gasification	7.4%	2

Figure 1A and 1B: Ranking of alternatives for Alberta using 13 impact categories (1A) and only climate change (1B)

An example of the results obtained is shown in Figures 1A and 1B. Figure 1A shown the overall ranking of alternatives for the province of Alberta. Anaerobic digestion of manure has the highest environmental impact mitigation potential with the 4Rs approach to feed crop production ranked last. However, the narrow range of priority scores for the alternatives show that all these technologies were closely matched when considered across 13 impact categories. Figure 1B is the result of the sensitivity check that only considered the climate change impact category. In this scenario, biochar addition to soil is ranked first with a priority score that is almost 5 times higher than the second ranked alternative. Comparing the two rankings shows the importance of considering multiple impact categories as acid scrubbers were ranked second using 13 impact categories and only 11th under climate change. Biochar addition to soil fell to third when all impact categories were considered. The sensitivity of the rankings to the criteria weights is also highlighted in this example where biochar addition to soil remains 3rd in the ranking despite being the worst performing alternative in 10 of the 13 impact categories considered. This is due to the higher weight given to climate change (0.222) with the next highest priority being particulate matter formation with a weight of 0.095. Overall, the rankings across provinces were largely consistent (except in those provinces where renewable energy generation has unsustainable payback times) but the rankings were sensitive to various methodological choices. Anerobic digestion, use of acid scrubber, biochar, gasification, and renewable energy were regularly the highest ranked alternatives. With the criteria weights being so influential, an important necessary next step is obtaining preference information from all relevant stakeholders to generate customized criteria preferences for the Canadian egg industry. Another important consideration for future research is the use of techno-economic analyses to generate more diverse information to support MCDA analysis that accounts for other sustainability considerations.

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Multi-objective diet optimization: A Brazilian pig diet case study

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Pig supply chains are estimated to produce 0.7 billion MT CO2e per annum, accounting for 9 percent of the emissions from the global livestock sector (FAO, 2018). Brazil is the fourth largest pig producer in the world with a population of 41,12 million pigs (FAO, 2020). Reducing environmental impact is one of the biggest challenges in animal production. Neglecting the sustainability dimension might revert food security gains over time (van Meijl et al., 2020). According to the conventional feeding program in Brazil, feed ingredients used during the growing-finishing phase account for up to 56% of the potential climate change impact of finished pigs raised (Andretta et al., 2018). Corn and soyabean are main ingredients in many commercial diets. Brazil is the world's largest soyabean producer and a third corn producer (FAO, 2020). Corn production accounted for 72% of the total potential carbon footprint attributed to commercial feeds, whereas 22% of the impact was due to the soybean production supply chain (Andretta et al., 2018).

Because feed ingredients used in animal diet formulations have the highest carbon footprint, mayor demand in animal production is formulating a diet which will satisfy animal nutrition requirement and reduce environmental impacts without the effect on diet price and loss of productivity. Historically, least cost formulation has been the most common way for formulation animal diet, however it is not enough to face all the challenges including increasing carbon, water, and land footprints. Multi-objective diet formulation is a promising way which can be used to provide solutions to decrease environmental impacts of animal diets. Garcia-Launay (2018) developed method to perform multi-objective formulation which included multiple environmental impacts and feed costs and allowed a wide range of potential weighting factors between economic and environmental indexes to be investigated. Results indicated that it is possible to simultaneously reduce all environmental impacts considered in the contexts investigated.

Main objective of this study was to develop animal ration formulation tool which would cover nutritional requirements with minimal effect on a diet price and reduce the environmental impact of animal production worldwide, without loss of productivity. By including different regions, this project aims to transform swine supply chain to a more sustainable and equitable one without compromising the baseline efficiency globally. Thus, the main outcomes of the research are reducing environmental impact of pig production and enhancing global food security. In this case study, we evaluated the feasibility to apply this formulation tool in Brazil, and discussed challenges, and limitations. Finally, we formulated feasible swine diets that will help reduce carbon footprint of swine production in Brazil. The animal ration formulation tool is based on multi-objective optimization algorithm (MOOA). The results of the MOOA are 20 Pareto-optimal rations, which enable robust conclusions about benefits and trade-offs for each alternative diet. While diet rations include all pig production phases from piglets, weaning pigs, growing pigs, fattening pigs, lactation sows and gestation sows, we focused only on grow-finish phases because that's where the largest amounts of feed are used. The main steps in formulating diets were: (1) to identify baseline swine ration currently used in Brazil and calculate its carbon footprint and cost, (2) to use MOOA and propose alternative Pareto-optimal rations based on two criteria: cost and carbon footprint, and (3) to compare standard Brazil pig diets to alternative diets using the pairwise Monte Carlo Uncertainty comparison, which will assess carbon, water, and land footprint differences between a baseline finishing pig ration and alternative diets of equivalent animal nutritional value. To calculate carbon footprints of baseline ration and alternative Pareto-optimal rations, we used life cycle assessment for each feed ingredient (ISO 14040 & ISO 14044). The list of feed ingredients which are commonly available on Brazilian market and feed ingredient cost was provided by personal communication (Monica Siegert 2020). For diet optimization we used Brazilian feed ingredients nutrition information and national pigs diet recommendation (Rostagno C.O. et al., 2017). The data for carbon footprint of ingredients was provided by GFLI database (The Global Feed LCA Institute, 2020) and US footprint database (Burek et. al 2014).

The sets of multi-objective optimization solutions show all opportunities to shift diets, which enables robust conclusions about benefits and trade-off of selected diet. With multi-objective formulations, the relative incorporation rates of feed ingredients are shaped by trade-offs between the nutritional value, cost, and environmental impacts of each ingredient (de Quelen et. al., 2021.). However, because certain rations can cause tradeoffs at the pig production farm, the future work will include importing alternative diets into a regional pig production calculator, which in turn will provide lifecycle inventory data for the cradle-to-farm gate Pig Production model developed in SimaPro software. The carbon footprint will be assessed on a per pound live weight and per swine at the farm gate. Relative cost differences will be provided between the diet formulations based on a cost-per-swine produced basis.

The impact of this research are: (1) formulated alternative diets may help diversify current pig diet formulations, (2) promote inclusion of more locally produced feed ingredient in different regions, (3) an open-source flexible and user-friendly GUI diet formulation tool will available to swine producers with support of the local Animal Science Extension offices and nutritionist, which will help swine producers make science-based decisions about how to mitigate their own pig diets' environmental impact. The tool may be adapted formulate diets based on three, and four criteria, for example water and land. Finally, we will provide recommendations on how to adapt the diet formulation model for other markets and livestock especially for developing countries.

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A systematic review of the life cycle optimization (LCO) literature, and development of guidelines for performance of agri-food LCO studies

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Rationale and Objectives: Originally proposed in 1998 (Azapagic and Clift, 1998), life cycle optimization (LCO) refers to the integration of LCA with mathematical techniques for process optimization. Since then, continued development of the optimization and LCO fields now allows practitioners to find optimal solutions to complex, multi-objective problems using a variety of advanced machine learning algorithms capable of handling many different types of objectives and constraints.

LCO provides a valuable opportunity for identification of environmental impact mitigation strategies for the agri-food sector. For example, in a case study of sugar cane production, Kaab et al. (2019) indicate that the environmental impact reduction potential suggested by LCO is greater than that suggested by other methods, such as joint LCA and data envelopment analysis. Applications of LCO, to the agri-food sector, however, remain relatively few, indicating the potential for substantial growth in agri-food LCO. Increased application of LCO in the agri-food sector may therefore be one way of decreasing the significant contributions to anthropogenic GHG emissions (Crippa et al., 2021), and other environmental impacts (Pelletier and Tyedmers, 2010) made by food production systems.

LCO studies, however, require many methodological choices to be made to be successful. Choices to be made include the type and number of objectives to be considered in the optimization as well as any constraints placed upon them, the optimization algorithm to be used, and other methodological considerations related to the LCA framework (i.e. attributional or consequential) used, uncertainty, etc. The goal of this work, therefore, is to review the LCO literature such that a set of guidelines may be developed to aid LCA practitioners in making the methodological choices necessary to perform an LCO study. These guidelines aim to support increased uptake of LCO methodologies, particularly in industries in which these analyses are relatively uncommon, such as the agri-food industry.

Methods: A systematic review of the LCO literature was performed using the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) (Page et al., 2021). Literature was identified through a Web of Science core collection topic search using the keywords ("life cycle assessment" OR "life cycle analysis") AND (optimi*?) AND (algorithm). To be considered for inclusion, articles had to be primary research articles (i.e. review papers and conference proceedings excluded), written in English, available through either open access, or accessible through University of British Columbia library subscriptions, and published within the last 10 years (i.e. 2012 – 2021). Literature related to all industrial sectors were considered to better account for variation in LCO application across sectors.

If literature met these eligibility criteria they were carried forward to the selection process to determine the total body of literature to be reviewed. To be selected for review, articles had to apply the LCA framework in conjunction with a mathematical optimization technique – that is, LCA had to be used in determining at least one objective function for optimization. This could include objective functions related to environmental impacts using environmental LCA, social impacts using sLCA, or economic impacts using LCC. The selected literature were subsequently reviewed for a number of characteristics. The system investigated in each study was classified according to the International Standard Industrial Classification of All Economic Activities (ISIC) (United Nations, 2008) to determine in which industrial sectors LCO is more or less commonly applied. The LCA framework (i.e. attributional or consequential), the specific objective function(s) and whether or not the optimization was constrained or unconstrained was recorded. Finally, the optimization algorithms used, and whether or not uncertainty was taken into account during optimization was also recorded for each source.

The information collected was used to determine the most common practices in LCO related to choice of objective function(s) and optimization algorithms used, as well as important considerations to take into account when performing LCO. Such considerations include the potential need to normalize LCIA results, the use of midpoint versus endpoint indicators, or some other aggregated measure, in defining objective functions, as well as the potential for integrating uncertainty in LCIA results into optimization. Commonly used optimization algorithms were also further reviewed to determine their strengths and weaknesses with regards to integration with LCA. The resulting information was used to develop a decision tree to aid LCA practitioners in making necessary methodological choices when carrying out LCO.

Results and Discussion: LCO studies have been carried out in many industrial sectors. The majority of studies investigated systems in the manufacturing, electricity, and construction sectors. In comparison, the agri-food sector is largely under-represented in the reviewed literature, suggesting significant potential for growth in this sector. The vast majority of these studies utilize an attributional LCA approach to multi-objective optimization, and the Non-Dominated Sorting Genetic Algorithm II (NSGA-II) to solve these problems. Use of NSGA-II simplifies application, and significantly reduces computational complexity compared to other possible algorithms while still being able to efficiently solve constrained multi-objective optimization problems (Deb et al., 2002).

Interestingly, only rarely is the multi-criteria nature of LCA fully utilized in LCO studies. In many cases, minimization of life-cycle GHG emissions is included as the only environmental objective function. When this is not the case, it is more common for a single, aggregated measure representative of cumulative environmental impacts to be used as an objective function, rather than multiple mid-point level indicators. While this approach may be useful from the perspectives of reducing the number of objective functions and increasing overall interpretability of the results, these advantages must be considered alongside the drawbacks of using endpoint indicators, notably increased uncertainty (Reap et al., 2008), as well as the decreased interpretability of results with respect to specific impacts. Further, only rarely is uncertainty taken into account during optimization. Doing so requires the use of stochastic optimization methods, rather than deterministic methods, which do not guarantee location of global optima (Liberti and Kucherenko, 2005).

Based on the results of this review, a decision tree has been developed to aid LCA practitioners in making methodological choices for performing LCO studies. This decision tree will be particularly useful for agri-food LCA practitioners, and may aid in increased application of LCO methods in this sector. Increased application of these methods is a potentially valuable way to significantly reduce the environmental impacts of food production systems by targeting impact hotspots in agri-food systems, such as manure management (Li et al., 2021), fertilizer production (Arora et al., 2018), etc.

Conclusion: The developed decision tree will help increase uptake of LCO studies in the agri-food sector, one in which LCO studies are currently underutilized. These methods may result in significant improvements to environmental performance of food production systems.

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Packaging shelf-life and potential food waste can influence the environmental impact of food products: the case of red beef

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Food packaging has been seen for a long time as an additional environmental cost within a packaged food life cycle. Packaging manufacturing and waste are widely believed to have a significant impact on the overall environmental performance of packaged food items. (Gallucci et al., 2021; Sazdovski et al., 2021). Recent scientific studies, on the other hand, have shown that food packaging has a favorable impact on the overall environmental profile of food packaging systems. This is attributable to the intrinsic qualities of packaging materials and solutions, such as those that might avoid and minimize food waste probability (Verghese et al., 2015; Wikström et al., 2018). For these reasons, packaging effective eco-design is a point of major concern in actual strategies towards environmental sustainability of food-packaging systems (Pauer et al., 2019). A well eco-designed system should balance waste reduction, both in terms of packaging and food, and preservative performance efficiency (Coffigniez et al., 2021; Verghese et al., 2015). Wohner et al. (2019) and Gutierrez et al. (2017) studied the role of shelf-life in reducing potential food waste and, consequently, the overall environmental impacts of the food-packaging system. Numerous food packaging materials, solutions, and systems are currently available on the market and characterized by different material compositions, properties, and characteristics that lead to different expected shelf-lives and eventually different potential food waste reductions (Gogliettino et al., 2020; Sumrin et al., 2021). In this scenario, the search for the best eco-designed solution is hard to achieve.
Among different food categories, animal-based products such as beef meat have a greater scope of improvement in terms of overall environmental impacts thanks to the use of innovative eco-designed packaging systems. This is because their environmental load is generally higher than the one of the packaging itself (Springmann et al., 2018). As a consequence, the potential reduction of beef waste, thanks to an extended shelf-life, ends in an overall improvement of the environmental profile of these food-packaging systems. The Life Cycle Assessment (LCA) approach is frequently used in the packaging industry with the goal of detecting environmental hotspots and identifying more environmentally friendly alternatives through comparative analysis(Molina-Besch et al., 2019; Vendries et al., 2020; Wohner et al., 2019). Even if a great amount of research is currently focusing on the environmental assessment of food-packaging systems, considering both direct and indirect effects of packaging solutions, knowledge and methodological approach gaps still occur. In this context, this study aimed at demonstrating this theory, by proposing an alternative LCA approach evaluating and comparing packaging performances in terms of expected shelf-lives and related potential food waste of beef.
A comparative environmental analysis of three different packaging solutions for sliced beef was carried out through LCA with a "cradle-to-grave" approach for both packaging and beef life cycles. The study compared Modified Atmosphere Packaging (MAP; gas mixture; 8 days of shelf-life) and Vacuum Skin (VS; under vacuum; 21 days of shelf-life) systems as innovative solutions, against

Overwrap packaging system (OW; in air; 2.5 days of shelf-life), identified as the conventional solution. The study was carried out following the requirements of ISO 14040:2021 and ISO 14044:2021 standards. The functional unit was defined as one unit of packaging containing 500 g of sliced beef in relation to the expected shelf life for each packaging system.
To account for the differences in performance given by the three packaging solutions, the study used a technique for evaluating shelf-life ratio and related potential food loss. The performance of the three packaging methods was calculated using the shelf-life ratio (SLR). As a consequence, the worst-case scenario, OW, was deemed to have the highest chance of food waste. Furthermore, literature was used to determine the percentages of food waste at retail (3.90%) and household (14.5%). (Mena et al., 2014; Caldeira et al., 2019). The amount of potential food waste was then determined at both the retail and household level.
Environmental impacts were analysed using SimaPro v 9.1.1.1. (PRé Sustainability, Amersfoort, The Netherlands) software and the database Ecoinvent v 3.6., Agrifootprint 5.0, and World Food LCA Database Version 3.5 and following cut-off allocation criteria.
Considering only the packaging life cycle, the environmental impacts of the three different packaging solutions are highly dependent on their average weights, dimension, and material compositions. From characterization results, the bottom part was identified as the main hotspot with an average responsibility of 59.7% (maximum of 68.4% in MAP and minimum of 46.6% in OW). The second hotspot was represented by the top lid (13.2%, with a maximum value of 19% in OW and a minimum of 3.9% in MAP), followed by packaging disposal (11.1%, with a maximum value of 13.8% in OW and 9.8% in VS and MAP), adsorbent pad (11%) and packaging creation process (5.0%). According to environmental impact results comparison, the OW system showed the best environmental profile mainly due to its lighter mass and composition. However, when the impact of possible food waste was taken into account, the packaging system with the longest shelf life (identified in the VS system) was shown to be the best choice in terms of environmental impact. In contrast to the previous situation, the OW system has the biggest environmental effect in practically every category studied (10 out of 11). The production and the end-of-life scenario of the wasted beef seemed to be the main responsible for the higher environmental impacts if compared to the other steps of the entire food-packaging life cycles. In this regard, the average influence of beef waste on all the impact categories is 76% for MAP, 89% for OW, and 67% for VS system.
As proven by Wikström et al. (2016), the high environmental responsibility of beef underlines the necessity to include food waste as an extra variable when designing packaging solutions in the framework of eco-design. Nevertheless, depending on the type of food product and packaging systems, the major conclusions drawn for this study could not be generally applied to all food-packaging systems (Williams & Wikström, 2010). Future eco-design approaches should consider the potential food waste reduction, as a direct consequence of improved shelf-life along with the environmental profiles of production and disposal of packaging materials. Moreover, harmonization among the scientific community should be reached to consider these aspects in LCA studies for food packaging.

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Comparative life cycle assessment of waste treatment options in the foodservice sector - A case study of a vegan and zero-waste restaurant in Florianopolis/Brazil

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Rationale and objective: Food waste (FW) is the unused food discarded during retail and final consumption stages (Falasconi et al., 2019), such as homes, restaurants, and other food services. In Brazil, the estimated FW is 60kg per capita per year (EMBRAPA, 2018). This information affects Brazilian households, bringing uncertainty to an estimate of the national FW (UNEP, 2021). For this purpose, some states and municipalities are developing specific laws to reduce FW generation. The city of Florianópolis has been an example of the implementation of solid waste management practices at the municipality level for more than three decades. An example is decree nº 18.646/2018, which settled directives to make the city become Brazil's first zero-waste capital (Florianopolis, 2018). One of the decree goals is to divert 90% of the organic waste sent to the landfill by the year 2030.
In agreement with the municipal law, the "Casa Origem " restaurant follows the same rationale and became Brazil's first certified zero-waste restaurant (ILZB, 2018). Therefore, in addition to being a vegan restaurant, it reduces waste generation by reusing and recycling waste, as well as sending the FW to industrial composting sites. In this context, in light of the decree nº 18.646/2018 (Florianopolis, 2018), this paper aims to compare the potential environmental impacts of waste treatment from a vegan and zero-waste restaurant with a regular restaurant.

Approach and methodology: Life cycle assessment (LCA) was applied to evaluate the waste treatment options of a certified zero-waste vegan restaurant for the year 2020. The system boundary considers waste transport and treatment options. The generated waste is treated via (1) sanitary landfill, (2) composting, and (3) recycling (for plastics and paper). The selected functional unit is the treatment of the waste generated for the production of 18.000 meals in the year 2020 (400g food per meal). The restaurant extends the opportunity for composting services to the neighborhood. For modeling purposes, the waste coming from these sources was accounted for as being generated by the restaurant. A hypothetical restaurant that disregards circular practices was also modeled for comparative reasons. The two analyzed scenarios are:

- **Scenario 1 (Baseline)** – Zero-waste and vegan restaurant. Waste treatment through reuse, recycling, composting, and sanitary landfill.
- **Scenario 2 (Regular restaurant)** – Substitution of vegetable protein options for meat and dairy products. All waste is directed to the sanitary landfill.

Data used in the Life cycle inventory (LCI) was provided by the restaurant and complemented with secondary data from ecoinvent® and agribalyse® databases. The life cycle impact assessment (LCIA) was performed with the openLCA® 1.10.3, using the ReCiPe method for climate change (CC), terrestrial acidification (TA), human toxicity (HT), marine ecotoxicity (ME), fossil depletion (FD), and urban land occupation (ULO).

Results and discussion: The baseline scenario performs better in five of the six impact categories assessed (CC, HT, ME, FD, ULO), the only exception is the TA category, in which operation of the industrial composting site results in higher environmental burdens. Table 1 presents the potential environmental impacts for the two scenarios assessed.

Table 1 – LCIA results.

Scenarios	CC (kg CO2eq)	TA (kg Peq)	HT (kg 1,4 DCBeq)	ME (kg 1,4 DCBeq)	FD (kg Oil)	ULO (m2a)
1	359.18	1.78	275.30	85.74	14.95	3.60
2	1138.64	0.38	992.03	314.70	23.99	9.46

The impact driver in four out of six impact categories for Scenario 1 is the treatment via sanitary landfill, the only exceptions are FP and TA. In these two cases, energy and diesel consumption for industrial composting are the main impact drivers. When comparing the carbon footprint of both scenarios, it can be noted that relying solely on waste treatment through the landfilling is 68% more impactful than adding composting, recycling, and reuse to the waste treatment options applied by the company. Expressive differences between the scenarios were also identified for HT and ME, in which Scenario 2 is 72% and 73% more impactful than Scenario 1, respectively.
Results point at the environmental benefit of the implementation of circular practices such as composting, reuse, and recycling to the foodservice business studied. Since the restaurant offers the opportunity to the local community to bring their organic waste to their site for further composting via a third party, we argue that this case study serves as a small-scale experiment for the directives part of the municipal composting law sanctioned by the city of Florianopolis in the year 2018.

Conclusion: In light of the decree nº 18.646/2018 (Florianopolis, 2018), this research points at the environmental benefits of diverting waste from the sanitary landfill and implementing circular practices for waste management in the foodservice sector. As Scenario 1 presented lower results than Scenario 2 in five out of the six impact categories assessed (CC, HT, ME, FD, ULO), LCA results show a considerable benefit of the studied vegan and zero-waste restaurant in comparison to a regular restaurant. These findings have implications for policymakers and stakeholders linked to municipal solid waste valorization, including food service professionals and academic researchers.

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Food Waste and its Climate Impact in Finnish Households

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Abstract

Households produce about half the food waste in Finland, as well in Europe, significantly affecting the environment and society. To measure and understand all the impact, there is a need for primary data, as well as an development of monitoring and assessment methods, including assessment of climate impact of food waste as a proxy for environmental impacts. The aim of the study was to assess amounts and types of food waste in households and estimate the climate impact of lost food. The method used was compositional waste analysis conducted in co-operation with local waste management companies, covering mixed waste and separately collected bio waste in urban and suburban regions in Southern Finland, covering about 25% of Finnish population. The study was done four times in years 2015-2019. We sorted and weighed originally inedible food waste and originally edible food waste, additionally edible food waste was sorted into nine food type categories. The average amount of food waste varied between 53.0 kg/cap/y and 62.1 kg/cap/y, and the amount of originally edible food waste varied between 23.0 kg/cap/y and 28.4 kg/cap/y. Highest share of edible food waste were Fruits and vegetables about 40%, while its share of the climate impacts was only 13-16%. Meat and fish contributed most to the climate impact of edible food waste (37–47%), while its share of food waste was much smaller, at 10–12%. The total climate impact of three regions was 104 million kilos of CO2-equivalents per year, and climate impacts per capita annually ranged from 52.9 kg CO_2-eqv-kg/cap/y to 61.4 kg CO_2-eqv-kg/cap/y in the different regions. Collaboration with waste management companies in sorting decreases the costs of food waste monitoring. Amount, type and climate impact of food waste did not vary significantly between three regions.

Introduction

UNEP (2021) estimated that global food waste from households, retail, and food services was about 17% of all global food production, around 931 Mt of food, and about 80–120 kg per capita annually. In Europe, food waste amounted to a total of about 88 Mt and about 173 kg per capita annually, which was about 20% of the total food produced in the same area (Stenmarck et al., 2016). This enormous amount of lost food causes significant environmental and economic impacts, affects food security, and is a resource efficiency issue for a healthy diet and sustainable food production. There is a clear need to monitor and decrease the amount of food waste and related climate and environmental impacts, which are caused through unnecessary food production. All actions, innovations and political initiatives to decrease food waste require support from data, knowledge, and understanding of the generation of FW, and there is especially a need for direct measurements and standardised methods (Xue et al., 2017). About half the food waste in Europe is caused by households (Stenmarck et al., 2016) and the European Union and its member states have adopted the UN SDGs to halve food waste at the retail and consumer levels by 2030. To make the measurements uniform and follow the targets, the European Commission has established a common measuring and reporting methodology for FW levels (EU, 2019). There the waste composition analysis is one of the methods suggested for households. Waste composition analysis is a method in which waste material and food waste and edible food waste are physically separated and sorted. As a method it has some disadvantages. There is a lack of data on liquid food waste, composting at home, and a lack of information about the causes of food waste and sorting has some uncertainties when trying to separate edible food waste components from the entire waste mass.

Objective

The goal of the study was to produce information on current food waste amount and quality in Finnish households, focusing on edible part of the food waste and estimate its climate impact, using waste composition analysis method, in three relatively large urban and suburban regions in Southern Finland (Helsinki, Turku and Tampere areas) covering about 25% of Finnish population. This was the first waste composition analysis to focus on Finnish households and included an analysis of both edible and inedible food waste fractions, when the previous Finnish diary study included only edible food waste (Silvennoinen et al., 2014).

Methods

We defined food waste as all wasted food or food material, including originally inedible food waste, including coffee grounds and vegetable peelings, and originally edible food waste, all the food that could have been eaten by humans before discarding, as basically defined in FUSIONS definitional framework (Östergren et al., 2014). We conducted four waste composition analysis studies, which included both mixed and bio waste, in three waste management areas: 1. the Helsinki area (2015 and 2018); 2. the Tampere area (2016); and 3. the Turku area (2019). All the studies were undertaken in cooperation with local waste management companies. The companies sorted mixed waste fractions to analyse the composition of mixed waste, and we further sorted the fractions, including food waste. Separately collected biowaste samples were taken directly from the loads and sorted. There were 79 waste loads, from which 140 samples were taken for sampling. Each sample's mass was around 100 kg of waste. The sorting method was manual by researchers and sampling was done according to the instructions of Finland's Organisation of Municipal Solid Waste and its standard for mixed waste composition analysis, and finally edible food waste was weighed by type: Vegetables; Potatoes; Fruit and berries; Bread; Meat and fish; etc., in different main food product groups. We divided the food waste masses of different food product groups by the number of inhabitants along the waste collection routes to obtain the amount of FW produced per inhabitant and year for each housing and food wasre type. We extrapolated this data to the whole city area by multiplying the amount of food waste per person by the total number of inhabitants in both housing types and divided the resulting total mass by the total number of inhabitants in the area. More description of the method regarding composition analysis can be found at Silvennoinen et al. (2022).

The climate impact assessment of sorted food groups and fractions was calculated based on life cycle assessment based information of foods from the literature, based on average on typical, best available carbon footprint (CF) results and estimates, concerning Finnish market situation and production of those foodstuffs. It was assumed that all products were sold by retails. System boundaries for CFs of food was from production of farm inputs up the delivery to the retailers. The main life cycle phases included in the system boundaries of the CFs were the production of inputs (e.g. fertilizers, lime, seeds) to agriculture, agricultural primary production, food processing stages and transportations. Shopping trips, retail, storing, packaging production, refrigerant leakages, or cooking of food and waste management were not included. Emissions from land use change and change of carbon stocks were not included, due to the lack data. The climate impact assessment were done in different products groups so, that sorted and reported food groups were partly divided for detailed fractions of food groups. Vegetables waste consists of mainly tomatoes, cucumber, pepper and lettuce. Majority of production of tomatoes and cucumber takes place in Finland, and e.g. pepper is mainly imported, mainly from Spain and southern Europe and also from Holland. The origin of food products affects the carbon footprints and weighted averages were used for different origins, when possible. CFs of major vegetable produced in Finland have typically higher values compared e.g. to import from Spain and that is why average CFs of vegetables are a bit higher than typically in global LCA based literature sources (see e.g. Neira et al. 2017, Ntinas et al. 2016, Page et al. 2012, Poore and Nemecek 2018, Silvenius and Katajajuuri 2021).

Potatoes are mainly produced in Finland, and partly Sweden. There are scientifically reported CF studies concerning potato cultivation in Sweden, but from Finnish potato production scientifically published data is not available. There are two recent Finnish research report on CF of Finnish potato production, done for large Finnish potato producers, and these were used as a basis of potato CF estimate as well. There were no major differences between potato CF results between Sweden and Finland. (Harrison et al. 2019, Räsänen et al. 2020, Röös et al. 2010). Consumption of fruits and berries in Finland is dominated by imported fruits, especially bananas, citrus fruits, apples and melons. CF estimates of Poore and Nemecek (2018) was used for Fruits and berries -category. The local apples were found one main specific OEF group in compositional analysis. No data exist in CF of local Finnish apples, but their CF was estimated to be rather low, based on Poore and Nemecek (2018) Clune et al. (2017). Concerning pasta and rice –category, pasta products are dominating consumption in Finland. Scientific results CF of pasta is rather limited, Swedish CF data of Röös et al. (2011) was used to illustrate Finnish pasta production, and additionally is was chosen to use updated CF data by large European producer Barilla (2020). CF of rice was based on Poore and Nemecek (2018). CF of bread was based on use of wheat and dark bread, using Poore & Nemecek (2018) and Silvenius et al. (2014) as main literature sources.

Most of the edible food waste of the Meat and Fish product group is meat. Meat consumed is produced mainly in Finland and it consists mainly pork, chicken and beef. Whole meat and minced meat were the ones mostly discarded. Finnish most recent CF data was used for meat and meat products. Most of the eaten beef is coming from dairy breed beef production. CF data of beef production was derived from Hietala et al. (2021a), taking into account of shares beef and dairy breed beef. Best up-date estimates of average Finnish chicken meat if from Usva et al. (2021) and respectively CF of average pork meat was based on Hietala et al. (2021b). Fish is mainly imported to Finland. The main data source for imported fish was Ziegler et al. (2021) and CF estimates of the Finnish fish products were from Silvenius et al. (2017). Chunk cheese and some other milk products (not milk) was discarded mostly from the cheese and other milk products category. Most of the consumed milk and milk products are mainly produced in Finland, but cheese is also imported. As there are not recent scientifically published CF results on these products, CFs of milk products and cheese were assumed to be similar than in Denmark and Flysjö (2012), Flysjö et al. (2014) and additionally EDA (2018) was used as a key literature sources for all the milk products. The *Other products* group consisted of many subproject groups and food items such as homecooked meals (which could not be divided into actual food types), cereal products other than bread, ready-made and takeaway food, gravies and spices, desserts, pastries, confectionary, and snacks, all food that could not be sorted in the other categories. In the climate impact assessment food product group specific literature sources were used when possible. Regarding some specific sub-groups such as ready-made-meals which consist of multiple types of product groups, we also made an estimate using the weighted average CF of all product groups in the case of Helsinki 2018. Finally, we combined the average climate impact of food waste per person per year for all three cities. We explored the climate impact for Finland as a whole by multiplying the climate impact per person per year by the total number of inhabitants of Finland.

Results and conclusions

The average food waste in all households varied between 53.0 and 62.1 kg/cap/y, depending on the study area and year. The originally edible food waste amounted to 23.0–28.4 kg/cap/y. The largest type group varied between regions, but the main types were Fruit and vegetables (including potatoes), 21–34%, Other products 22–30%, Bread 12–20%, and Meat and fish 10–12%. Together, all three regions produced about 0.1 Mt of food waste annually. The total food waste in the Finnish food chain is about 0.64 Mt/y (Riipi, et al. 2021), so households of these three regions produced about 15% of all food waste in Finland. This new food waste monitoring result is less than previous estimate by Katajajuuri et al. (2014) in the entire food system. Meat and fish made the most remarkable contribution to the climate impact in all studied regions, ranging from 36 to 45% of the total climate impact. The Other products group, comprising all homecooked food, including meat, makes the second largest contribution to the climate impact, at 20–29%, depending on the region. Per capita climate impacts in the studied cities differed. They were largest in Tampere (61.4 kg CO_2-eqv-kg/cap/y), while climate impacts in Helsinki ranged from 51.9 to 57.9 kg CO_2-eqv/cap/y, and in Turku 54.6 kg CO_2-eqv-kg/cap/y. To decrease the climate impact of unnecessary food waste, the most essential issue is to limit the amount of meat and meat product waste. When extrapolating the climate impacts of edible food waste (0.10 Mt CO2-eqv/y) in the three main Finnish regions) to the national level and all households, the climate impact was 0.31 Mt CO_2-eqv/y in average. This national annual total climate impact of food waste is approximately the same as the climate impacts of driving an average of 139,000 passenger cars a year in Finland.

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Food waste and product residuals as animal feed

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Introduction

In circular food production, it is important to make the best possible use of all resources to prevent losses from the food system. Valuable resources, such as food waste and by-products, could have several potential usages, as for instance soil improvement, energy production or animal feed. Historically, uncooked food has been used as feed in pig production, but in recent decades specific disease outbreaks have occurred and therefore different regulation have been introduced for using food waste as animal feed. Concerns about the risk of transmitting bacteria, prions, parasites and viruses have made it difficult to use food waste for animal feed if it cannot be ensured that it does not contain animal tissue (Shurson, 2020). However, the requirements for sorting, traceability and heat treatment can be satisfied for food waste from the food industry and therefore this can be safely used as feed. For instance, whey from dairy production is still used as feed in the specialized pig production, historically often at very cheap prizes or even for free if the farm is nearby the dairy. Wet by-products as dairy residuals are beneficial used as liquid feed and Brooks et al. (2001) showed that wet feeding of pigs was more effective, positive for health and gave less salmonella. Food co-products such as dried whey, fish meal and heat processed cereals can be used in diets for weanling pigs, and moderate levels of food waste can be used in the diet for growing finishing pig without negative effect on growth performance and meat quality (Fondevila et al., 2021; Kjos et al., 2000). Rajeh et al. (2021) made a comprehensive review of using food waste as animal feed and found that various types of food losses and wastes are generally nutritious and can be converted into safe feeds by modern technologies, and animals fed with waste-based feeds had comparable feed conversion ratios to those grown using conventional feeds. In addition, inclusion of co-products and former food products in the diet for growing-finishing pig can in some cases reduce the environmental impact of livestock systems (Mackenzie et al., 2016; Pinotti et al., 2021). Therefore, this study aims to document the environmental impact of using food waste and by-products for animal feed.

Material and method

The study involved both a feed function and a treatment function and therefore a functional unit was chosen that reflects both: Production of 1 kg pork and treatment of the corresponding amount of food waste/residual. The systems included in this study was as follows:

- DAIRY - Production of 1 kg pork (slaughter weight) from cradle to farm gate and treatment of residual from the dairy industry
- MIXED - Production of 1 kg pork (slaughter weight) from cradle to farm gate and treatment of mixed food waste from the food industry.

In both systems, the use of dairy residuals or mixed food waste as feed was compared to the use of standard feed and anaerobic digestion of the food waste or residuals as the reference cases. Interviews were conducted with farmers who use these feeds to gather knowledge about experiences in practical use. Details regarding the pig production system and the standard diet used in the reference cases, is described in Møller et al. (2022). In the reference cases, the mixed food waste or dairy residual were assumed to be treated in a biogas plant that upgrades biogas to fuel quality and substitute diesel. A sensitivity analysis has also been performed where biogas is used for biogas district heating. The digestate is assumed to be transported to farmers which uses it as biofertilizer and substitute artificial fertiliser (N 22%, P 3%, K 10%) (Lyng et al., 2015). The nitrogen content for mixed food waste was estimated based on several publications (Bouallagui et al., 2009; Cavinato et al., 2010; Murto et al., 2004; Rossi et al., 2004) and the biogas potential from Carlsson & Uldal (2009). Methane leakage from the biogas tank was 2.9% of the biogas produced.

The dairy residuals are a mix of whey from cheese production, buttermilk from butter production and waste due to product changes and errors in production process. The dry matter and content of dairy waste was specific data given by the dairy company and the nitrogen content was calculated based on the protein content assuming 16% of nitrogen per kg protein (Table 1). The residual dairy feed is mixed with a feed concentrate from the feed supplier to achieve a balanced diet. The feed provides good growth and in addition the acidified residuals, e.g., yogurt, reduces any problems with diarrhoea.

The mixed food waste consists of waste from the food industry and wholesale warehouses (dairy residuals, bread, flour, fruit and vegetables, dairy, chips, finished goods, mayonnaise, caviar, chocolate, brewers' grain, etc.). A software is used to calculate the content of energy and protein and it is thus possible to compose it into a specific nutrient content to keep the nutrient value of the feed stable throughout the year (details in Table 1). If the available waste does not have sufficient protein or energy content, it is adjusted by adding soybean meal or oil. The packaging is sorted out and either recycled or incinerated and the food waste that cannot be used as feed is delivered to anaerobic digestion. The food waste is heat treated and transported to the pig farms in the region. Return transport is used to collect food waste. The farmer uses the mixed food waste with a special adapted feed mix from the feed supplier because there is a need to add extra vitamins and minerals that disappears during the heat treatment. The feed has a low pH value due to use of soft drink in the mixture and can therefore be stored for up to 14 days.

Table 1 Details for dairy residuals and mixed food waste regarding dry matter, net energy, protein content, nitrogen content and the theoretical biogas potential.

	Dairy residuals	Mixed food waste
Dry matter (DM) %	8,5	22
Energy (MJ/kg DM)	7,6	20,5
Protein g/kg DM	171	145
N content (kg/tonne DM)	27	23
Theoretical biogas potential (Nm^3/tonne DM)	494	600

Table 2 shows the amount of feed for the reference case for sows, piglets and growing finishers and how much of the standard diet that can be replaced by dairy residuals or mixed food waste.

Table 2 Quantity of feed for REFERENCE and proportion of dairy residuals and mixed food waste which replaces feed concentrate in DAIRY and MIXED for sow, piglet and growing finisher.

	REFERENCE	DAIRY	MIXED
Kg feed/sow per year	1 370	24 %	-
Kg feed /piglet	32	16 %	-
Kg feed/growing finisher	229	30 %	85 %

The impact assessment is based on the product environmental footprint category rules (PEFCR) for *feed for food producing animals* (FEFAC, 2018) where six impact categories have been identified as the most relevant.

Results

The results for climate change are shown in Figure 1, where the REFERENCE cases are shown as both gross impact for pig production and biogas treatment and the total net impacts compared to the MIXED and DAIRY cases. The figure shows that there is an insignificant difference between REFERENCE and MIXED (2%) and DAIRY (-1%), respectively. This is because there is a large climate benefit in upgrading methane to fuel quality that can replace diesel, i.e. avoided emissions which are resulting in negative impacts.

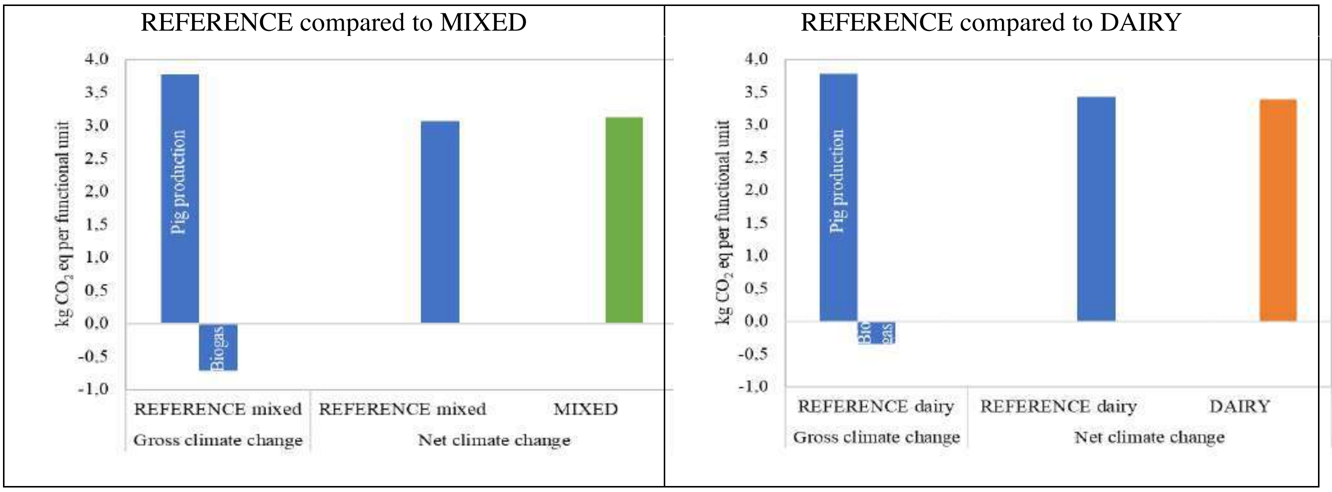

Figure 1 Results for climate change for the REEFERENCE case, gross impacts for reference pig production and reference biogas treatment and net impacts compared with the MIXED case and DAIRY case, respectively.

All the six included environmental impact categories are shown in Figure 2, where MIXED case and DAIRY case are compared with the REFERENCE cases. The results are converted to relative values, and the REFERENCE cases are set to 100%. As already described, climate change is at the same level for both MIXED and DAIRY when compared to REFERENCE, but for the other impact categories MIXED and DAIRY have lower impact. The only exception is water use for DAIRY, which is at the same level as the REFERENCE. The land use is considerably lower for MIXED than for DAIRY and this is because the mixed food waste replaces a much larger part of the feed for the slaughter pig than with the use of dairy residuals.

The sensitivity analysis, where assuming that the biogas in the REFERENCE had been used for district heating instead of upgrading to fuel quality, shows that the impacts are lower or at the same level for MIXED and DAIRY when compared to the REFERENCE. For particulate matter the sensitivity analysis shows an increase. When replacing diesel, the avoided emissions from combustion of diesel give lower emissions, but when the biogas instead replaces district heating, this effect is not achieved.

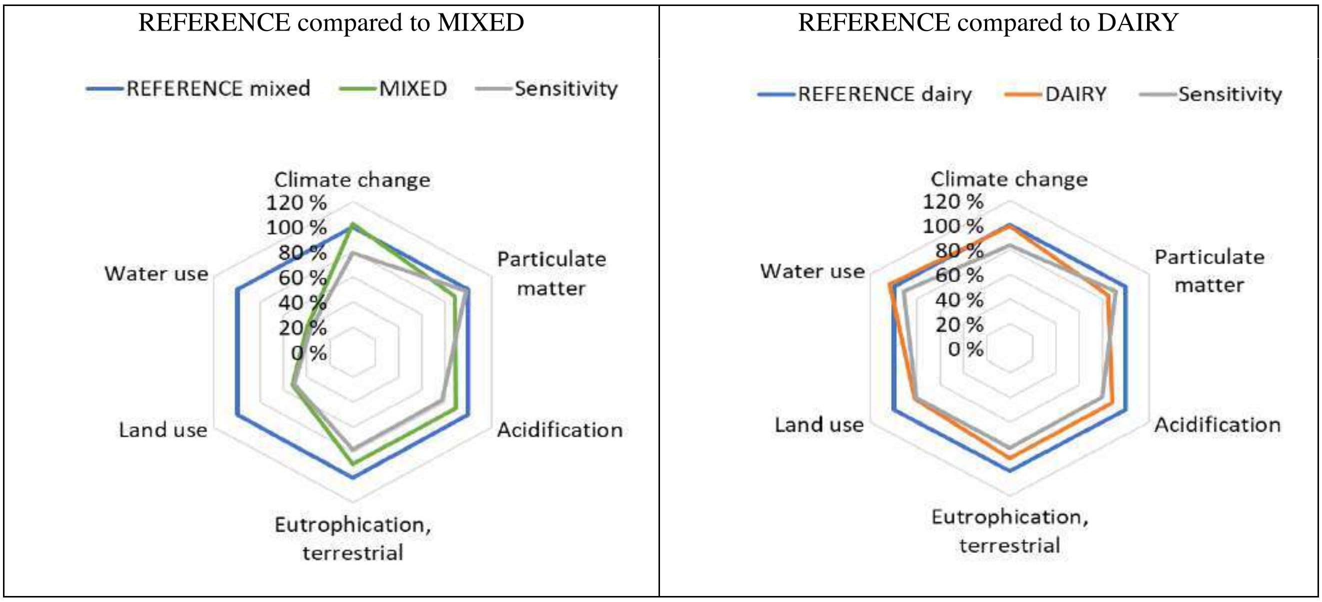

Figure 2 MIXED case and DAIRY case are compared with the REEFERENCE cases, where the results for six impact categories are converted to relative values, and the REFERENCE cases are set to 100%. The figure also shows results from the sensitivity analysis, where the biogas in the REFERENCE cases replaces district heating.

The interviews with pig farmers who used mixed food waste and dairy residuals as feed showed that they were satisfied with using this as feed in terms of growth, well-being of the pigs and financially. Use of these liquid feeds, however, requires investment in equipment at the farm for storage and pumping and a larger manure pit needed as there is a lot of water in the feed.

Discussion

The results show that by using mixed food waste and dairy residuals for feed, a reduction in environmental impacts can be achieved. How large this reduction is, depends on what is the current use of the biogas and thus what it replaces. The reduction in climate change is greatest when biogas replaces district heating. Even when a reduction in climate change is not achieved, such as when biogas replaces diesel, the other environmental impacts will be reduced when using food waste and dairy residuals as feed. Land use is considerably reduced, and this means that agricultural land, which in reference was used to produce feed, instead can be used for direct production of human edible food. Reuse of food, utilization of by-products and food waste increases the circularity of the food system, as described by Jurgilevich et al. (2016). The waste from the food system should be recycled back into the food system and livestock should be used to convert bioresources that humans cannot eat into valuable food products which could otherwise be lost from the system (de Boer & van Ittersum, 2018).

The use of residual feed is well suited for pig production and experience shows that it provides a good growth performance and animal welfare. However, it is important to consider the food safety aspect when using these feeds. Residual waste is a limited resource and will mostly be available to the farms that are within a certain distance from the collection and treatment facility. Therefore, residual waste cannot replace standard feed on a large scale. Nevertheless, reducing food waste should always be the priority mitigation option.

Conclusion

The study documents that the use of food waste and by-products for feed can be a good environmental solution and an important resource for farmers who have access to this. The reduction of impacts depends on the basis for the reference and what the biogas replaces.

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Utilization of animal by-products and waste at slaughterhouse stage to reduce the environmental impact of pork products

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Keywords: *Life Cycle Assessment (LCA); Pig slaughterhouse; Allocation methods; Circular bioeconomy; By-product utilization; Food loss*

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Background and purpose Food loss is of high importance since the environmental emissions and impacts along with the consumption of scarce resources such as land, water, and energy in all parts of the supply chain that was used to produce the food goes to waste and more environmental impacts and resources will be needed to feed the growing world population. Therefore, reducing food losses is widely recognized to meet the challenges of global food security, global warming, biodiversity loss, and protection of natural resources (Munesue et al. 2015). Food loss in relation to livestock products are even worse since they have high impacts on climate change and other environmental problems. Pork production represents one of the world's largest livestock categories and is expected to increase in the future due to increasing population, rising incomes, and urbanization. In Europe, approximately, 23% of the production in the meat sector is lost or wasted in all stages of the food chain (Lipinski 2020). The largest share is generated at the consumption level followed by the processing (Hodges et al. 2010). Several studies have tried to quantify the consumption-stage food waste, but less is known about the processing stage considering inputs of resources, outputs of edible products and inedible by-products, and all associated environmental impacts (Mogensen et al. 2016). Furthermore, most data on food loss are only related to a few industrialized countries, and most are based on secondary data. Therefore, the focus of this study is the food loss in the slaughterhouse stage, where the live animal is processed into edible products and inedible by-products. Increasing the share of live animal that ends as edible products for humans can reduce the environmental footprint per kg of edible products significantly (Mogensen et al. 2016). In addition, slaughterhouses generate many inedible by-products which can be used for various purposes. Optimal usage of slaughterhouse products and by-products in-line with circular bioeconomy principles can reduce the use of resources, avoid disposal costs, and create environmental credits for the entire system (Mogensen et al. 2016). Considerations of food loss in the meat supply chain also require considerations of its fate. This implies modelling the waste treatment process (e.g., incineration) or if the by-products can be beneficially used (for animal feed, biogas production, etc.). In this modelling, these co-production processes were handled by using either system expansion or allocation. The aim of this study was to examine the environmental performance of the pork production system covering the entire chain from the farm to the edible products and side streams leaving the slaughterhouse, to explore the potential of mitigating environmental impacts at the slaughterhouse stage. Three different approaches to handle by-products were applied to assess their ability to capture environmental improvements at slaughterhouse level.

Methods A complete cradle-to-slaughterhouse gate LCA was performed. The functional unit was 1 kilo edible pork product. Four different environmental indicators were considered, global warming potential, eutrophication potential, acidification potential, and abiotic depletion. The system boundaries include the environmental emissions associated with the primary pig production, transport of pigs to slaughterhouses, the slaughtering process, and the waste management of inedible by-products when using system expansion, see Figure 1. The primary production was modelled based on secondary data, because the focus in this study is on food losses at the pig slaughterhouses, and the effect of reducing the amount of food loss on the environmental impact of one kilo of pork product for human consumption. The most recent study on the Danish pig production was used for the environmental emissions associated with the farm stage (Dorca-Preda et al. 2021), where more details about the system can be found. Life cycle inventory data from four different meat-processing sites in Europe (Denmark, Sweden, Poland, and Germany) was used for benchmarking and identifying risks and opportunities within the slaughterhouse stage. An LCA was conducted on the current practices and possible future scenarios involving an increasing utilization of edible products for human consumption and the use of inedible by-products. Modelling the use of inedible by-products implies expanding the system boundaries to include the marginal use of the by-products for either animal feed, medical purposes, biogas and biodiesel production, production of fertilizers, or waste management. Modelling of the by-product treatments included all associated environmental impacts at the production stage as well as the avoided products.

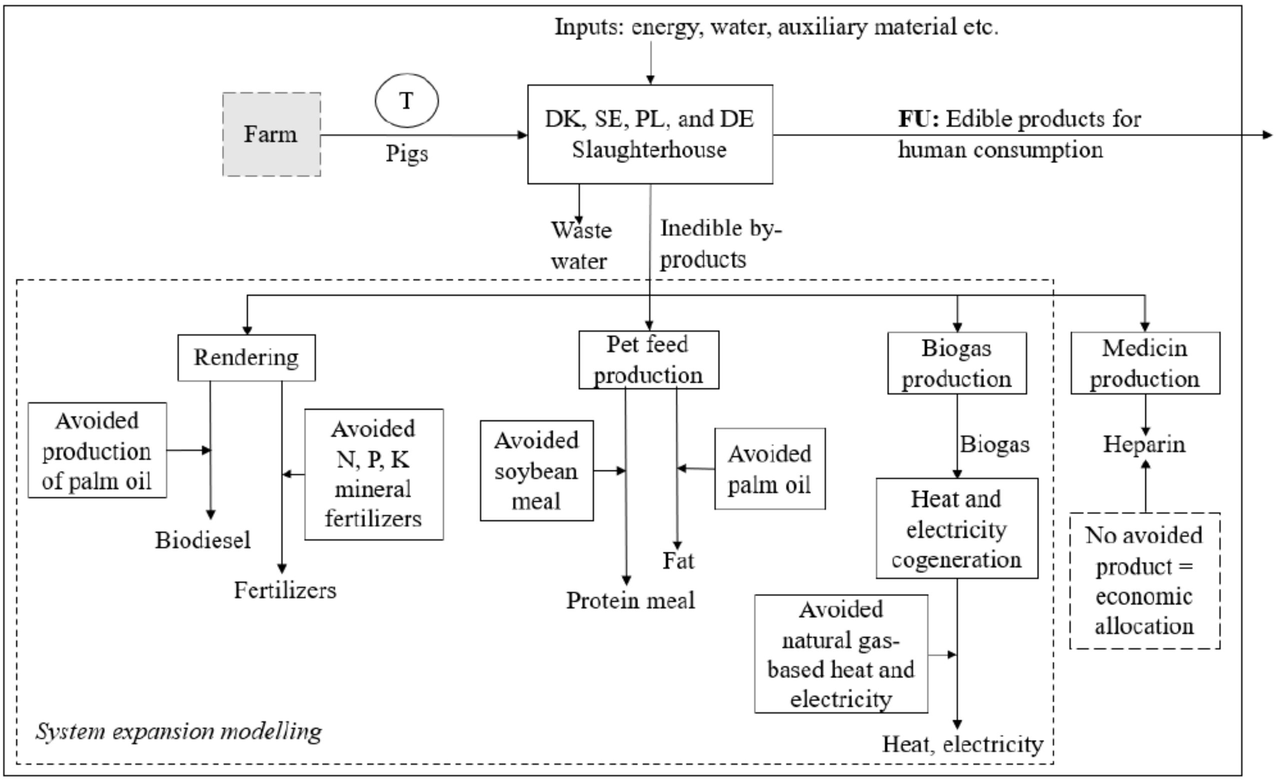

Figure 1 System boundaries. T = Transport, DK = Denmark, SE = Sweden, PL = Poland, and DE = Germany.

A sensitivity analysis was performed using three different approaches to handle multifunctionality and several products at the slaughterhouse stage: 1) system expansion, 2) mass allocation, and 3) economic allocation. In the processing, slaughterhouses are particularly important since they generate a lot of edible products and inedible by-products. To optimize the slaughterhouse processing to reduce the environmental impact, a central methodological issue is allocation. The basic role for partitioning the environmental burdens in mass allocation is based on 'weight as is' and follow the approach explained in UECBV 2019. To conduct the allocation at the slaughterhouse, the main product, by-products, and wastes should be categorized in the following product groups:1)

Products used for human consumption, 2) Products for animal feed applications, such as pet food or feed for fur animals, 3) Products sold for rendering, 4) Products sold to pharma industry, and 5) Products sold for biogas production. Economic allocation is performed as suggested in Zampori and Pant 2019, except for the categorization, where the same product group is applied like for mass allocation. To calculate the environmental impacts the following formula is applied:

Equation 1 $EI_i = EI_w * AR_i$

Where, EI_i is the environmental impact per mass unit of product *i*, (i = a slaughterhouse output), EI_w is the environmental impact of the whole anima divided by live weight mass of the animal and AR_i is the allocation ratio for product *i* (calculated as economic value of I divided by mass fraction of *i*) (Zampori & Pant 2019). Economic data was collected for all four slaughterhouses, two of them are considered large-scale (DK and DE) and the two others are considered small-scale slaughterhouses (SE and PL). The small-scale slaughterhouses experience less price fluctuations because products are sold to the domestic market, whereas large scale-slaughterhouse have larger market access and they export most of their products. Moreover, small-scale slaughterhouses have less ability to utilize waste streams and upcycle the inedible products.

Results and discussion The yield of edible products per animal slaughtered showed a large variation between the different slaughterhouses from 72% of live weight (LW) from the Swedish slaughterhouse to 88% of LW for the German slaughterhouse. The large variation was mainly due to sales opportunities. A lower utilization of the animal for human consumption was detected in small-scale slaughterhouses because the untraditional cuts like the feet, tail, and head cannot be sold to the domestic market in Europe. These products are often sold to countries in Asia, where such cuts are culturally considered a delicacy. There is a public understanding that 'eating locally' can help to reduce the environmental footprint. However, in this case, eating locally can be largely ineffective in reducing the environmental footprint of meat products if local consumption does not imply eating all parts of the animal. This study does not include the additional emissions for processing, transportation, and packaging when utilizing more of the animal for human consumption. Nevertheless, recent findings from Poore and Nemecek 2018 suggest that these life cycle stages account for around 10% of the carbon emissions in the production of pig meat. These emissions are overshadowed by the emissions related to land use changes, farm-related emissions, and emissions associated with animal feed production. When considering optimal utilization, which implies that all by-products that could be sold for human consumption on a global market are utilized (not taking into account conditions about production economy and access to market), the results showed that the greenhouse gas (GHG) emission per kg of edible product was reduced significantly. The slaughterhouse process is only associated with low levels of environmental emissions which can be offset by the by-product recovery when applying system expansion. The major barriers on slaughterhouse level to increase the share of edible products for human consumption were identified. These were mainly a) lack of packaging and freezing capacity and therefore favoring high-value meat cuts, b) large pigs exceed optimal slaughterhouse weight being discharged or causing issues with machinery in the slaughterhouse, c) spillages due to fast production time for the employees, d) missing processes such as melting of fat, and e) lack of market outlets which lead to downgrading the share of human edible products. There is a large variation in GHG emissions per kg of edible product when using the different allocation approaches. The lowest environmental impact per kg of edible product was from using mass allocation. When using mass allocation, the same amount of emission is assigned to the edible products as to the inedible by-products. This allocation approach leaves therefore no incentive to increase the human yield or ensure optimal use of the side streams at the slaughterhouse level. Economic allocation is better suited to capture measures to mitigate environmental impact, which will create an incentive to utilize the largest share of the animal.

Increasing the share of live animal for human consumption entails using meat by-products such as blood, hearts, liver, lungs, and other offal, which would undergo a further processing. The most popular processed red meat products are sausages, pre-cooked ready-to-eat products like frankfurter and mortadella, liver pâté, and fermented sausages e.g., salami, chorizo, and pepperoni). The processing of meat is subject to many additives to increase flavor, assist in reducing and preventing microbial growth, colour fixative etc. One example is sausages that contain nitrites added to meat product as preservative, colouring, and antimicrobial agent (Libera et al. 2021). Current studies have found that high red and processed meat intake increases the risk of all-cause mortality, type-2 diabetes, colorectal cancer etc. At the same time, the price of processed meat is significantly higher than fresh meat products. Hence, companies are in favor of processing meat to increase their profit margin. While there is an economic and environmental benefit of utilizing more of the animal for human consumption by processing some of the "boundary" products there is a trade-off regarding human health and the consumption of processed red meat.

Conclusion There is a large potential to improve the utilization of the live weight of pigs at the slaughterhouse stage. Increasing the share used for human consumption will decrease the environmental footprint per kg edible product considerably. Optimal use of the by-products is of great importance, and to secure that the applied LCA method can help to understand and evaluate whether the claimed environmental benefits of circular bioeconomy solution can be achieved and to what extent. Using an incentive-driven allocation method is of high importance if wanting to stimulate to a more resource-efficient pork production and capture improvements within the slaughterhouse to mitigate environmental impacts.

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Connection between food waste generation and household fuel use: Trends and implications in Peru

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Accelerated population growth and urban expansion in recent years has led to a progressive increase in municipal solid waste (MSW) generation (Kaza et al., 2018), evidencing the need to implement realistic and coherent policies, with informed decisions (Margallo et al., 2019). Thus, considering that households are one of the main sources of MSW generation (Urbina-Reynaldo & Zúñiga-Igarza, 2016) and that an important fraction of this waste is organic, especially in developing and emerging nations (Vázquez-Rowe et al., 2021), the main objective of the current study was to analyze the connection between cooking fuel consumption and food waste. Peru was the selected country for the analysis, considering the abundant amounts of food loss and waste (FLW) that are generated (Bedoya-Perales & Dal' Magro, 2021). To this end, a linear regression and principal components analysis was performed to explain the influence of fuel use and type on food waste generation in households. A database was constructed using information processing software (e.g., MS Excel, STATA, among others). The sources of information that fed this project are mainly the ENAHO (INEI, 2018) and ERCUE (OSINERGMIN, 2018), both nationally-conducted surveys.

Fuel consumption is used for different activities in daily life, including cooking, which is directly related to the generation of organic solid waste (Huamaní Montesinos et al., 2020). In this sense, the consumption trend of the different types of fuels at a national level was analyzed per region. Regarding the distribution of households by geographic area, in urban environmental, 81% used liquefied petroleum gas (LPG) and 12% natural gas (NG); while in rural areas 40% used LPG and 45% used firewood (OSINERGMIN, 2021a). Regarding the use of electricity for cooking, it is insignificant if compared to the main fuels used such as NG and LPG (i.e., 5.7% nationwide) (OSINERGMIN, 2021b). Likewise, the trend in the use of certain fuels has changed over time; for example, certain fuels have been abandoned (e.g., kerosene) and the use of others has increased (e.g., LPG).

In order to process the information and construct the statistical models, it was assumed that the observations provided through national reports are representative and reflect the dynamic behavior of each region. In addition, due to the use of asymmetric samples, the median was considered as the reference statistic. Thus, from the linear regression analysis performed, it was obtained that this explains 66% of the data provided. In addition, from the database generated, some of the variables used present an important correlation; for example, number of rooms vs. electricity expenditure, variables associated with homes that use LPG, NG or electricity for cooking, with their respective monthly expenditure, among others. Thereafter, using R as the programming language, it was determined that the regression model taking the per capita generation of MSW as a proxy to evaluate the generation of food waste was formed by: number of inhabitants per dwelling, most recent electricity fee, LPG, food expenditure within the household and use of charcoal and firewood. In addition, the principal component analysis showed that the first 2 components generated can explain approximately 55% of the sample. Dimension one has an important influence of electricity as the fuel used for cooking; while the second one, by LPG, NG and number of inhabitants.

The analysis carried out for this first exploration at a regional level suggests that there is a directly proportional relationship between the use of fuels (e.g., NG, LPG, electricity and wood) and the food waste generation. In addition, it also makes visible the variation in consumption patterns, which vary from region to region. Also, due to the demographic imbalance present, the study suggests using a specific observation level (e.g. regional or district) in order to get a better handle on the information (e.g., uncertainty). Finally, considering that nowadays regional governments are increasingly interested in environmental care (Mesjasz-Lech, 2021), their interest should be reinforced not only with the existence of sustainable and financially viable environmental management mechanisms for the adequate treatment of these wastes (Sharma & Chandel, 2021), but also with preventive measures to minimize the production of food loss and waste (FLW).

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Importance of (properly) including food waste at retail and consumer in LCA

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More and more people are paying attention to sustainability of food. But how do you determine if food is sustainable? A life cycle assessment (LCA) can be a great way to provide fact-based information on the environmental impact of a food product. Many food producers are executing LCA's for their products. They know their processes and supply chain like no other. However, as soon as the product leaves their factory or distribution centers it is out of their control. To analyze the full life cycle, LCA practitioners have to model these last steps based on assumptions. Two important assumptions LCA practitioners must make in food product LCAs are the percentages of food waste at retail and consumer. With food waste being responsible for 8-10% of total anthropogenic GHG emissions (Mbow *et al.*, 2019), it's clear that the assumptions made can have a large influence on the environmental footprint. To properly account for food waste in LCA and accurately represent the true environmental footprint of the food product, practitioners need to find reliable data sources.

Approach/methodology
In an LCA study for a large frozen food manufacturer we tried to find this more reliable food waste data. In this study, we compared the full cradle-to-grave environmental footprint on 22 frozen food products and their alternative products (i.e. the same product of different preservation methods). Looking for secondary data sources for product and preservation method specific food waste percentages at retail and at consumer, we ran into some challenges described below.

Challenges of finding food waste percentages
Product categories are too broad
The Product Environmental Footprint method (PEF) of the European Commission (Zampori and Pant, 2019) provides default values and guidance for addressing assumptions made in product LCA's. The PEF provides waste percentages for the biggest product categories, such as fresh fruits and vegetables. However, with such a big product category you are comparing apples with oranges.

Contradicting definitions of food waste
When looking for other data sources, it is important to realize different definitions of food loss and waste exist. A common split is made into categories such as avoidable, possibly avoidable and unavoidable food (WRAP, 2016) or edible, questionably edible and inedible food (NRDC, 2017). These categories are meant to indicate that not all food loss and waste can be prevented. Bones, pits, inedible peels and other parts may be typically part of food purchased, but were never expected to be consumed by humans. Some food parts may be considered edible by some people but not by others, covering many things from potato peels to chicken feet. These fall under the category of 'possibly avoidable' or 'questionably edible' food loss and waste. Food loss and food waste are two different things. According to the FAO (n.d.) food waste is the decrease in quality or quantity of food by retail, food service providers, and consumers. When the decrease in quality or quantity takes place at an earlier stage in the food supply chain, this is called food loss. Another point of

discussion around the definition of food loss and waste is whether or not food that is used as animal feed is food loss/waste. In the FAO definition this food that is used as animal feed is not seen as food loss/waste since it re-enters in another productive utilization. According to WRAP (2016), food used as animal feed is not legally defined as waste since it is seen as a method of waste prevention. Since the system boundaries of a food LCA do often not include the animal system that uses the waste as input, LCA practitioners might often want to include the food sent to animal feed in their waste percentage.

These different definitions and broad categories make the search for suitable, product-specific data challenging. To overcome these challenges, LCA practitioners could collect primary data from retailers and consumers according to a clearly set definition of food waste.

High variability of food waste percentages
In the LCA study we did for a large frozen food manufacturer, we collected and compared primary data from four retailers and literature data (including PEF data) based on a set definition of food waste. For consumer food waste, we used literature data only. This resulted in a big range of numbers where for frozen food in retail, the waste percentage from one source was 60 times higher than the waste percentage of another. After excluding outliers and unspecific data, this was still a factor of 6 difference. For some chilled products in retail, the highest data point was 24 times higher than the lowest data point.
At consumer the spread of the frozen food waste data was even higher with a factor of 42 difference between the highest and lowest data point (excluding outliers).

The sensitivity of LCA results to changes in food waste percentages
In this study, we found that the results are very sensitive for food waste numbers. For some products, the food waste number changes the results of the comparison of carbon footprint of the frozen product and its alternative. Meaning that depending on the food waste number, the frozen product has a lower impact than its alternative or the other way around. Results of the case studies are used to illustrate this.

Conclusions
The different definitions of food waste, the high spread of data, and the high impact of the used food waste numbers ask for guidance on how to (properly) include food waste in LCA. This could include a clear definition of food waste and product-specific default values for modelling food waste at retail and consumer.

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04 Poster Session

Allocation in the LCA of meat products: is agreement possible?

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Keywords: *agricultural LCA, co-products, meat supply chain, stakeholder consultation, ISO standards, LCA guidelines*

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Context: Allocation is a key methodological issue in LCA, since allocation rules in ISO standards are commonly subject to several interpretations. Although ISO standards recommend avoiding allocation, it is often applied to agri-food systems, as LCA faces the problem of the multi-functionality of agriculture and the complexity of the system extension (Notarnicola et al., 2017). The present study focusses on impacts allocation in the meat supply chain, as this sector produces numerous products (meat) and co-products (e.g. skins, viscera, bones), with multiple uses and actors involved, leading to many conflicts of interest (Chen et al., 2017). Our study aims to develop a method determining the allocation rule as consistent, impartial, unbiased, and applicable as possible using as a case-study the meat supply chain.

Methods: The study is conceived in three phases: (i) a general literature review of factors influencing the choice of allocation rules based on around 30 LCA guidelines and allocation-focussed scientific articles (see Wilfart et al, 2021), (ii) the consultation of 22 stakeholders involved in the meat supply chain to identify underlying reasons for their allocation-rule preferences The interest of the workshop was more to cover a wide range of opinions and to decrypt them, than to build opinion profile types with a statistical approach. To avoid the subjectivity that often prevails when choosing an allocation rule, each allocation rule was analyzed through its properties determined during the workshop: basic principle, sensitivity to conditions, expected influence on the relative weight of each co-product, limits of validity, and position in the ISO hierarchy; (iii) and the building of assessment matrix of allocation rules.

Results: The literature review shows divergent recommendations even if economic allocation is mainly preferred for agricultural products. Stakeholder consultation reveals the 4 criteria underlying the divergent choices (figure 1): meaning, compliance with recommendations, stability in time and space, and ease of implementation. This study highlights that the main criterion was the meaning, which is also the most subjective one, and which leads to two different rules - biophysical or economic allocation (figure 2). Stakeholders often ranked the economic or biophysical rule first, but never the physical rules. Each rule except economic one received the lowest score from at least one stakeholder, which highlights the diversity of opinions.

Discussion: This study highlights two main consistent trends to allocate in attributional LCA of the meat supply chain: one based on social reality (economic rule) and another based on (bio)physical reality. This work showed the inability to choose a single "best" allocation rule based on scientific or technical arguments alone. It revealed the predominance of "meaning", which is a subjective criterion that refers to different ways of representations and vocation of the sector. However, this study regrouped for the first time the ideas that underlie these two schools of thought and indicated consequences of their use. Besides helping LCA practitioners consider allocation in the meat supply chain, this study can help them spending less time on allocation rules choice, and share detailed arguments to conduct choices in participative approaches with their stakeholders. Ultimately, we have to admit that no allocation rule is perfect in LCA, since allocation is always artificial a and compromise.

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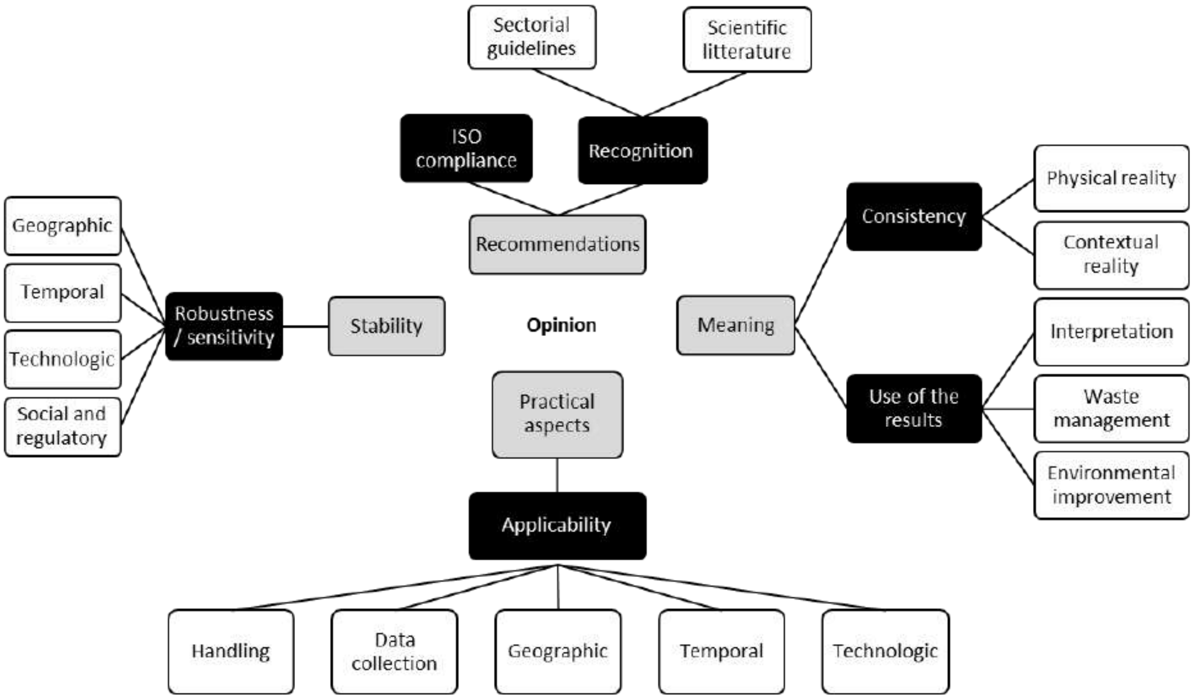

Figure 1. Mind map of criteria and qualities underlying the thinking patterns of the stakeholders. Gray ( ) for the principles, Black ( ) for Family of criteria and white ( ) for criteria.

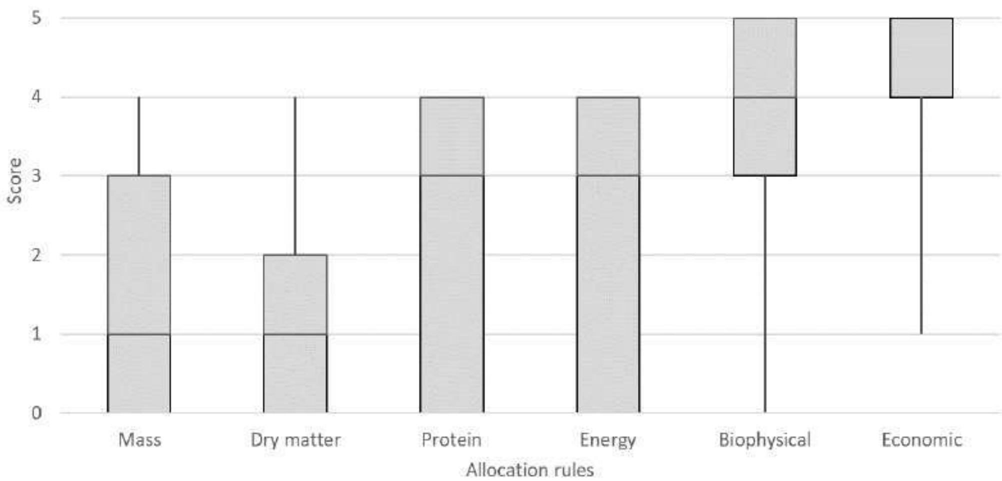

Figure 2. Box-and-Whisker plot (min, max, median, Q1 and Q3) of scores given by the 22 stakeholders for the allocation rules (from 0 (no opinion) to 5 (top preference)).

Improving efficiency of Finnish beef production through breeding with genomic selection effects climate impact of beef

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Rationale Currently in Finland beef consumption is approximately 103 million kg, while the beef production covers about 80 million kg as about 7 million kg of the total production volume is exported (Luke 2022a, 2022b). Major part (80%) of the Finnish beef is produced as dairy breed. However, the number of dairy cows has declined 11% over period of ten years 2011-2021 (Luke 2022c). Thus, the amount of beef from dairy breed is declining while the consumption rate has remained on the same level. The resulting gap is covered with import and increasing domestic beef breed production. Beef production is one of the largest sources of greenhouse gases within agricultural sector and thus, more ecologically efficient beef production is needed. According to Gerber et al. (2013), there is a lot of variation in the emission intensity within beef sector. Recent research has shown that the key factor to reduce both the gross GHG emissions and the emission intensity is to improve efficiency of the beef sector (Hietala et al. 2021; Quinton et al. 2017). Quinton et al. (2017) showed that both gross GHG emissions and the emission intensity can be reduced by improving the volume of production and as important is to have durable and small dams with good feed efficiency to reduce the environmental impacts of beef production. The key factor in obtaining the above-mentioned characteristics in the beef cattle is genetics.

Objective This study aims to evaluate the impact of breeding with genomic selection of traits directed towards efficiency on global warming potential (GWP) of beef. Genomic selection is directed to improve the efficiency and self-sufficiency of Finnish beef production based on suckler cows by upgrading the current traditional beef breeding scheme into genomic evaluation scheme, by developing genomic evaluations for the selected traits. Impact of the beef production systems, ranked by the selection traits, are assessed for their GWP.

Approach and methods The ranking of the slaughter animals was conducted in terms of breeding values. The best and poorest ranking (the best 25%, Q75, the worst 25%, Q25) slaughter animals within breed and sex were selected from the national slaughter weight evaluation and compared to average production within a cohort. Assessment was conducted for two different types of beef breeds: Hereford (Hf) and Charolais (Ch). Related environmental impacts were assessed with LCA. The LCA was conducted with the assessment model described in Hietala et al. (2021), following IPCC methods. It includes modules of animal production, on- and off-farm crop and grass production, manure management, input production, and quantifies related direct and indirect greenhouse gas emissions. LCA model was complemented with specific excretion and retention models for Hf and Ch (Nousiainen et al. 2022). It was assumed that the average Finnish beef breed production as described in Hietala et al. (2021) is representative for the different breeds as well. Collected, breed and sex specific data on the two breeds were used for slaughter weights, slaughter ages, daily growth and birth weights. The system boundary was set from cradle to farm gate and functional unit (FU) was defined as 1 kg carcass weight. Here, the assessment results of the slaughter animals are presented without allocated emissions from suckler cows.

Results and discussion

The results of the slaughtered bulls and heifers indicated that in comparison to average production, the best ranking quarter based on breeding values performed also best regarding GWP. With Charolais and Hereford the difference in GWP of average and Q75 was -1.9 - -3.3% per FU (Fig.1 and 2). Comparison between Q25 and Q75 revealed a difference of up to approx. 15% per FU.

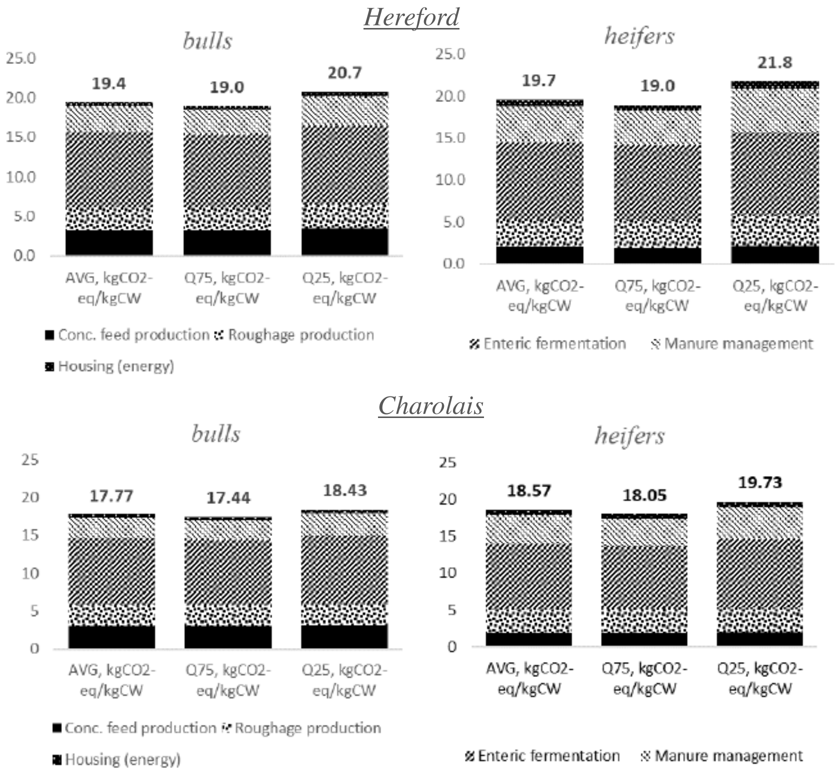

Fig.2 GWP of Finnish Hereford (above) and Charolais (below) beef, per kg carcass weight, for average (AVG) production and best quarter (Q75) and poorest quarter (Q25). Bulls and heifers are presented separately.

Discussion and Conclusions The study highlighted that the best genetics for slaughter traits resulted in the lowest emissions. It was found that best performing quarter had the lowest emissions. Between average and best performing quarter, the difference was less than between average and poorest quarter, indicating that efficient breeding is a powerful tool to mitigate emissions. Between the best and poorest quarters, the difference was up to 15% in emissions. Yet, uncertainty analyses are to be conducted further in the study. Finland is currently upgrading its breeding scheme from traditional into genomic evaluation. Thus, it is expected that the difference between best and poorest genetics will be even higher. In this study, only the slaughter animals were studied without suckler cows. Suckler cow's performance and efficiency can affect GWP largely. Thus, in further studies the investigation is to be extended to include emissions from suckler cows.

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Life cycle assessment of tomato cultivation in Sicily: comparison between traditional and innovative method

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The agri-food sector adversely affects the environment through the loss of biodiversity, climate and land use change as well as the risk of chemical contamination. It can also have repercussions on the economic fabric due to difficult access to food and its distribution (Campi et al., 2021) just as on the social structure because of insufficient protection of human health and food quantities, often of poor quality (FAO et al., 2018). Within the life cycle of an agri-food product, the agricultural phase is responsible for most of the negative aspects mentioned above. It is characterised by an excessive use of land, fertilisers and others resources and a bad management of agro-losses (Ingrao et al., 2021). For these reasons, the aim of the research is to highlight the environmental impacts of tomato cultivation, in Sicily (Italy), by comparing a traditional cultivation model and an innovative one, to determine the most sustainable. The first represents an agro-ecological model, which envisages a reduced use of inputs in the cultivation process and the reduction of machinery used. At the same time, the objective of the traditional model is to represent a regenerative one for the ecosystem aimed at preserving and increasing organic matter in the soil, while reducing the synthetic inputs employed. The innovative model, on the other hand, is a productivist one that has provided important negative externalities over time having repercussion on functional biodiversity (Gurr et al., 2017), human health (Barański et al., 2014) and the environment (Bernhardt et al., 2017). It is based on the intensification of chemical use and the employment of advanced machinery, abandoning manual cultivation practices such as transplanting and harvesting. The tomato cultivations examined, follow the conventional method. They differ only in the degree of innovation implemented, such as the number and type of machinery used, as well as the quantities of fertigation and pesticide treatments. Many comparative lca studies on tomatoes can be found in the literature, which mainly focus on: imported tomatoes compared with local ones (Webb et al.,2013); composting (Martínez-Blanco et al., 2009), urban farming (Ceron-Palma et al., 2012), and pest management (Anton et al., 2004). Other studies instead combine LCA with new perspectives, such as social LCA (Petti et al., 2018), ready-made meals (Schmidt Rivera et al., 2014), new impact category methods (Mu~noz et al., 2010), packaging (Ganczewski et al., 2014), and improved methodologies (Chapagain and Orr, 2009). For this reason, the aim of the study is to compare two cultivation processes, which although apparently similar in terms of following conventional farming principles, differ greatly in the level of technologies and inputs employed.

The methodology used for quantifying environmental impacts is Life Cycle Assessment. The study was carried out considering 1 ha of area cultivated with tomatoes for each farm examined, and 1 kg of product harvested. For this purpose, the LCA was carried out with a "from cradle to farm gate" approach, setting the boundaries of the system from the finding of the seed to the harvesting of the product. The inventory analysis was implemented through the use of primary and secondary data. The former collected through questionnaires and face-to-face interviews with farmers and the latter extrapolated from databases of recognised value such as Ecoinvent 3.6 (Wernet et al., 2016) available on the SimaPro 9.1 software used for the analysis. Secondary data mainly concern the preparation of materials and energy inputs used in all steps of the investigated systems (Zingale et al., 2021). The available literature on the subject shows how comparative evaluation involves the comparison of two or more equivalent products or services to determine which has better environmental performance (Pineda et al., 2021). In addition, no allocation was implemented of the analysis. With regard to impact analysis, this consists of quantifying potential environmental impacts through the selection of impact categories. 18 were analysed, including: Global warming, Terrestrial acidification, Freshwater eutrophication, Land use, Mineral resource scarcity, Fossil resource scarcity, Water consumption and others. The results of the study conducted on 1 ha of cultivated area, in order to study the ecological function of the cultivation process, showed a higher impact of innovative tomato (IT) than traditional tomato (TT) for all impact categories analysed. Table 1 shows the results per ha of cultivated area while Table 2 shows the results per kg of harvested product.

Table 1 comparative lca per ha of cultivated area (*)

Impact category	Unit	Traditional Tomato	Innovative Tomato
Global warming	kg CO2 eq	2848.55	4737.77
Stratospheric ozone depletion	kg CFC11 eq	0.07	0.08
Ionizing radiation	kBq Co-60 eq	31.40	124.22
Ozone formation, Human health	kg NOx eq	10.64	16.86
Fine particulate matter formation	kg PM2.5 eq	9.12	16.81
Ozone formation, Terrestrial ecosystems	kg NOx eq	10.73	17.05
Terrestrial acidification	kg SO2 eq	17.53	27.10
Freshwater eutrophication	kg P eq	0.40	0.81
Marine eutrophication	kg N eq	0.02	0.06
Terrestrial ecotoxicity	kg 1,4-DCB	5550.20	16404.23
Freshwater ecotoxicity	kg 1,4-DCB	101.57	363.12
Marine ecotoxicity	kg 1,4-DCB	129.52	459.00
Human carcinogenic toxicity	kg 1,4-DCB	28.38	100.16
Human non-carcinogenic toxicity	kg 1,4-DCB	2520.55	5580.01
Land use	m2a crop eq	32.32	303.35
Mineral resource scarcity	kg Cu eq	10.10	70.62
Fossil resource scarcity	kg oil eq	337.75	839.50
Water consumption	m3	810.24	4063.88

(*) our elaboration

Table 2 comparative lca per kg of fresh mass (*)

Impact category	Unit	Traditional Tomato	Innovative Tomato
Global warming	kg CO2 eq	0.0159518565	0.0525892318
Stratospheric ozone depletion	kg CFC11 eq	0.0000003707	0.0000009321
Ionizing radiation	kBq Co-60 eq	0.0001758422	0.0013788852
Ozone formation, Human health	kg NOx eq	0.0000595811	0.0001871733
Fine particulate matter formation	kg PM2.5 eq	0.0000510578	0.0001866427
Ozone formation, Terrestrial ecosystems	kg NOx eq	0.0000600641	0.0001892269
Terrestrial acidification	kg SO2 eq	0.0000981507	0.0003007998
Freshwater eutrophication	kg P eq	0.0000022635	0.0000090454

Marine eutrophication	kg N eq	0.0000000968	0.0000006428
Terrestrial ecotoxicity	kg 1,4-DCB	0.0310811357	0.1820869353
Freshwater ecotoxicity	kg 1,4-DCB	0.0005687894	0.0040305847
Marine ecotoxicity	kg 1,4-DCB	0.0007253165	0.0050948528
Human carcinogenic toxicity	kg 1,4-DCB	0.0001589382	0.0011118057
Human non-carcinogenic toxicity	kg 1,4-DCB	0.0141151019	0.0619380830
Land use	m2a crop eq	0.0001809921	0.0033671787
Mineral resource scarcity	kg Cu eq	0.0000565578	0.0007838922
Fossil resource scarcity	kg oil eq	0.0018913771	0.0093185001
Water consumption	m3	0.0045373593	0.0451091010

(*) our elaboration

The higher impact of IT is due to the increased amount of fertilisers and pesticides used as well as the increased use of machinery for the cultivation process. The same is confirmed for the kg of product harvested, where the objective of the study is the production function and where TT performed even better than IT due to the higher yields and despite the reduced level of technology applied. The results highlighted by the LCA of Sicilian tomato cultivations, comparing two farms that differ in their level of innovation but not in their method of cultivation, show that the degree of mechanisation and the high quantity of inputs used do not always represent an advantage for the environment and for the farmer. Reduced environmental impacts as well as higher yields demonstrate this double advantage. Improving tomato cultivation sustainability requires increasing production by reducing losses and the associated environmental burden. In relation to the different production contexts of tomatoes, innovative cultivation might be the best choice in cases of reduced available labour, high cultivated areas and limited product quality requirements.

The aim of the study is to provide farmers with a framework of useful practices to pursue sustainable development; therefore to support them in the choice of agroecological practices in order to make tomato cultivation more sustainable, providing products which contains both environmental and health value due to lower quantity of inputs used.

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Strategies for reducing the carbon footprint in maize silage based dairy cattle farms from the Basque Country (northern Spain)

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Rationale: Milk is one of the most produced agricultural commodities worldwide, accounting for approximately 27% of the global value added of livestock production (FAO, 2018). During the last decade, there has been an increasing interest on assessing the environmental impacts of different milk production systems in Europe, particularly regarding the carbon footprint (CF) of raw milk from dairy cattle (O'Brien et al., 2015, Cortes et al., 2021). Mitigation of greenhouse gas (GHG) emissions per unit of milk has been identified as a key issue for the European dairy sector (O'Brien et al., 2015). This objective is expected to be more ambitious in the next future in accordance with the European Green Deal (EGD) agreement, which aims to make Europe the first carbon-neutral continent by 2050.

Objective: The aim of this study was to analyze the potential of different feeding and management strategies in reducing the CF in maize silage based dairy cattle farms from the Basque Country (northern Spain).

Approach and methodology: The study was conducted on a typical dairy cattle farm from the Basque Country (Northern Spain), in which maize silage is an important forage source. The farm was characterized according to data collected from 17 dairy farms, which belonged to this typology (RTA 2015-00058-C06 project). The dairy herd had 123 cows (105 milking cows), 39 heifers and 42 calves. Total milk production was 1,111,501 kg FPCM/year. Mean age at first calving was 25 months. The ratio of maize silage to grass silage in the ration of milking cows was 50:50, and the mean concentrate intake was 11.7 kg/cow/day. Concentrates were characterized according to the ingredients identified in the surveys conducted at farm level. The total utilized agricultural area (UAA) was 57 ha: 30.5 ha grassland, 23 ha maize cropland, and 3.5 ha for grazing (heifers and dry cows). Considering the maize cropland area and the maize silage consumption by the milking herd, it was assumed that no maize silage was purchased at the farm. The following CF abatement scenarios were simulated: (i) reduction of soybean meal in the concentrates (from 20% to 10% in DM), (ii) increased digestibility of rations due to improved forage quality (4%), (iii) 10% reduction in replacement herd, (iv) 20% reduction in replacement herd due to an earlier age at first calving (22 months), (v) installation of solar panels at the farm (100% renewable energy), (vi) soil C sequestration, and (vii) the combination of previously described scenarios. No milk yield changes were assumed for both nutritional strategies. Alternative concentrates to soybean meal replacement were isoproteic and isoenergetic in relation to the reference concentrate. Soil organic C (SOC) sequestration of grasslands was estimated according to the value reported by Petersen et al. (2013), who stated that 9.7% of SOC added to soil in terms of manure or crop residues would be stored in a 100-year perspective.

A cradle to gate LCA approach was used. Simulations were carried out using SimaPro 9.1 software, with an allocation of 96.1% to milk production. IPCC (2006) methodology was used to calculate on-farm GHG emissions, and 100-year global warming potential (GWP) values reported by IPCC (2013) were applied. The functional unit was kg CO_2 eq/kg FPCM (fat-and protein-corrected milk).

Results and discussion: The CF of the reference farm was 1.72 kg CO_2 eq/kg FPCM, in which enteric CH_4 emission from dairy cattle, and the soybean meal of concentrates were the major contributors to CF. They accounted for 33.0% and 15.1% of CF, respectively. Figure 1 shows the distribution of the different elements that contributed to CF at the simulated dairy farm (cut-off, criteria 1%). On-farm GHG losses accounted for 53.6% of total CF.

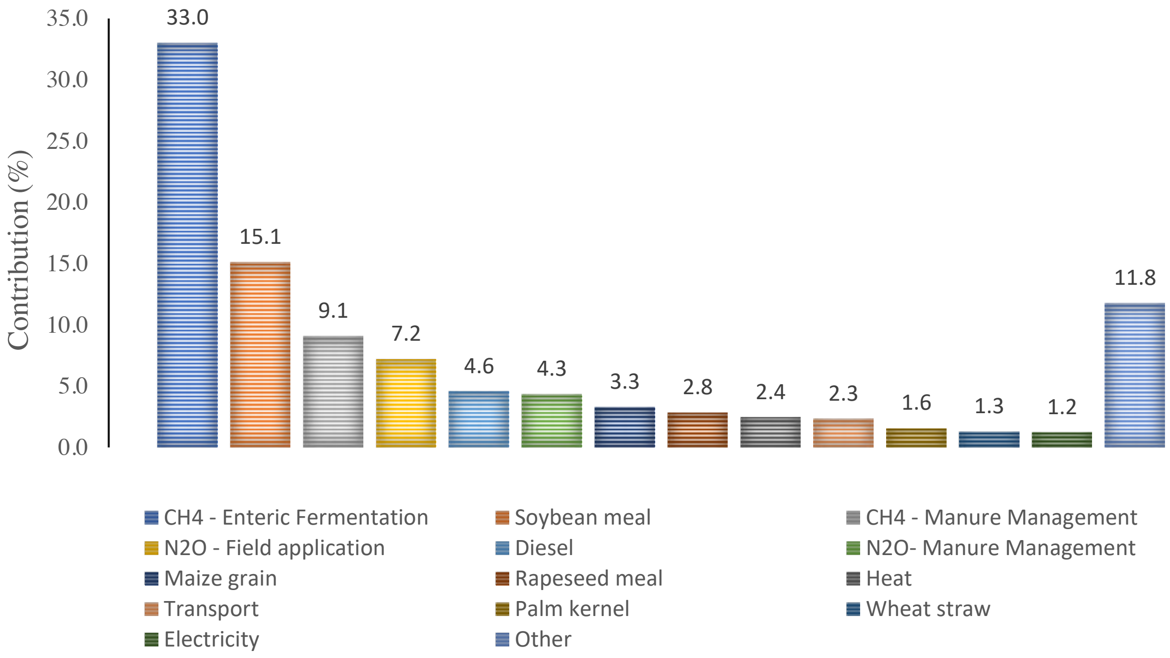

Fig. 1. Contribution of the most relevant processes in the carbon footprint at default dairy farm.

This value was slightly higher than the mean CF (1.60 kg CO_2 eq/kg FPCM) reported by Cortés et al. (2021) in Galicia (northern Spain). A similar methodological approach was conducted in both studies. Such difference was attributed to the farm typology selected in our study. The high concentrate inputs at farm level, in which soybean meal (3.73 kg CO_2 eq/kg soybean meal, Spain) accounted for ≈15% of the ingredients, would have mostly contributed to the higher CF observed in our study. Besides, Cortés et al. (2021) assessed the CF of 96 dairy cattle farms allocated to different milk production systems.

Figure 2 shows the effect of different CF abatement strategies at the default dairy farm. The partial substitution of soybean meal in concentrates by rapeseed meal and maize DDGS was the most promising abatement strategy as CF was reduced by 7.0% (1.60 kg CO_2 eq/kg FPCM). Increasing the theoretical digestibility of rations by improving the quality of forages (maize silage and/or gras silage) reduced the CF by approximately 3.5% (1.66 kg CO_2 eq/kg FPCM).

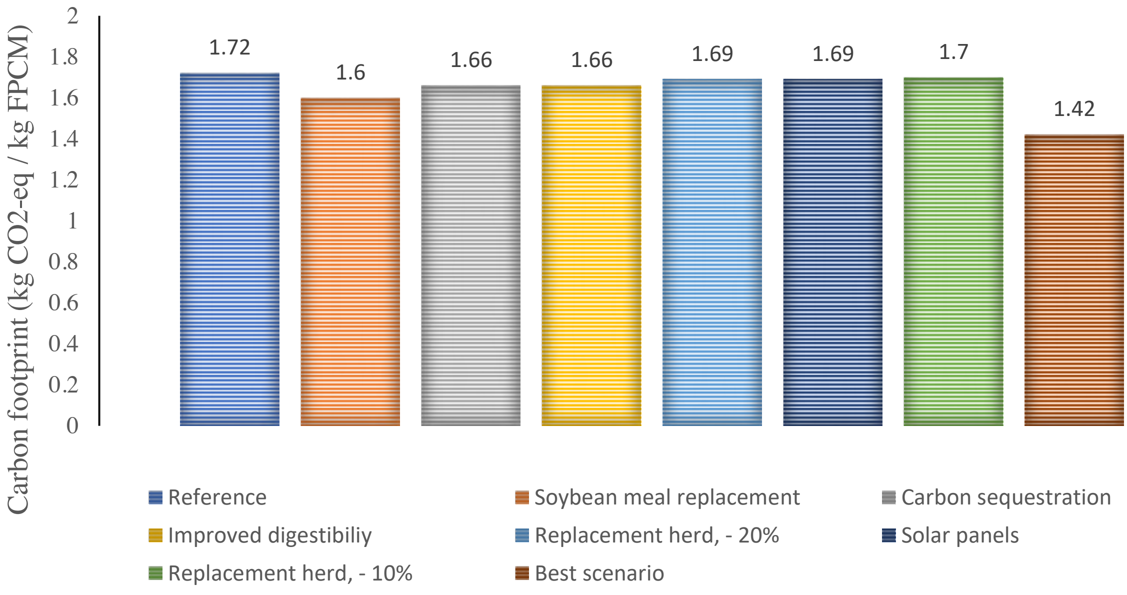

Fig. 2. Carbon footprint after different abatement scenarios at default dairy farm.

When grassland SOC sequestration was included in the simulation, the CF of the reference farm was 1.66 kg CO_2 eq/kg FPCM. The mitigation rate attributed to grassland SOC sequestration in this study (3.5%) was slightly higher to those rates reported by O'Brien et al. (2014) for maize silage based dairy farms in UK and US. It should be noted that there is not currently consensus on how the impacts of land use on SOC stocks would be best quantified when performing LCA of agricultural products (Joensuu et al 2021). The reduction estimated for the rest of scenarios did not exceed 2% of CF of the reference farm. The joint application of above-mentioned strategies reduced CF by 17.4% at farm level (1.42 kg CO_2 eq/kg FPCM). The success of the practices above described in the abatement of CF depends on their real adoption at farm level. This depends on public and private incentives, public policies and taxes, costs and logistics of implementation, and trade-offs (Herrero et al., 2016).

Conclusions: It is concluded that CF reduction in maize silage based dairy cattle farms from the Basque Country (northern Spain) is feasible through nutritional and management strategies (≈15%). Among simulated scenarios, herd nutrition strategies would have the highest mitigation potential.

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Determining the carbon footprint of Dutch raw milk over 30 years: Challenges and opportunities

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Introduction

In 2019, dairy production used 26% of the land in The Netherlands, exported 7.8 bn euros and was the main income for around 17,000 farmers (ZuivelNL, 2020). The Netherlands represents 5% of the global dairy market exports (NZO, 2020). On the other hand, milk and meat products are seen as the food products with one of the highest carbon footprint (Parodi et al., 2018; Poore and Nemecek, 2019). However, the carbon footprint of raw milk from different regions varies considerably (from 6,67 kg CO_2 eq. kg FPCM in SSA to 1,29 in North America) depending on the productivity level of the dairy farming systems (FAO and GDP, 2018). In the Netherlands, farmers, governments and the industry have worked over the last decades to improve productivity and reduce the environmental impact of dairy production. This has reduced the carbon footprint of raw milk, but the exact extent of this reduction and the drivers for reduction were unknown. In order to have reliable metrics of the progress, long term data series are needed. This raises a series of problems: availability of reliable data, evolving emission factors and global warming potentials, assumptions to be made. Here, we discuss the main challenges when determining the Dutch raw milk carbon footprint between 1990 and 2019.

Materials and methods

We applied Life Cycle Assessment (LCA) to estimate the carbon footprint of raw milk in the Netherlands for the period 1990 to 2019. To the best of our knowledge, this is the longest time-series data of carbon footprint of a product. For this, we worked with the average Dutch dairy system following van Bruggen et al (2021). Data was collected from different sources including national statistics (CBS, 2021; van Bruggen, 2020; van Bruggen et al., 2021), and data from the farm accountancy data network (FADN, 2021).

Purchased feed is one of the most relevant sources of GHG emissions in dairy systems. Up to now there is no Life Cycle Inventory dataset available for long-term carbon footprints of animal feeds. To obtain this, the historical recommended feed composition was retrieved from a knowledge and research institute for the feed industry (Schothorst Feed Research B.V.) and adjusted to align with other farm system data and nutritional requirements of the dairy herd. For feed ingredients origin we retrieved from FAO data (FAO, 2021)for im- and export of feed ingredients to the Netherland and production data of the crops in the identified sourcing regions. Land use change data were based on different sources based on the region of the world (FAO, 1988, 1976; Persson and Olan, 1974).

This is one of the first carbon footprint studies to include carbon sequestration on dairy farms over a longer time series based on dynamic model Roth-C (Coleman and Jenkinson, 1996). Working with

carbon sequestration led to decisions into the method to assess sequestration, assumptions to define crop rotations, grassland renewal and rates of sequestration over time.
A sensitivity analysis was performed on the most important methodology choices affecting the absolute carbon footprint and the trend over the years to assure the reliability of both the absolute carbon footprint level as the reduction rate.

Results and discussion

Several challenges were found in the process of completing the data collection and performing calculations. Going back in time, further than 2015 with the same data source implied that data collected from individual dairy farms (Annual Nutrient Cycling Assessment – ANCA (KLW, 2020)) was not an option as these are only available from 2015 onwards.
Estimating on farm land use for production of grass and maize production was another challenge. For this, we started from the cow's feed intake and, through records on average yields per hectare, which were quite variable over time, we estimated the area used to produce the dairy feed. While this is the best option available, contradictions can arise when yields change due to climatic events such as droughts. Therefore we included a sensitivity analysis based on farm land ownership data.
Connecting farm, national and companies' databases into one logic and consistent database required a process of understanding and translating each other's vision and interpretation on variables.
This learning process highlighted the relevance of having consistent and reliable activity data and emission factors. Systems like the ANCA that collect farm specific yearly farm data to calculate different environmental impacts are key in order to have a solid basis for monitoring progress towards environmental targets. Furthermore, the main sources of emissions, the evolution and changes in particular events such as droughts or regulations give important learnings on how to reduce, or avoid an increase in GHG emissions from the dairy industry in the future. Moreover the study shows that differences in weather between years and resulting yields affect farm productivity, the ration of cows and therewith the carbon footprint of milk as well as carbon sequestration rates. This is an important learning knowing that our future climate will be more variable.
Data on compound feed composition was lacking. Therefore, compound feed composition was based on compositions optimized for lowest cost-price, based on single feed ingredient prices and availability in the specific year. We adjusted compound feed composition to match the protein content data retrieved. To make the match we needed to add single protein rich feeds to the diet. For the protein ingredients in the diets we assumed that 50% was soybean meal and 50% was rapeseed meal. This may not be the exact compound feed fed to the dairy herd. As soybean meal is a feedstuff with a high carbon footprint, this assumption has a significant impact on the carbon footprint of compound feed. For the period between 1990 and 2001, no information on compound feed composition was available and we used an average composition equal for all these years based on feed experiments.
Our study shows that though productivity can reduce the carbon footprint per kg of milk, it also often leads to an increase of total milk production, i.e. less reduction in total GHG emissions, a relevant learning for countries that aim at reducing national GHG emissions through improving farm productivity. While we did this analysis *ex-post*, the same analysis could be done *ex-ante* before implementing regulations or planning for climate adaptation.
Calculating carbon sequestration shed light on the need of an international standard to account for it in carbon footprinting and the high variability in year on year carbon sequestration due to weather circumstances, which makes carbon crediting of carbon removals problematic. The sensitivity analysis shows that though the choice of emission factors and assumptions of farm management affects the absolute level of estimated GHG emissions, the reduction rate however was largely unaffected by choices in carbon footprint methodology .

Conclusion

Estimating the longest time series of carbon footprint of raw milk led to several challenges, including gathering reliable data, making assumptions and connecting data from different sources to represent a Dutch average farm. However a solid estimation of these time series was possible for the Netherlands and led to interesting lessons for the feasibility of future climate targets. In this process lessons were learnt over the potential of *ex post* analysis to do *ex ante* work, highlighting the relevance of having centralized databases on activity sources and emission factors. Furthermore, the collaboration between businesses (dairy and feed company) and researchers (consultants and university) provided synergies in knowledge, data access and validated methods to achieve the end goal.

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Environmental impact and circularity of dairy products packaging

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1. **Introduction:** Dairy products are considered one of the most important products for our diet. Various studies have been focus on the environmental impact of the dairy industry, since it is classified the fifth consumer of energy after chemical industries, contributing to several environmental issues (Munir et al., 2014). On the other hand, the packaging stage has gotten a lot of attention, and different methodologies for reducing its environmental impact have focused on its weight and the use of recyclable and renewable resources.

The circular economy plan aims to recycle 50% of plastics by 2025.Yet, to achieve the circularity objectives, doubling the present capacity of recycling is needed (Plastics Europe, 2022). For aluminium packaging, 51.9% of recycling rate was achieved in 2019 in Europe, being the cans the major aluminium food-packaging that undergo a recycling treatment (Eurostat, 2019a) . In 2018, 36% of the aluminium metal supply in Europe was made up of recycled aluminium (pre- and post-consumer scrap). By the middle of the century, post-consumer aluminium recycling might meet 50% of the Europe needs for aluminium, thus earning €6 billion for the European economy each year (European Aluminium, 2018).

The main objective of this study is to environmentally compare the use of aluminium or plastic for Danone custard packaging, using life cycle assessment (LCA), and evaluate their circularity, using the newest indicators to assess product circularity: the Material Circularity Indicator (MCI), proposed by the Ellen MacArthur foundation (EM Foundation, 2019), and longevity indicator introduced by Figge et al. (2018) (Figge et al., 2018).

2. **Materials and methods:** The environmental impacts and the circularity of the containers have been anticipated using LCA, MCI, and longevity indicators.

2.1. **Life cycle assessment:** A 'cradle-to-grave' LCA was used and preserving 100 g of custard during 45 days has been chosen as a functional unit. The processes studied were extraction of raw materials, packaging production, distribution and end of life. The Inventory data (Table 1) were collected based on a dairy factory and completed using Gabi Software, which was used to model the system. Several impact categories are presented: AP: acidification; CC: climate change; Ecotox_water: freshwater ecotoxicity; Eu_water: freshwater eutrophication; Eu_marine: marine eutrophication; Eu_T: eutrophication terrestrial; HT_cancer: Human toxicity, cancer; LU: land use;

OD: ozone depletion; POF: photochemical ozone formation; RU_fossils: Resource use, fossils; RU_mineral: Resource use, mineral and metals; Water: water use.

Table 1: Inventory data of the containers

	System 1		System 2	
Process	**Input/Output**	**Amount/FU (kg/FU)**	**Input/Output**	**Amount/FU (kg/FU)**
Raw Materials	I-Aluminium_cap	5.37E-04	I-Aluminium_cap	2.51E-04
	I-Aluminium_jar	3.99E-03	I-Polypropylene_jar	4.49E-03
	I-Cardboard	3.62E-03	I-Cardboard	2.90E-03
Packaging production	I-Electricity_jar	5.54E-04 kWh	Electricity_jar	5.45E-03 kWh
	O-Waste_jar	3.63E-04	O-Waste_jar	1.27E-04
	O-waste_cap	4.88E-05	O-waste_cap	2.28E-05
Distribution to retailer	Weight total	7.74E-03	Weight total	7.49E-03
	Distance	600 km	Distance	600 km
End of life	O-Aluminium (49.1% R, 51.9% L)[a]	4.10 E-03	O-Aluminium (49.1% R, 51.9% L)[a]	2.28E-04
	O- Cardboard (72.9% R, 23.63% L, 3.47% In)[a]	3.62E-03	O-Plastic (51.5% R, 33.2% L, 15.3% In)[a]	4.37E-03
	-		O-Cardboard (72.9% R, 23.6% L, 3.47% In)[a]	2.90E-03

I: input, O: output, FU: Functional unit, R: recycling, L: landfilling, In: incineration

a: (Ministerio para la Transición Ecológica y el Reto Demográfico, 2019)

2.2. **Measuring circularity**

<u>MCI indicator</u> (EM Foundation, 2019): the Material Circularity Indicator (MCI) quantifies the linear flow minimization in comparison with the restorative flow, as well as how long and intensively it is used. MCI takes a value of 1 when the product is fully circular, and 0 for a linear product. The equation used to determine the MCI of a product is given below:

$$MCI = 1 - \frac{\mathrm{LFI} \times 0.9}{\mathrm{X}} \qquad \text{Eq. (1)}$$

Where: X is the Utility and LFI is the Linear Flow Index

<u>Longevity indicator</u> (Figge et al., 2018): the longevity indicator attempts to determine how long a product has been utilized (the length of time). It can be determined using the sum of three components as shown in Eq. (2), the initial lifetime (L^A) of which a product is firstly used, the refurbishment lifetime (L^B) of which a product is returned to use due to refurbishing and the recycling lifetime (L^C) when the resources are reused due to recycling.

$$\text{Longevity} = L^A + L^B + L^C \qquad \text{Eq. (2)}$$

2.3. **Results:**

2.3.1. Environmental impacts of the container

As illustrated in Figure 1, the aluminium container presents the highest impacts for almost all impact categories, which is mainly attributed to the production of aluminium as seen in Figure 2.

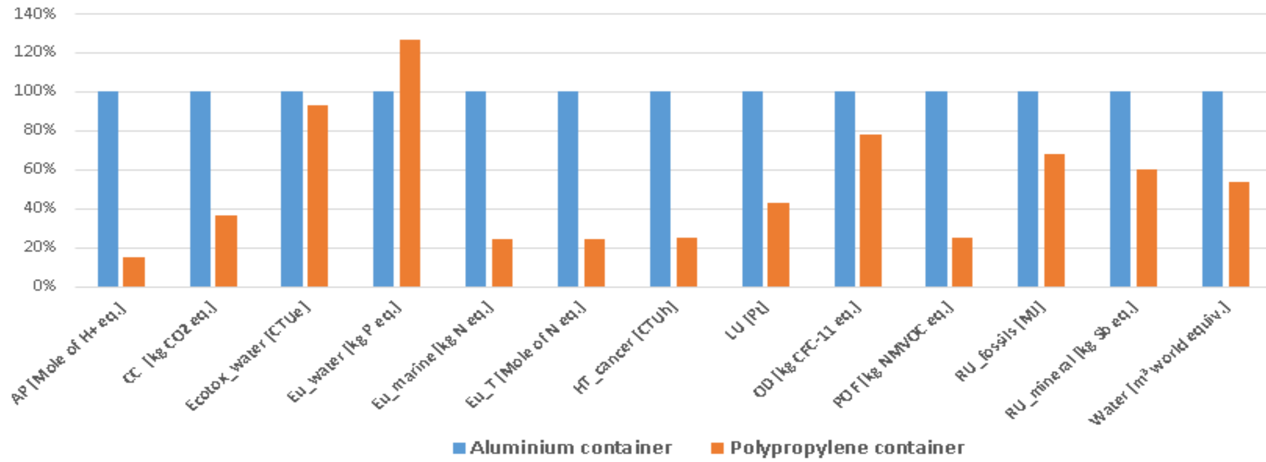

Figure 1: Environmental impacts of the aluminium and plastic containers. AP: acidification; CC: climate change; Ecotox_water: freshwater ecotoxicity; Eu_water: freshwater eutrophication; Eu_marine: marine eutrophication; Eu_T: eutrophication terrestrial; HT_cancer: human toxicity, cancer; LU: land use; OD: ozone depletion; POF: photochemical ozone formation; RU_fossils: resource use, fossils; RU_mineral: Resource use, mineral and metals; Water: water use.

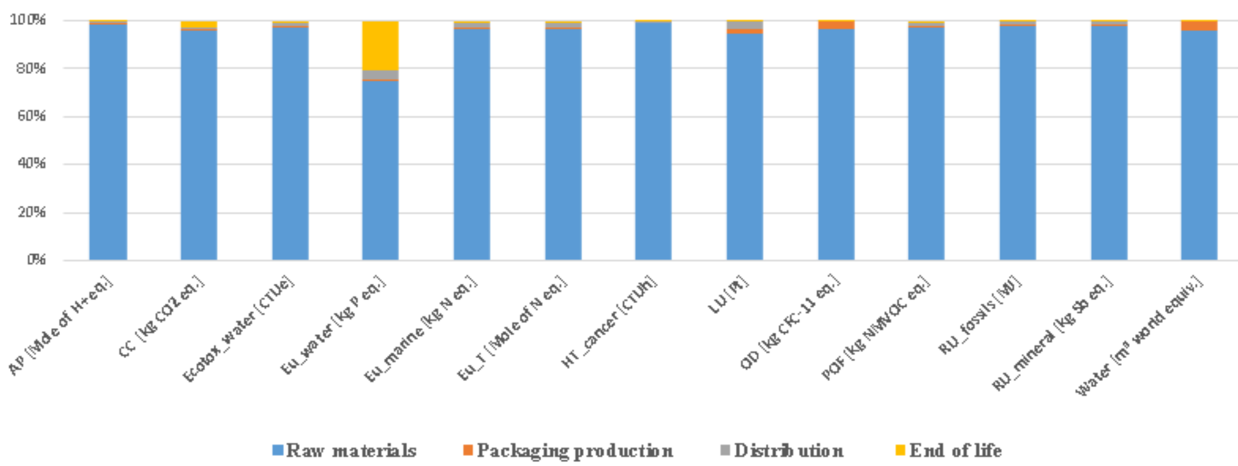

Figure 2: Environmental impacts of the aluminium container. AP: acidification; CC: climate change; Ecotox_water: freshwater ecotoxicity; Eu_water: freshwater eutrophication; Eu_marine: marine eutrophication; Eu_T: eutrophication terrestrial; HT_cancer: human toxicity, cancer; LU: land use; OD: ozone depletion; POF: photochemical ozone formation; RU_fossils: resource use, fossils; RU_mineral: Resource use, mineral and metals; Water: water use.

2.3.2. Circularity indicators

The Material Circularity Indicator (MCI) of the two containers was calculated using Eq. (1). Both containers are made from 100 % virgin sources. At the end of life, 53.7 % of aluminium (Eurostat, 2019a) (Valpak Limited, 2017) , and 69.4 % of plastic packaging (Eurostat, 2019b) (Valpak Limited, 2017) are usually collected for recycling. The efficiency of the recycling process is 91.4 % for aluminium, and 74.2 % for plastic packaging (Valpak Limited, 2017). Then, the MCI of the aluminium container is quantified to be 0.304, and that of the plastic container to be 0.268.

The longevity indicator was measured of the two containers following Eq. (2). The corresponding data are used to measure it: 53.7% of returned aluminium containers (Eurostat, 2019a) (Valpak Limited, 2017), 91.4% of aluminium retained through recycling (Valpak Limited, 2017), LA (initial lifetime) of 45 days, 69.4% of returned plastic containers (Eurostat, 2019b)(Valpak Limited, 2017), 74.2% of plastic retained through recycling (Valpak Limited, 2017). Then the longevity of the aluminium container is 88 days and of plastic container is 90 days.

2.4. **Conclusion:** Most companies found in the market prefer packing the egg custard in aluminium containers, while plastic is reserved for other types of custards. No difference on the expiration date has been considered between both packaging. This study has evaluated for the first time the environmental impacts of aluminium and polypropylene containers used as custard packaging. The results revealed that the polypropylene container seems to be the best alternative with lowest impacts for almost all impact categories. However, regarding circularity measured by MCI, aluminium presented better results (higher circularity, MCI=0.30) against polypropylene (MCI=0.26), due to lower amount of waste landfilled at the end of life. Whereas, polypropylene presents better longevity (90 days) against aluminium (88 days). Increasing the recycling rate with a very efficient recycling process leads to a more circular product (MCI close to 1)

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Environmental and socio-economic performance of the feed value chains using the cereal side streams

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Recent interest in single cell proteins (SCPs) has focused on valorization of side streams by using microbes (Ritala et al. 2017). Cereal side streams are not yet used efficiently (Valoppi et al. 2021). The annual use of oat in food industry is predicted to be 1.1 million tonnes in EU (The Finnish Cereal Committee, 2021). However, the cereal peel mass is mostly incinerated or used as livestock feed. Developing a circular economy approach to cereal side streams would help the grain production and processing industry to be more sustainable. A higher degree of processing of the food side streams may result in higher market value, consequently.

Consumption of fish is increasing worldwide leading to continuous growth in aquaculture. Currently, fish feed protein is based on plant proteins and fish meal. In global scale, soy is currently the most used plant protein source in aquaculture feeds. With increasing demand and limited supply, focus has been set on new fish feed alternatives and protein sources.

Life cycle assessment analyses facilitate quantitative comparison among different feed production systems to support decision making and improves the understanding of environmental and socio-economic performance of the feed compared to conventional feed alternatives.

In contrary to the generally optimistic views on novel food technologies, the findings of this work highlight the paradoxical impact of novel fish feed production systems on the environment and society, compared with the conventional production models currently ongoing.

Research objective

The objective of this study is to understand and evaluate the environmental and socioeconomic performance of the feed formula value chains. In our study, oat processing side streams are utilized in production of single cell protein as fish feed ingredient. We hypothesize that utilization of the cereal side streams as feedstock may deliver both environmentally and commercially affordable feed formulas.

Materials and methods

Environmental life cycle assessment (LCA), social life cycle assessment (S-LCA), and life cycle costing (LCC) methodologies were used for the environmental, social, and cost analyses of novel fish feed systems, respectively. An oat side-stream from oat bran processing for oat protein concentrate was investigated as carbon source for SCP production with yeast. LCA results were compared with conventional protein source, soybean protein concentrate. Functional units were selected as 1 kg of dried SCP product and 1 kg of protein. The SCP production models were contributed by Nordic countries.

Attributional LCA was conducted based on experimental data of this study and data from literature. The SCP production method used here is based on Liu (2020) and Wittmann et al., (2017). SimaPro PhD 9.3.0.2 with ReCiPe 2016 Midpoint (H) method was used for the calculation. The system boundary includes from resource extraction to fish feed production. Economic allocation was used.

The social assessment is concerned with the impact of fish feed production systems on relevant stakeholders including workers, local communities and society. The European data were taken as a reference baseline to identify the social risk levels of the different production models.

Given a feed production model with different processes and countries involved, the results considered process-based and country-based contributions to calculate social scores (SC_n), followed by the social risks (SR_n):

$$SR_n = Exp\left(Ln(0.5) \times \frac{SC_n}{Base}\right) \qquad (1)$$

When a higher value of SC_nthan the reference point ($Base$) reflects a more negative impact

$$SR_n = 1 - Exp\left(Ln(0.5) \times \frac{SC_n}{Base}\right) \qquad (2)$$

when a lower value of SC_nthan reference point ($Base$) reflects a more negative impact.

The economic assessment considered the cost analysis of the SCP and SoyPC production models at the Finnish scale. Fixed and variable costs were the basis of determining the operating cost structure of all models in this study.

Results

The results showed a high contribution of the fermentation phase to the global warming potential (GWP) in Finland. Energy required in this process was the highest contributor of GWP. It is notable that the country specific electricity mix had a lot of influence on the GWP.

Soybean protein-based fish concentrate had 28% to 34% higher land use compared to the SCPs. Due to the allocation of the impacts, resulting land use was relatively small for oat side streams. However, in the Finnish production scenario, GWP of the SCP based feed was twice as that of soybean protein concentrate. In Sweden and Iceland, this difference was smaller.

The social results show slight variations in SCP production across the Nordics. This is partially due to the different countries from where raw materials are imported to Finland, Iceland, and Sweden.

The social results show slight variations in SCP production across the Nordics. This is partially due to the different countries from where raw materials are imported to Finland, Iceland, and Sweden.

The Finnish SCP model had around 80% of the indicators with a social risk lower than the average European baseline, contributing to significant improvements compared with soybean production system where risks for rights violations and child labor declined by around 46%, insufficient income by 31%, forced labor by 23%, gender inequality by 62%, occupational safety by 60%, income inequality and environmental violations by up to 17%. In contrast to the soybean protein production, SCP model possessed higher risks of employment declines by around 57%. Common high risks were associated with deforestation, and potentially insufficient hospital vacancies for workers and staff.

The location of cereal cultivation plays a key role in predicting the feasibility of SCP models. The utilization of locally cultivated cereals is expected to decrease the total operating costs by around 16%. This is mainly due to the impact of transportation costs of raw materials for the Icelandic production model (22% of total operating costs).

The results demonstrate the commercial advantage of Soybean protein concentrates over the SCP in Finland. Higher costs for SCP were associated with heat and electricity intensive operations as well as chemical additives (around 15% and 26% of the operating cost structure, respectively).

Conclusions

SCP production for fish feeds contributed heavily to the GWP mainly driven by high energy inputs. This reflects the high carbon energy sources used during the production and particularly the fermentation stage. The need for a future assessment that considers low carbon energy sources seems inevitable to tackle the carbon emissions and global warming potential consequently.

Socially, the variation in results is highly influenced by the geographical factor where each region possesses different social issues. The high social quality that Finland has in terms of human and labor rights, equal opportunities and income equalities reflects the positive contribution towards minimizing social risks for SCP production. On the other hand, production of conventional soybean protein contributes to the societal economic development characterized by higher employments compared with SCP production models, regardless of country or production location.

The commercial feasibility of SCP production requires significant cuts on transportation costs particularly on cross-country routes where shipping, clearance, fuel and import costs occur. Also, significant energy inputs contribute to a high-cost structure particularly in an era of energy crisis and uncertainty.

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Analysis of economic, environmental, and energy use for the production of grafted watermelon seedlings in a greenhouse and a vertical farm

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Keywords: life cycle assessment; life cycle costing; sustainable agriculture; vegetable grafting; vertical farming.

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Rationale. Iran is in the Earth's dryland belt, struggling with severe drought and other challenges due to climate changes, such as food insecurity. These challenges require us to seek techniques such as using grafted vegetable seedlings instead of traditional methods to produce high-quality crops with higher yields and lower energy and water use. There are two systems for healing and acclimatizing grafted seedlings: conventional tunnel systems (CTS) and LED-equipped vertical systems (LVS; Moosavi-Nezhad et al., 2022). Previous studies show these systems can be used in drought regions to produce more robust seedlings to reduce risks of uncertain climate changes while conserving energy and reducing costs of meeting increased production (e.g., Moosavi-Nezhad et al., 2021). Yet, there is a need to evaluate and improve these systems' overall efficiencies in achieving these goals.
Objective. The objective of the current study is to assess and compare the energy use, economic, and environmental impacts of two different healing and acclimatization systems, the CTS and the LVS, in the production of grafted seedlings.
Approach and methodology. A life-cycle assessment approach is used to characterize grafted watermelon seedling production systems, comparing CTS and LVS, using a functional unit of one million grafted watermelon seedlings (MGWS). Life cycle assessment (LCA), cumulative exergy demand (CExD), and life cycle cost analysis (LCCA) approaches are used to assess the impacts associated with the defined production systems.
Main results and discussion. Overall, the energy and environmental impact analyses show that CTS contributes to higher energy consumption and damage to human health, ecosystems, and resources than LVS (Figure 1).

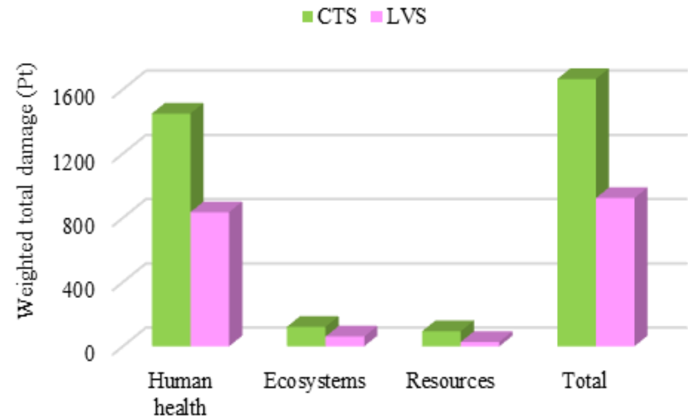

Figure 1. Comparison analysis between conventional tunnel systems (CTS) and LED-equipped vertical systems (LVS) scenarios from weighted environmental damages perspective

In addition, the economic analysis indicates that the net profit in LVS with only five floors is 24% higher than that of CTS (Figure 2). Specifically, higher seedling survival ratio, using less land area, higher insulation of buildings (for accommodating LVS) than greenhouses (for accommodating CTS), and multi-floors in LVS improve the overall environmental and economic aspects of these systems in the production of grafted watermelon seedlings (Moosavi-Nezhad et al., 2022).

Figure. 2. Comparison analysis between conventional tunnel systems (CTS) and LED-equipped vertical systems (LVS) scenarios from economical (A) and cumulative exergy demands (CExD; B) perspective.

The main contributors to energy consumption in CTS include diesel fuel (76%), nylon (8%), polystyrene (7%), electricity (3%), perlite (3%), and polypropylene (2%). The LVS main energy consumers are electricity (33%), polystyrene (31%), diesel fuel (16%), perlite (12%), and polypropylene (7%) (Moosavi-Nezhad et al., 2022).

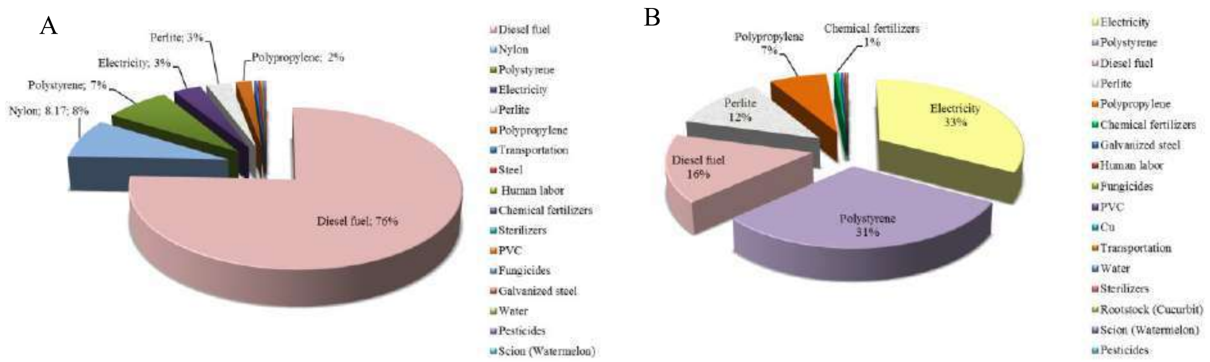

Figure. 3. Percent of each input in total energy consumption for conventional tunnel systems (CTS; A) and LED-equipped vertical systems (LVS; B).

Conclusion. In conclusion, the study results show that LVS is a less energy consumptive, less environmentally burdensome, and more profitable system than the CTS. In addition to the previously noted benefit of LVS compared to CTS, the LVS can be further improved through modifications to the minimum day length and light intensity requirements for optimal seedling quality to define the best use of LED and reduce electricity usage. Also, determining best practices for organic fertilizer usage, biological controls (for pests and diseases), and minimum rhizosphere required for seedling roots will increase the overall energy and economic efficiencies of the LVS (Moosavi-Nezhad et al., 2022).

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LCA of two West African market vegetables value chains: a field-test for the agro-ecological transition

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Keywords: agro-ecology; conventional; *organic; value chain mapping; West Africa*

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In West Africa, vegetable production most often takes place in urban and periurban (i.e. suburban) areas and commercial production is aimed at providing the cities. In various countries, such as in Côte d'Ivoire, the production of vegetables is insufficient to fulfil the national demand, thus the country resorts to importing vegetable products (de Bon et al., 2019). Moreover, vegetable production in the region is generally unsustainable due to a combination of factors (de Bon et al., 2019; El Bilali, 2020; Levasseur et al., 2007):

i) there are seldom national programmes for the introduction and selection of varieties,
ii) vegetable crops are generally grown in a conventional manner (using chemical inputs that are often unapproved and overdosed) and in monoculture on large plots of land,
iii) the level of production of the main vegetable crops is very low and sometimes insufficient to supply the local market,
iv) exotic vegetables with a high added value are often preferred to (more robust, easier to grow and richer in nutrients and vitamins) local vegetables,
v) yields remain very low, market garden crops are frequently sprayed with high doses of chemical pesticides (which reduce the quality of the produce, reduce biodiversity and pollute the environment),
vi) soils are impoverished due to the intensification of practices,
vii) the sanitary quality of products sold on local markets is not guaranteed (nor controlled and little studied by research), and, finally,
viii) the regular arrival of new pests increases the use of chemical pesticides thus further reducing the natural enemies that could contribute to better regulate them.

The so-called agro-ecological transition (or intensification) is expected to play a role in improving the sustainability of West African market vegetables production. Agro-ecological agriculture implies reducing chemical inputs such as pesticides (similar to the so-called *Lean agriculture* or *Agriculture raisonnée* (Rosenberg & Gallot, 2002)), but also other changes in agricultural practices, such as the total or partial replacement of mineral by organic fertilisers, the use of fertilising or sanitising service plants and/or of beneficial indigenous micro-organisms, and the diversification of cropping systems including a shift towards agroforestry.

Through two research projects featuring a dominant LCA component, we analysed the market vegetables value chains in Benin (Avadí et al., 2020) and Côte d'Ivoire (https://www.projet-marigo.org/), including an LCA component to assess their environmental impacts throughout the production continuum (from conventional to organic, through various stages of agro-ecological transition).

In Benin, significant differences in environmental scores were found amongst some of the types of production in the continuum (consisting of conventional, lean and organic systems of carrots, tomatoes, leafy vegetables such as lettuce and *Cucurbitaceae*), with the larger impact associated with organic production (Figure 1 and Figure 2). In this case, yields from organic systems are generally lower than those of conventional ones (the so-called organic/conventional yield gap (Ponisio et al., 2015)), yet the causes of differences in impacts are multiple and go well beyond yield (Avadí et al., 2021). Overall improvement of these systems would be achieved by improving organic waste processing and knowledge on the fertilising value of resulting organic fertilisers, and by enhancing agricultural extension services or technical guides on good agricultural practices to reduce over-fertilisation.

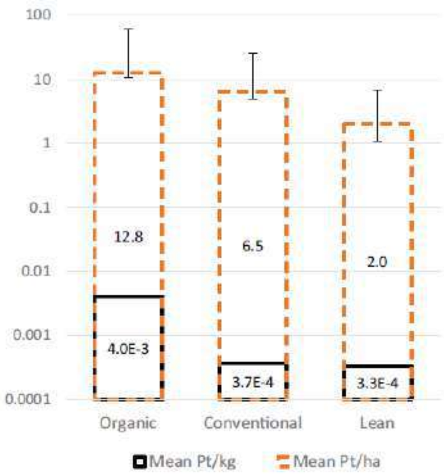

Figure 1. Mean impacts (ILCD single score, in Pt) of three production types of vegetables production in southern Benin

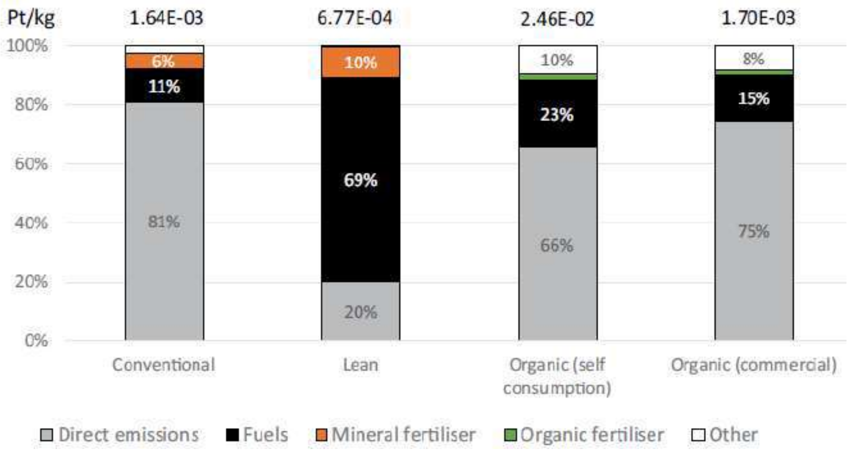

Figure 2. Contribution analysis of tomato produced in southern Benin, based on the single ILCD score per kg of product, all sites combined

In Côte d'Ivoire, the productive continuum is dominated by conventional systems (de Bon et al., 2019), but several initiatives support the evolution of horticultural systems towards more sustainable ones, and there are systems featuring diverse stages of transition into agro-ecological systems. Such initiatives should overcome the land tenure issues prevalent in the country, particularly affecting vegetable producers. *A priori*, the typology of producers is rather complex, as practices are geographically and technically heterogeneous. Results were not yet available at the time of writing this abstract, but we are currently studying the current situation and intend to assess the (expected) changes in impacts due to the introduction of agro-ecological practices.

For the analysis on Benin vegetables production, compiled ICVs were representative of a specific moment in time, at which the studied systems were at a particular position in the productive continuum. For the analysis in Côte d'Ivoire, a sample of producers engaged in a transition towards agro-ecologic systems are being accompanied over a few years, and LCIs collected at different moments in time.

These two case studies demonstrate the validity of LCA (in combination with socio-economic indicators) to compare the relative sustainability of agricultural production system alternatives.

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Comparing carbon footprint of maize production in low-input, high-input, and agroforestry systems in Zambia

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Keywords: Agroforestry; Life Cycle Assessment; Zambia; Maize; Faidherbia albida

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The fertilizer consumption has been increasing in Zambia during the last 10 years. This has been caused by the Zambia's government's goal to increase the fertilizer use in Zambia to reduce rural poverty and hunger (IFDC, 2013). Since the production of chemical fertilizers is emitting remarkable amount of greenhouse gases (GHG), and the use of chemical fertilizers is known to increase the soil emissions, this study was made to study agroforestry as an option for higher fertilizer consumption to increase the maize yield levels in Zambia while reducing the carbon footprint.

Objective of the study was to calculate the carbon footprint of three different maize production systems in the Central Province of Zambia, since maize is the most produced crop in Zambia (IAPRI, 2019). The three different systems were: the low-input maize monoculture scenario without other inputs than maize seeds for sowing, high-input maize monoculture scenario with chemical fertilizers and seeds for sowing, and maize-*Faidherbia albida* agroforestry scenario without other inputs than seeds for sowing.

Cradle-to-gate Life Cycle Assessment (LCA) was done to assess and compare the carbon footprint of Low-input, High-input, and Agroforestry scenarios. The data for the yield levels in Low- and High-input scenarios were gathered from the national survey report (IAPRI, 2016), and the yield level for Agroforestry scenario was gathered from the peer-reviewed literature (Yengwe et al., 2018). The yield levels were 1690, 2530, and 2900 kg d.m. ha^{-1} maize grain yield in Low-, High-, and Agroforestry scenarios, respectively. Other data for the maize production systems were gathered from the national survey reports and peer-reviewed literature. Soil and land-use emissions were calculated by following IPCC guidelines (IPCC, 2006; IPCC, 2019). Data for the fertilizer production and maize seed production were gathered from Ecoinvent 3.7.1 cut-off regionalized database (Wernet et al., 2016). The data for the above-ground biomass of the F. albida in agroforestry scenario was calculated based on the equation by Beedy et al. (2016) (Eq. 1).

$$Ln(TAGB) = -2{,}68 + 2{,}5 \cdot Ln(DBH) \tag{1}$$

Two different functional units (FU) were used to study the carbon footprint of the three different maize production scenarios under study. In the Case 1 the FU was 1000 kg d.m. maize grain and in the Case 2 the FU was 3 ha field, since this is an average farm size in Central Province of Zambia (IAPRI, 2019 p. 15). In Case 1, the land use change was considered, i.e., it was assumed that primary forest was cleared for maize production to produce 1000 kg d.m. maize grain yield. The carbon in above-ground biomass of F. albida was considered as a carbon stock since it was assumed to be used as a construction material. In Case 1, the carbon stock in above-ground biomass of F. albida was not considered in the results, whereas in Case 2, the carbon stock in above-ground biomass of F. albida was considered to the results as the whole field system was studied.

Agroforestry scenario had the lowest carbon footprint in both cases (Figures 1 and 2). The reason for the lowest carbon footprint found in agroforestry scenario in Case 1 was higher yield level, and therefore lower demand for the clearing of primary forest for the production of 1000 kg d.m. maize grain. The reason for the lowest carbon footprint of Agroforestry scenario in Case 2 was the carbon stock in above-ground biomass of F. albida. In the Case 2, where the 3 ha maize field system was studied rather than only maize, the carbon stock in above-ground biomass of F. albida was causing negative carbon footprint in agroforestry scenario because there were more carbon removals to above-ground biomass of F. albida than there were emissions from the system.

Considering the results of this study, as well as many other ecological benefits found in agroforestry systems in previous studies, the agroforestry system could be suitable to be used in the Central Province of Zambia as a maize production system, from the ecological point of view. Yet, other sustainability aspects need to be studied as well as more complex agroforestry systems.

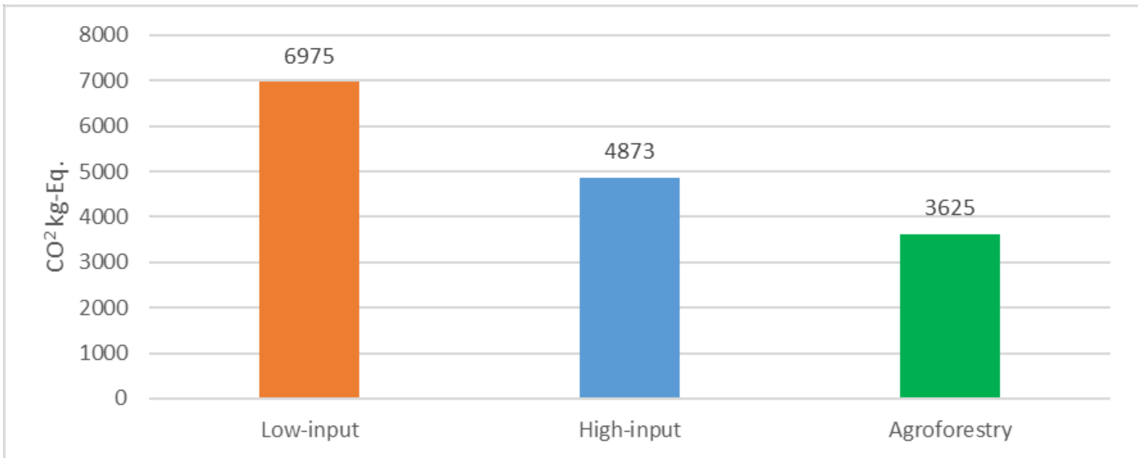

Figure 1 Carbon footprint (kg CO_2-Eq.) for each scenario in Case 1 (FU = 1000 kg d.m. maize grain). Land use change was considered.

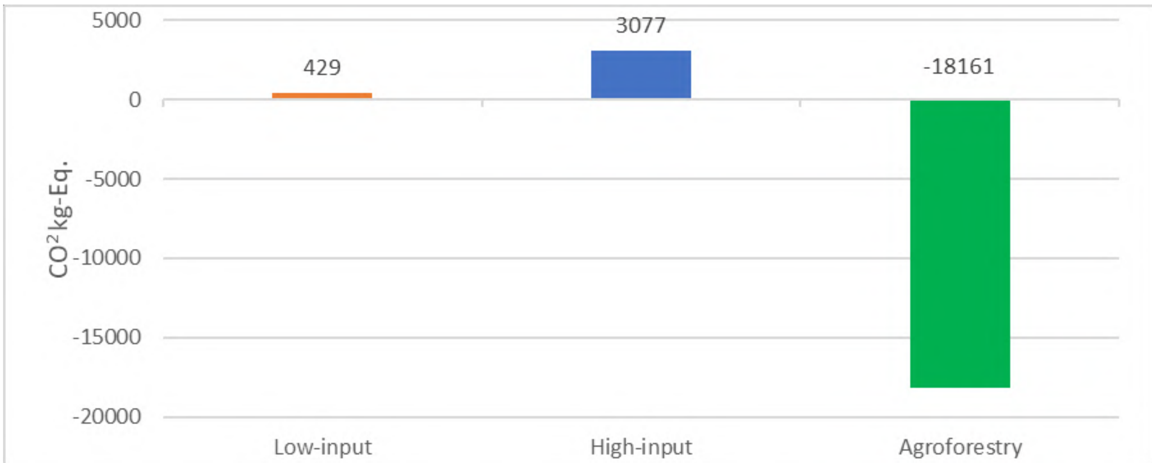

Figure 2 Carbon footprint (kg CO_2-Eq.) of each scenario in Case 2 (FU = 3 ha maize field). Carbon stock in above-ground biomass of F. albida in Agroforestry scenario was considered.

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CalCafé: a specialized friendly environmental footprint tool for producers and consumers in the Peruvian coffee sector

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Keywords: *agroforestry; certification scheme; climate change; coffee production, Life Cycle Assessment.*

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Introduction

Agro-forestry is an important economic sector in Peru, an important producer and exporter of coffee, cocoa and Brazil nuts. Beyond the economic and social benefits of these expanding activities in Andean and Amazon areas of Peru, a set of environmental benefits have been identified in recent decades. These benefits, that included climate change mitigation through carbon sequestration or soli health enrichment, have fostered the promotion of these production systems by public policy. In fact, Peru's climate actions in the frame of the Paris Agreement include the sequestration of carbon in agroforestry systems as part of the strategy to mitigate GHG emissions by 2030 (Vázquez-Rowe et al., 2019).

In Peru, coffee production tends to be low-input and organic by-default (Jezeer and Verweij, 2015; Jezeer et al., 2018). However, recent scientific studies have highlighted poor soil management practices among producers, enhancing soil degradation (Pokorny et al., 2021) and leading to a process which consists in clearing primary forests in the search of new fertile cultivation areas (Barham and Weber, 2012). In certain regions this trend has shifted due to the fact that farmers are enrolling in voluntary certification standards (e.g., CUSAF), in which management practices have been adopted such as the application of soil amendments and fertilizers, the systematic pruning of plants or the implementation of composting systems to recirculate nutrients on site (Barham and Weber, 2012). However, in most cases, life-cycle studies to analyze the trade-offs of these changes in the production systems are not undertaken.

In parallel, an increasing number of importers of green coffee, mainly in European nations, are demanding Peruvian producing cooperatives to implement environmental management schemes, which include, among other requirements, the measurement of their carbon and water footprints, the implementation of best available techniques to reduce environmental impacts and the compliance with the product environmental footprint (PEF) methodology. The rationale behind these requirements is linked with providing standardized environmental practices and environmental accountability and transparency to consumers. However, despite the fact that coffee is a buoyant sector in Peru, capacity building in these topics has been scarce in the sector, and the economic viability for coffee cooperatives to implement environmental management actions is limited.

Considering these domestic and international trends, a consortium of public institutions in Peru, together with academia and NGOs, initiated a few years ago a process in which environmental footprint accounting and measuring in the Peruvian coffee production sector was set as a priority to aid producers in becoming competitive in the international market. This process, in which UNEP and partners in other coffee-producing nations in Latin America participated, reached an important milestone in November 2020 with the presentation of the CalCafe software. This software, created by the Peruvian LCA & Industrial Ecology Network (PELCAN), with the support of UNEP, the Ministry of the Environment (MINAM) and PromPeru (i.e., the international commerce agency of the Peruvian government) is intended to provide a user-friendly framework for stakeholders in the Peruvian coffee sector to calculate the environmental impacts linked to coffee production. In this context, the aim of the present study is to present the CalCafé software from a methodological perspective, as well as describing the support that its use has given to the coffee sector since its official presentation in November 2020.

Materials and Methods

CalCafé is an open access Excel-based PEF compliant software that aims to provide a mathematical computation of the environmental impacts of coffee production and consumption of Peruvian coffee. From a standardization perspective, the software is based on the Product Category Rule (PCR) developed for green coffee in Costa Rica (INTECO, 2020), as well as on the ISO 14040 and 14044 standards (ISO, 2006a, b). The software was adapted, thereafter, to local geographical, climatic and technological conditions in Peru, allowing users to select among a variety of traits depending on their production characteristics. Although the main functionality of the software is to provide a computation of green coffee, either organic or conventional, ready to export in a Peruvian port to other nations, a second functionality was added to measure the impact of consuming different types of coffee by consumers in Peru and selected European nations (e.g., Italy or Finland).

From a data acquisition perspective, the user of the software is in charge of including most of the primary data manually for the main stages of production: nursery, cultivation, harvest, depulping, fermenting, drying and hulling, as well as storage and transport activities to a Peruvian port for export. Consequently, users have to introduce data on, for example, use of fertilizers, water use, pesticide application or transport distances of acquired raw materials or exported green coffee. Most foreground processes are covered with this system, whereas the background processes are included in the software based on the ecoinvent v3.5 database (ecoinvent, 2022). Carbon capture by coffee plants and other tree species in the canopy of shade-trees was computed following allometric equations for quantifying tree biomass and carbon sequestration, in which altitude of the cultivation area and plant and tree densities were also taken into consideration. It should be noted that land use changes (LUCs) were not included in the computational framework of the software, constituting the main limitation of the software. Although LUCs are important sources of GHG emissions, it was decided to exclude these given the lack of granularity of the software to detect the cultivation areas were LUCs may occur.

From a life cycle impact assessment perspective, the five impact categories suggested by the Costa Rican PCR were considered (i.e., climate change, aquatic acidification, freshwater toxicity, eutrophication and water scarcity), and three additional categories were added (i.e., fine particulate matter formation, non-carcinogenic human toxicity and carcinogenic human toxicity). The latter were added as they can be important metrics to evaluate in terms of effects and damage on human health.

Results

Once CalCafé was constructed in its final version and verified by the scientific team, it was presented publically through virtual presentations in November 2020 with the support of MINAM, UNEP and PromPeru. This first presentation was divided into two main blocks. On the one hand, a general presentation explaining the major environmental management challenges and policy repercussions that the use of the software could entail was performed for policy makers and academia. On the other hand, a first workshop was presented destined at transferring knowledge on the use of the software to technicians from the cooperatives. A second phase was established in August 2021, in which two separate initiatives allowed a series of activities that included capacity building, quantification of environmental impacts through the software and monitoring by PELCAN-PUCP, and, finally, the recognition of each cooperatives' efforts through the delivery of a diploma and environmental report with essential results linked to the functional unit evaluated.

The first initiative was led by PromPeru in an effort to train a set of 20 different coffee cooperatives in different Peruvian regions. Due to the aftermath of the COVID-19 pandemic, training sessions were virtual, as were the individual follow-up sessions with each cooperative in order to continue with practical training. The final outcome is a full computation of a significant sample of coffee producers in each cooperative which will help the sector to report their environmental footprint. Currently, a total of 17 coffee cooperatives throughout Peru have already undergone or are currently undergoing this process, which aims to empower them in terms of transparency and accountability, becoming more competitive in a context of increasing requisites to comply with environmental management policy and certifications.

Conclusions

CalCafe is aimed to become a reference calculation tool for the environmental footprint of Peruvian coffee production and can be seen as a proxy for the implementation of similar schemes in other agro-forestry products or in neighboring agro-export nations with similar limitations when it comes to empowering small producers.

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Life cycle assessment of small-scale crude palm oil production in West Africa region to inform greener production

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Keywords: *Small-scale processing, palm oil extraction, life cycle assessment, crude palm oil.*

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Rational and objective

Palm oil is the most important edible oil in the West Africa region (Awere, 2021). Crude Palm Oil (CPO) is processed from fresh palm fruits using various techniques depending on the level of mechanization and processing. According to their throughput and the degree of complexity, the scale of operations can be classified as traditional, small, medium or large-scale mills (MASDAR 2011). In West Africa region, the palm oil processing industry is dominated by informal small-scale mills that produce 60 - 80% of the national production output (Angelucci, 2013, Osei-Amponsah et al., 2012). At most small-scale mills, the only mechanized operations are the digestion of boiled fruits and the pressing to extract the final oil product (Osei- Amponsah et al., 2012).
Nevertheless, the production processes of CPO have undoubtedly been associated with several environmental impacts: the generation of solid and liquid waste, air, noise and odour pollution among many (Awere, 2021). Pollutants/by-products generated in palm oil processing mills:

- Solid waste: This comprises of empty fruits bunches (EFB), Palm Pressed Fibre (PPF), Chaff and Palm Kernels (PK). The EFB is mostly not used readily as solid fuels for their high moisture content. The proportions of solid wastes produced are dependent on the variety of oil palm fruit (Dura or Tenera) but generally they are in the order EFB > PPF > PKS > chaff (Sulaiman et al., 2010).
- Liquid waste: main liquid Palm Oil Effluent (POME), a mixture of water, uncovered oils, cell debris, and fibrous materials. At the small-scale mills, the wastewater is generated during boiling of fresh fruits and clarification of crude palm oil. The characteristics of the wastewater from the various unit processes differ. POME from small-scale mills is hardly given any form of treatment before disposal.
- Air pollution: Small-scale mills do not have in place measures and appropriate technologies to control or manage smoke produced from their activities. Another source of air emission is biogas produced from digestion of POME. The wastewater undergoes anaerobic digestion releasing methane gas and odour into the environment.
- Noise pollution: At the small-scale mills, there are no technology to control the noise generated by the machinery used for processing.

Generally, across West Africa, small-scale mills have been cited for their failure to comply with environmental regulations. However, the extent of environmental impacts of the activities of small-scale palm oil processing mills using life cycle methodologies have not been performed. Within this framework, the objective of this study is to analyse specific environmental burdens of a small-scale CPO production through the application of a life cycle-based approach.

Methodology

The Life Cycle Assessment is indeed a powerful methodology able to assist in environmental impacts evaluation (ISO 14040, ISO 14044). Specifically, a gate-to-gate analysis was conducted, starting from the receipt of fresh fruits bunches (FFB) at the processing mill up to the final production of Crude Palm Oil (Figure 1). The distribution to external consumers and the eventual use and disposal of crude palm oil products were not considered part of the research.

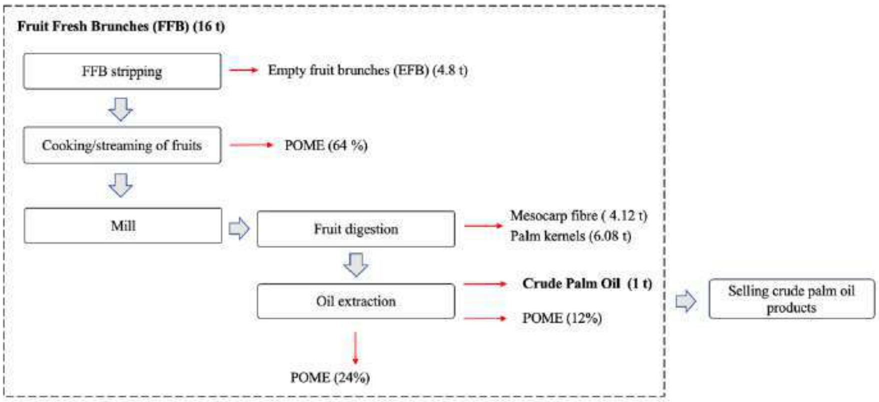

Figure 1 Crude Palm Oil processing processes.
--- Dashed line represents the boundaries within which the impact assessment was calculated.

The modelling was developed considering a functional unit equal to 1 ton of crude palm oil extracted and the calculation was performed using the SimaPro software version 8.5. Data gathered were mainly primary data obtained from studies conducted on 25 small-scale palm oil processing mills in Ghana. Nevertheless, secondary data were additionally collected from the Ecoinvent v.3 database and then complemented by some literature data (Anyaoha et al 2018; Ohimain and Izah, 2014; Ohimain et al 2013). Potential environmental burdens were calculated through the CML-IA baseline V3.05 methodology and considering 11 different impact categories.

Results and discussion

The results (Figure 2) shed light on important impacts especially imputable to the cooking and the stripping phase. The cooking stage has inevitably higher impacts due to frequency and the intensive operations of the boilers and due to the POME generation and disposal. This can particularly be observed in relation to marine and human toxicity, respectively contributing to the 85 % and the 79 % of the total impacts. On the other hand, the initial stripping phase is mainly responsible for environmental burdens related to terrestrial ecotoxicity and to eutrophication. The said outcome can be a consequence of the untreated empty fruit bunches wasted during the stripping process.

Upstream activities and the POME generation also specifically affect the global warming potential due to the origination of several air pollutants. A similar result was seen and discussed also in (Vijaya et al., 2008).

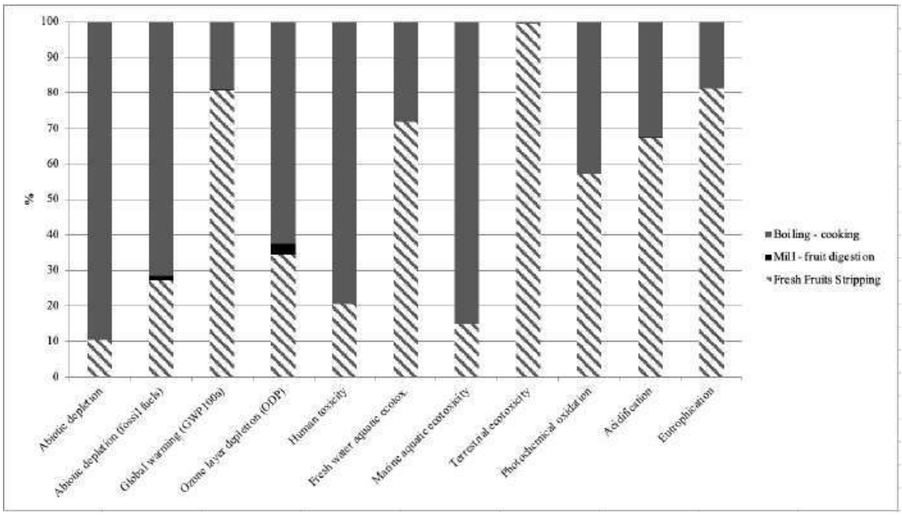

Figure 2 Life Cycle Impact Assessment. CML-IA baseline V3.05 results

Conclusion

Considering the present results some recommendations can be drawn to potentially lower the environmental impact profiles. The waste streams resulting from the main production flows (the stripping, the digestion and the oil extraction) should possibly be addressed by separate and specific end of life solutions. For instance, the Empty Fruits Bunches (EFB) could further be shredded and be used as a manure substitute in farming as seen in (Sung et al., 2010), the POME should adequately be treated in a waste water treatment plant supported by a biodigester to caption biogas for the cooking stage, and last, the boiling method could be changed to sterilization, which could potentially lower the water use by 50 %.

However, those mentioned alternative solutions are not simply to be achieved by a small-scale CPO production. Especially a biogas capture requires high cost, good logistics and quite advanced technology to be installed as correctly underlined by (Vijaya et al., 2008). To this end, an interesting complementary analysis would be a comparison between a small, medium and large-scale palm oil industry to delineate strengths and barriers for a more sustainable small-scale crude palm oil production.

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Green Coffee Carbon Footprint of Dominican Republic

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The Dominican Republic is a country with a great tradition in the coffee sector and the main source of income for 67% of family members of coffee farmers. This product is the main crop in the mount ain areas and in particular in the 8 agricultural regions of the country, although mainly in the norther n, central, central-northern and southern regions.
The carbon footprint of green coffee was analyzed through the LCA analysis of coffee produced in t he Dominican Republic in the coffee year 2018-2019, with the aim of formulating a project for a N AMA strategy that makes it possible to propose innovative actions that help reduce the environment al impact generated by its cultivation. The objective is to identify the actions most responsible for th e environmental impact to reduce their effects and increase the environmental sustainability of gree n coffee in the country. The study covered the entire coffee supply chain, from the production of see dlings in nurseries, to sowing and crop management, up to post-harvest processes.
Average size of the coffee area and farms: The most important producing regions are found in the m ain mountainous areas of the Northern and Central Cordillera, Sierra de Neyba and Sierra de Bahor uco. The largest coffee area is found in the central and southern regions, south of the Cordillera Cen tral and the Sierra de Neyba; it represents 44% of the total cultivated area and concentrates 37% of t he coffee plantations in the communities of the provinces of San Cristóbal, Peravia, Ocoa, Azua, Sa n Juan and Elías Piña. In 2001, 133,000 hectares of coffee were registered on a national level; in 20 18 about 75,000 hectares, a stable value in recent years. In 17 years, the country has lost around 58, 000 hectares of coffee, with a 43% reduction in the area under coffee cultivation compared to 2001. The average size of coffee plantations is around 3.4 hectares. In general, these are small farms with a very low level of productivity, (almost 193 kg per hectare). This is due to a greater extent to the ol d age of the plantations (it is estimated that 74% of the plantations are over 60 years old and 15% be tween 25 and 30 years old), and to poor technology and innovation. National production is a theme directly linked to land occupation: in fact, the highest volumes were recorded at the beginning of th e 80s, with subsequent significant reduction until the mid-90s. The following period recorded yields of about 40,000 tons per year with the worst coffee harvest in 2015 with just 9,900 tons of coffee, li nked to the massive attack of coffee rust of 2009-2010. However, production has resumed since 201 5, mainly thanks to the promotion of rust-tolerant varieties of coffee, the renewal of plantations and the improvement of management with the use of fertilizers and other components.
Methods The carbon footprint of coffee cultivation in the Dominican Republic was determined for t he 2018-2019 coffee year. The study follows the standards relating to Life Cycle Assessment (ISO 1 4040-44). PCR 2018: 03 v1.0, espresso coffee, and PCR 2013: 21 v1.01, green coffee, were also use d. The functional unit is 1 kg of green coffee, ready for transport (ex warehouse). The study covered the entire coffee supply chain, including: production of seedlings, establishment and management o f plantations, harvesting and post-harvesting. The LCA calculations were performed with the LCA s

oftware SimaPro 9.1.0, ecoinvent version (3.6, cut by classification). The population corresponded to 23,808 coffee producers in the D.R., stratified according to the size of the production unit (Small Producers: plantation with an area of less than 3.12 hectares; Average P.: area between 3.12 hectares and 12.5 hectares ; Large P.: surface greater than 12.5 hectares) and at the altitude of the company above sea level (Altitude less than 500 meters; Altitude between 500 and 1000 meters; Altitude greater than 1000 meters). Within these clusters, based on the percentage of participation in each one, sub-samples were selected, for a total sample of 228 producers. The analyzed system includes all the operations and materials necessary for the cultivation of coffee, from sowing to harvesting, passing through processing in the coffee processing centers, ready for storage and subsequent shipment. The primary data used refer to the consumption of fossil fuels, water, electricity for processing in nurseries, plantations and mills; quantity of fertilizers, pesticides and soil improvers applied in nurseries and plantations. For other processes, such as the active ingredients of fertilizers and pesticides, or the gas and water emissions of fertilizers, secondary data with reference to the Ecoinvent database and literature data were used. In the case of polycultures, an allocation between coffee and other species was envisaged only for nitrogen fertilizers (such as green coffee PCR). Products subject to recycling and composting are considered inputs for the next life cycle, according to the cut-off approach. The approach used to carry out the evaluation throughout the coffee life cycle is attributive.

Biogenic CO_2 emissions and sequestration: The carbon neutrality approach is adopted for atmospheric CO_2 emissions from materials of biogenic origin. Neither CO_2 sequestration nor emissions related to materials of biological origin are evaluated, assuming that the net carbon sequestration is zero. This approach to carbon neutrality follows the guidelines issued by the IPCC 2006 - Vol. 4, chap. 5 Agricultural land for annual crops.

Land Use Change: Changes in the amount of stored carbon that have occurred over the past 20 years due to land use change for plantation settlement should have been included in the calculations.

Environmental Impact Assessment Method: The method adopted for the assessment of environmental impacts for this study is the IPCC 2013 method, developed by the International Panel on Climate Change.

The impact of 1 kg of green coffee processed in Dominan Republic is 7,038 kg of CO_2e. As mentioned, the final blend of green coffee is composed of a percentage of green coffee processed by manual mills (75.6%) and industrial mills (24.4%). The main causes of the impact are fertilizers, the combustion of diesel for cultural activities and the transport and management of cultural waste. Focusing in particular on the agricultural part, the analysis of the contribution shows that over 60% of emissions are due to the production and emission of fertilizers, followed by the impacts of agricultural residues. The types of fertilizers applied have different origins and nitrogen has diversified from urea, chicken manure, manure and compost, and phosphorus and potassium from chemical sources. Most chemically applied NPK fertilizers have a 15-15-15 or 16-20-20 rating. Organic fertilizers applied are: abodom, compost, manure and chicken manure. For the latter, according to the publication of the EPA (National Environmental Protection Agency) and the technicians on site, the chicken manure was associated with the 2-2-0 rating and the others with the 5-0-0 rating.

The ecoinvent processes chosen to define the fertilizers used in coffee cultivation do not evaluate the emissions into air, water and soil, which were included in the study using scientific models available in the literature. The methods chosen are EMEP (EEA 2013) for ammonia (NH_3), IPCC 2006 for N_2O, SALCA-nitrate (Europe) and SQCB for nitrate, SALCA-P (Prasuhn 2006) for phosphorus and Freiermuth (2006) for heavy metals. The choices made comply with the methodological guidelines of the WFLDB and the ecoinvent reports. Data analysis shows that there is a direct correlation between the amount of N and the environmental impact on GWP (global warming potential). Urea has a greater impact on directly emitted CO_2. NPK-type chemical fertilizers also have a minimal contribution to GWP due to their production, which is not the case with organic fertilizers. With respect to the impacts of the different methods of organic matter treatment, soil degradation in plantations appears to be the most impactful option for the environment, compared to discharge and incineration.

The power of dietary changes and changes in farming practices towards climate mitigation and biodiversity conservation – the case of Finland

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Keywords: *food system, LCA, biodiversity, land use and land-use change, diets, regenerative agriculture*

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Introduction

Food production is one of the main contributors to many environmental challenges of today, such as climate change, land degradation, water scarcity and biodiversity loss (Campbell et al. 2017; Poore and Nemecek 2018). The production of food requires vast amounts of land and about half of the habitable land on Earth is currently occupied for agricultural purposes. About 77% is used for livestock production, delivering only about 37% of the protein produced globally (Ritchie and Roser 2019). Land use and land-use change (LULUC) is known to be a main driver for biodiversity losses (Maier, Lindner, and Francisco 2019). Unsustainable land management practices are additionally increasing land pressure by soil degradation, leading to problems like loss of topsoil and desertification, thereby both releasing existing carbon stocks and eliminating the potential to store carbon into the soil biomass (Mirzabaev et al. 2019). Land use impacts are, however, rarely implemented in life cycle assessments (LCA) (Bos et al. 2020). Although life cycle impact assessment (LCIA) methods are available to estimate the impact of LULUC on biodiversity, none of these methods integrates all impacts contributing to biodiversity losses (Winter et al. 2017).

Rational

Western countries are known for having a high rate of animal–based product consumption leading to consumption-related environmental impacts. Many of these impacts are linked to LULUC that takes place in developing countries, such as GWP and loss of biodiversity (Wood et al. 2018). High-animal consumption pattern in western countries with a relatively small population, coupled with the high impact of animal-based products, could therefore potentially have a higher environmental impact globally than might sometimes be thought, including in nations with emerging economies. Therefore, we hypothesize that Finnish dietary changes will likely show potential pathways to reduce greenhouse gas (GHG) emissions and biodiversity losses on a global scale through changes diets that lead to differences in imported animal-based products, feed products and imported vegetables. In addition, a move towards regenerative agricultural practices could increase the biodiversity of the land.

Expected results

In this project, we aim to explore the potential effect of several dietary change and agricultural production scenarios in Finland on biodiversity impacts of terrestrial, marine and freshwater ecosystems globally by 2030. Several different scenarios for 2030 will be presented showing a combination of different dietary pathways in combination with expected changes in agricultural practices, such as the implementation of regenerative farming techniques. Changes in land use will be visualized using a global GIS map indicating places that experience changes in both land pressure as well as changes on biodiversity as a result of the different scenarios.

Data and Methods

Data will be taken from the FABIO environmental input and output database, while data on regenerative agricultural practices can be taken from literature and projects such as Carbon Action (Baltic Sea Action Group, 2022). Historic consumption data, such as the FinDiet 2017 surverys, will be used to find dietary change trends that can be utilized to predict food patterns in 2030. Other dietary scenarios will be made based on dietary recommendations, considering both the nutritional composition and the environmental impact of the products (Mazac et al. 2022). Dietary changes will include both a switch between currently available products as well as the switch from current products to novel foods products produced through cellular agriculture. The functional unit will be expressed in terms of the food consumption of Finland. Possible changes in the Finnish population by 2030 will be considered. The LC-IMPACT method will be used to quantify the biodiversity impacts of terrestrial, marine and freshwater ecosystems as it considers several midpoint impact categories that impact biodiversity. The results of the LC-IMPACT assessment are multiplied with the global extinction probabilities (Verones et al. 2022).

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Feed-food competition: the importance of land footprint method in assessing meat products and diets

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Keywords: *Meat, diets, land use, consumer information, labeling*

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Introduction

Environmental metrics are increasingly used in public decision-making processes. They can even be displayed at consumer level. In 2020, the French government launched a call for proposals for methods and format of labeling in order to inform consumers on the environmental footprint of food purchasing products. In this context, the relevance of the underlying methodology is strategic to steer consumer choices.

The question of land scarcity is, on a global scale, a major issue and food production is a major contributor. Livestock, as secondary producers, have mechanically a larger land footprint per kilogram than plant production. However, livestock are also cellulose transformers and can thus make use of non-arable grassland areas that are not in competition with food production for direct human consumption. On the other hand, grain-eating animals such as pork and poultry consume feed that is generally produced on land potentially usable for (vegetal) food production.

With the goal of analyzing both food production and consumption (diets), we identified two relevant approaches i) ADEME study in France (Barbier et al., 2020a, 2020b) and ii) land footprint in Australia (Ridoutt et al., 2020; Ridoutt & Garcia, 2020)

The purpose of this work is therefore i) to compare the methodological choices of these two studies and ii) to examine the differences induced in the results per type of meat and diets.

Material and methods

For the Australian footprint, we use the "cropland scarcity footprint" which characterizes the intrinsic productive capability of land. Lands that cannot be used for crop production, including (permanent) grasslands, are not accounted for.

First, we compared indicators of the soil footprint of various animal productions on their respective lands, per kg liveweight at farm gate. As the two metrics are not in the same unit, we normalize results to beef production.

For diets, French food categories had to be grouped together to match the broader Australian categories. For both countries, we obtained three typologies of diet composition (in g/day) with detailed type of meat (livestock/pork/poultry).

Results and discussion

We observe a clear difference in hierarchy between meats according to the chosen methodology (Figure 1). In the French study, poultry is the least impactful, followed by pork. The impacts of beef and lamb are respectively 5 and 10 times greater. In the case of Australia, lamb has the least impact, followed by beef, poultry and pork, with a footprint 3 times greater than beef.

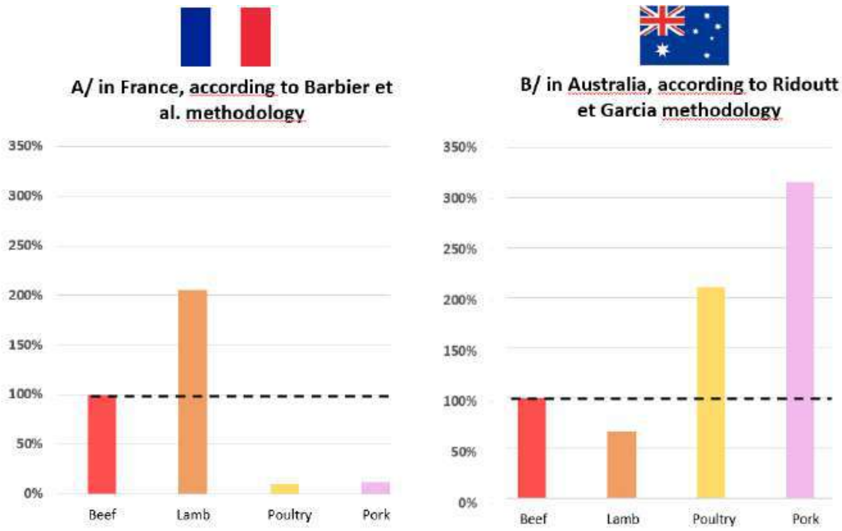

Figure 1: Land footprint of meat productions, normalized to beef A/ production in France, computation according to Barbier et al. (2020) B/ production in Australia, computation according to Ridoutt & Garcia (2020)

We also analyzed the land footprint of diets. The share due to meat within diet footprint is around 2,5 times higher in France, e.g. reaching for high-meat diets 72% of the total footprint in France (170g_{meat}/day), compared to 29% for Australia (154 g_{meat}/day).
Despite some differences between countries in production techniques and yields, the two methods take different approaches. The French one only accounts for m^2.yr used for production, whereas the Australian method discriminates between cropland and non-arable land (including grasslands). Cropland can indeed be used either for feed or food production, whereas grassland (especially used by livestock) is not in competition with direct human production. This methodological difference has major consequences in the hierarchy of meat products and in the share of meat within the land footprint of diets.
These two approaches do not account for other functionalities of land, such as the preservation of biodiversity or carbon storage.

Conclusion

This study raises questions on the way to account for grassland surfaces in land foot printing, and shows that metric matters, especially in the context of consumer decision making. The Ridoutt metric addresses the feed-food competition and could be a relevant approach to account for in labeling methodology for consumers information.

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Regional Life Cycle Impacts of Dietary Patterns: A Case Study of Canadian Provinces

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Keywords: *Environmental Impacts; Dietary Pattern; Life Cycle Stages; Life Cycle Assessment; Regional Aspects; Canada*

Rationale and Objective of the Work:

The current food system, from farm to fork, has high impacts on the health of the environment and individuals (Campbell et al., 2017; Willett et al., 2019). Globally, there has been a substantial amount of research into the life cycle impacts of various dietary patterns (Aleksandrowicz et al., 2016). However, the majority of these studies have focused on a single country or region, and it is challenging to compare impacts between countries and regions due to differences in methodological approaches, including how dietary patterns are formulated and which environmental impacts are considered (Notarnicola et al., 2017). A limited number of studies have compared environmental impacts of multiple countries using individuals' food intake data, which can provide an average of usual intake at the group level (Mertens et al., 2019). A few studies have compared environmental impacts of food consumption for various regions of a country, using data from household surveys (Esteve-Llorens et al., 2020; Vázquez-Rowe et al., 2017). These studies have found that the environmental impacts of food consumption vary across regions of a country mainly due to food choices.

Similarly, there are few studies that consider the life cycle stages from farm-to-fork (Corrado et al., 2019; Esteve-Llorens et al., 2019). This is an important aspect to consider because they could potentially contribute significant impacts based on the location of food production, transportation, and energy sources used. For example, for a particular country, fresh fish consumption could have lower environmental impacts in a region where it is harvested compared to another region where it is air transported. These regional differences are important to consider for providing further insights into the drivers of impacts.

The purpose of this research is to evaluate the farm-to-fork environmental impacts of food consumption based on nutritional function, with consideration of life cycle stages for Canada's ten provinces. The results are used to identify hot spots in each dietary pattern. This study will contribute to an enhanced understanding of the impacts of dietary patterns by including more impact categories and including all stages of the food system. It will also provide insights to inform appropriate policies and interventions for shifting towards sustainable food choices.

Approach and Methodology

This research uses the life cycle assessment (LCA) approach as outlined by the ISO standard for conducting LCA studies (ISO, 2006b, 2006a). Canada has vast geography and a multi-cultural population, which results in large differences in which foods are produced locally and what individuals consume. We identify average food consumption for each province using the latest and comprehensive individual food intake data for up to 20,487 Canadians from the Government of Canada's 2015 Canadian Community Health Survey (Health Canada, 2017). Comparisons of province food consumption and impacts are based on calories. Region-specific life cycle inventories are developed to reflect origins of production and regional technologies. We use openLCA software with the ecoinvent v3.8 database for modelling life cycle inventories of foods consumed from 'farm to fork'. We assess multiple environmental impacts of the diets using TRACI.

Main Results and Discussion

Preliminary results from average diets in the province of Ontario show that beef contributes the most to the total global warming potential (GWP), followed by milk, greenhouse tomatoes, cheese, chicken, and fish. These foods make up 60% of the total GWP. The production stage for beef and greenhouse tomatoes contributes the most to GWP. This is because of both high carbon intensity of beef production, and the amount consumed. Similarly, greenhouse vegetables are known for being carbon-intensive in cold conditions due to additional heating from fossil fuels. Interestingly, the life cycle stages associated with fish consumption show similar impact contributions for the processing and transportation stage (35%), which are also very similar to the fish production stage (40%). These large contributions reflect aquaculture-sourced fish, which has been processed and transported by refrigerated truck for approximately 4500 km. Based on these preliminary findings, it is likely that hotspots of diets in life cycle stages will be different across provinces, due to amount of foods consumed, the regional electricity grid, etc. It is also expected that environmental impacts of dietary patterns across provinces will be different, as there are differences in consumption of animal-based foods (e.g. fish vs beef) across the various provinces. Similarly, in a study of three regions in Peru, Vazquez-Rowe et al. (2017), found that the higher GWP was due to the higher consumption of red meat in the Andean region. Similarly, Esteve-Llorens et al. (2020) assessed the GWP across seventeen regions of Spain and found a higher GWP in the north relative to the south-east regions due to higher consumption of animal-sourced foods in the northern region.

Conclusion

Preliminary results highlight the importance of what individuals consume, and the challenges of providing a healthy and low impact diet to Canadians in relation to food security and climate change mitigation. This research provides a baseline of environmental impacts of food consumption at a regional level that would help find strategies in consumption and food supply chain to meeting 2050 climate targets. Even though these findings provide insights for climate change mitigation and food security, the underlying demographic factors are not assessed. In future research, we are interested in understanding the effects of demographic factors for consuming certain food types.

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Análisis del Ciclo de Vida de Consumo de Alimento en Ciudades de Chile

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Keywords: *Impactos Ambientales de Alimentos, Dietas, Pérdida y desperdicio de alimentos, Puntos críticos ambientales.*

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Los alimentos son un recurso indispensable para la humanidad, y su demanda ha sido creciente durante los últimos años (FAO, 2019). Para satisfacer esta demanda, se estima que la producción de alimentos deberá aumentar en 50% al 2050 (FAO, 2019). El incremento de la producción generará efectos en el sistema alimentario, llevando a una mayor demanda de recursos naturales (Batlle-Bayer et al., 2020; FAO, 2019; Xiong et al., 2020) y a una agricultura y ganadería cada vez más intensivas, lo que incrementará las cargas ambientales de la producción de alimentos (Batlle-Bayer et al., 2020; Chapa et al., 2020; Notarnicola et al., 2017).
Debido a los múltiples subsistemas (combustible, fertilizante, electricidad, etc.) y flujos asociados que participan en el sistema alimentario, el análisis del ciclo de vida (ACV) se ha aplicado ampliamente en la industria de los alimentos (Batlle-Bayer et al., 2019; Djekic et al., 2018), como una herramienta para determinar impactos ambientales, puntos críticos ambientales. En este sentido, el ACV es una metodología que permite cuantificar aspectos e impactos ambientales asociados a un proceso o producto a lo largo de todo su ciclo de vida, desde la extracción de materias primas, hasta su disposición final (ISO 14.040, 2006). Por este motivo, este estudio buscó analizar los impactos ambientales del ciclo de vida de los alimentos, asociados a dietas según ubicación geográfica y nivel socioeconómico de habitantes de ciudades de Chile.
El análisis fue llevado a cabo siguiendo la metodología de ACV establecida en los estándares internacionales ISO 14040 (ISO, 2006a) e ISO 14044 (ISO, 2006b). La unidad funcional utilizada fue la alimentación consumida por una persona al año. Por lo tanto, el flujo de referencia corresponde a la suma de todos los alimentos que permiten satisfacer las necesidades alimenticias de una persona durante un año. Para la obtención de datos de consumo de alimentos se realizaron encuestas en hogares de 6 ciudades distribuidas a lo largo de Chile. En la zona norte se aplicaron encuestas en la ciudad de Iquique, en el centro a Pedro Aguirre Cerda, Providencia y Macul (estas 3 comunas parte del Gran Santiago), y en el sur a Temuco y Coyhaique. Se aplicaron 100 encuestas por ciudad con el objetivo de levantar información asociado al número de habitantes por hogar, promedio de ingresos per cápita, tipos y cantidad de alimentos consumidos. Se logró completar un total de 702 encuestas correspondientes a 2.851 personas. Para la evaluación de los impactos ambientales se utilizó el método ReCiPe Midpoint (H), seleccionando las categorías de impacto de cambio climático (kg de CO_2 eq), eutrofización de agua dulce (kg de P_eq), acidificación terrestre (kg de SO_2 eq), agotamiento de recursos fósiles (kg Oil_eq), toxicidad humana (kg de 1,4-DCB eq), ecotoxicidad terrestre (kg de 1,4-DCB eq) y uso de suelo (en m^2·año eq). Tanto la modelación del sistema producto como la evaluación de impactos ambientales fue realizada a través del software SimaPro 9.0.
Los resultados muestran que las carnes rojas son el principal punto crítico ambiental en las categorías de impacto de cambio climático (31%), acidificación terrestre (43%), eutrofización de agua dulce (64%) y uso de suelo (52%). Los cereales son el principal punto crítico ambiental en ecotoxicidad terrestre (34%), y el segundo en importancia en eutrofización de agua (32%) y uso de suelo (21%). Las verduras son el principal punto crítico ambiental en ecotoxicidad de agua con 19%

del impacto y, además representan el segundo grupo de importancia ambiental en las categorías de ecotoxicidad terrestre (25%). Los lácteos representan el segundo grupo que contribuye con mayores cargas ambientales en las categorías de impacto de cambio climático (17%) y acidificación terrestre (18%), y el tercer contribuyente en eutrofización del agua (14%) y uso de suelo (18%).
En relación con las ciudades, Coyhaique es la que presenta los impactos ambientales más elevados en todas las categorías evaluadas, lo que se debe a características propias de su ubicación geográfica. Coyhaique está ubicada al sur de Chile por lo que el transporte de alimentos juega un rol importante, además de presentar el mayor consumo de alimentos con respecto al resto de las ciudades evaluadas. Junto a esto, presenta mayor consumo del grupo de carnes rojas que son uno de los principales puntos críticos ambientales.
En conclusión, la etapa de producción de alimentos es la que presenta mayor carga ambiental dentro del ciclo de vida de los alimentos, seguido de la pérdida y desperdicio de alimentos. Para los distintos grupos alimenticios estudiados, la mayor contribución de impactos ambientales la genera la producción de alimentos de origen animal, en especial las carnes rojas, a excepción de las categorías ecotoxicidad terrestre y ecotoxicidad del agua, en donde los alimentos de origen vegetal son el principal punto crítico ambiental. Además, los impactos ambientales se ven influenciados por el consumo de alimentos que varía según la ubicación geográfica debido a la cantidad y tipo de alimentos que se consumen en cada región, así como el nivel socioeconómico de sus habitantes.

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Meat analogs: technological demands, substitution of nutrients and environmental impacts

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Keywords: *meat substitutes; meat alternatives; alternative protein sources; life cycle assessment; nutritional properties.*

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Rationale and objective

Meat is a major source of proteins (28 g of protein per capita daily) and calories (30%) in the current average diet of Europeans (Bonnet et al., 2020). Meat production is often associated with a large share of environmental impacts (e.g., livestock emits 65 Tg N yr^{-1}, equivalent to one-third of current human-induced N emissions (Uwizeye et al., 2020). In case the tendencies of meat consumption remain, it is also predicted that by 2030 it will be responsible for 37% and 49% of the greenhouse gas emissions (GHGE) budget allowable under the 2°C and 1.5°C targets, respectively (Harwatt, 2019). Consumers increasingly seek for options to enjoy the taste of meat without negative environmental and health consequences. "Meat analogs" therefore determined as a quite complex range of products, which can be further differentiated according to the product intended application (processing functionality) into meat analogs mimicking: (1) whole muscle tissue, (2) mimicking prepared fragmented whole muscle tissue (e.g., minced meat); (3) processed meat products (e.g., sausage) (McClements et al., 2021). This review accounts for the potential variations in the level of processing of meat substitutes but relies on "meat analogs" and "meat substitutes" as interchangeable terms referring to physically, enzymatically, or biologically structured meat imitates composed of proteins, fats, carbohydrates, and other substances originated from non-animal sources and less commonly consumed animal species. Therefore, the study aims to systemize the latest available knowledge both from own research and from the literature on the technological demands, substitution of nutrients and environmental footprints of meat substitutes and analogs.

Approach and methodology

The study is based mainly on a review of the studies published in the last 10 years containing quantitative information on environmental impacts and/or resource demands and dealing with the analysis of meat substitutes in its wide understanding (including plants, microalgae, insects and cultured meat).

Main results and discussion

Plant-based foods in human diets provide the most of proteins (63%) and calories (82%), while being responsible for the smaller share of impacts (17% of farmlands, 42-44% of different emissions) comparing to animal-based products (Poore and Nemecek, 2018). It can be tempting to conclude that all plant-based proteins always lower the environmental impacts of the meat substitutes as compared to all meat. However, processed plant-based meat substitutes have 1.6-7 times higher environmental impacts (different impact categories) than less processed sources (e.g., tofu, pulses, and peas) (Santo et al., 2020). Extruded plant-based meat substitutes in certain conditions could have a carbon footprint very similar to chicken meat, and in terms of resource demand (land, energy, water), it could be even higher (Detzel et al., 2021). Impacts of both animal and plant-based ingredients can vary widely, and there is a range in which results of impact assessment overlap (Poore and Nemecek, 2018). Beef is typically taken as a product with high environmental impacts, higher than most meat substitute ingredients. Still, for some protein sources like microalgae, the analysis shows that, on a weight basis, the GHGE and the non-renewable energy (NRE) demand of microalgae can be much higher than beef and plant raw materials. Cell-based cultures and insects also tend to increase the environmental impacts when added as meat substitute ingredients. The water footprint was not indicative with results being different in a few orders, which could relate to the application of different assessment methodologies.

The incorporation of raw materials in ready-to-consume products shifts the relative impacts. Plant-based extrudates (intermediate products) demonstrate to be quite low in GHGE, having an impact in the lower range compared to chicken meat: 7.7-7.9 kg CO_2eq. kg^{-1} protein versus 7.7-11.3 kg CO_2eq. kg^{-1} of chicken meat protein (Detzel et al., 2021). Plant-based meat substitutes at the same time are significantly lower in carbon footprint than hypothetical cultured meat; however cultured meat has a potential to have a lower impact than beef and farmed crustaceans.

Meat-based foods had higher environmental impacts in terms of GHGE and land use than most products, with only a few cases falling in the upper impact ranges of mycoproteins and pea-based foods. Such differences are not that obvious when NRE and water footprints are compared. For the last categories mycoprotein and plant-based meat substitutes can have higher impacts than meat products on a kg basis. The analysis of impacts of meat substitutes on the protein basis did not define the significant difference between plant- and mycoprotein-based products in all categories. It was not possible to draw conclusions due to the limited data available in some categories (NRE and water footprint). Availability of comparable data is quite limited for microbial protein, cell meat, pea protein, nuts and microalgae and the spread of data for such sources is of low agreement.

Conclusion

Meat analogs can be a great strategy for food system impact reduction, if assured they substitute meat on the market instead of adding another product and impact to the existing diet. Plant-based meat substitutes on average have at least 50% lower environmental impacts than meat products in most impact categories; however, some exceptions connected to the specific cases of raw materials production (e.g., the water footprint of nuts, ecotoxicity due to pesticide use and deforestation problems) and levels of processing (protein isolation and reutilization) could demonstrate as high environmental impact as poultry and pig meats. Meat substitutes based on mycoprotein, microalgae, and meat cultures demonstrate a positive tendency to be environmentally beneficial products; however, in some categories (energy use, water footprint) their impact is very high. Insect biomass can be a promising source for hybrid meat substitutes; however, a careful selection of relevant species is needed for beneficial techno-functional properties.

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Comparative environmental performance of a UA lettuce crop under a daylight-restricted environment

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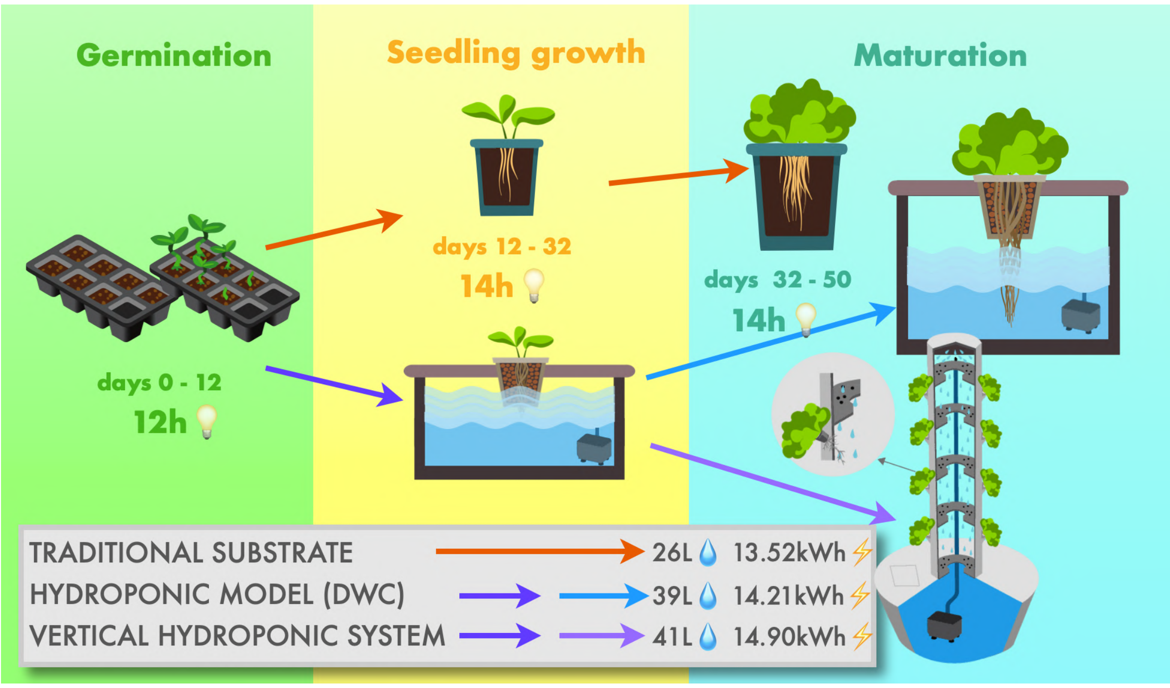
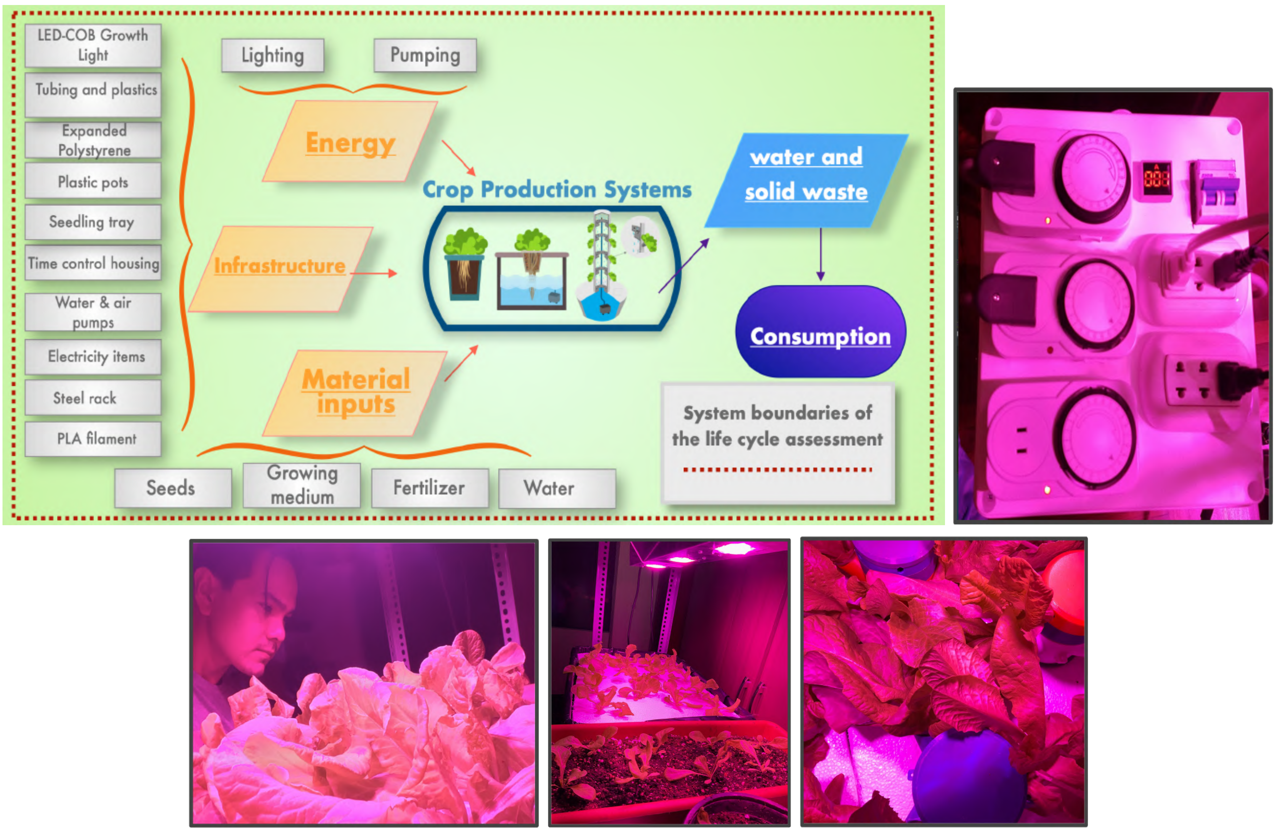
Overview of the research:
An experimental lettuce indoor farm was assessed with a Life Cycle Assessment for acquiring feasibility insights and strategies for an holistic approach. Results presented are average of the 05 crop cycle performed for each cultivation system evaluated, hence all inputs/outputs were registered for the study. Biomass yield obtained for each system were equivalent to retail unit mass of lettuce, and carbon footprints obtained were relatively higher in comparison with the literature overview, in consequence of laboratory experimental conditions.



Water and energy consumption per lettuce in each experimental growth system

Introduction: Urban Agriculture has been spotlighted as a potential alternative to secure food supplies, thus alleviating stress on agriculture land (Specht et al., 2014). Indeed, this has arisen multiple forms of UA approaches in cities, e.g. are post-construction adaptations in buildings like rooftop gardens, indoor farms or rooftop greenhouses (fig 1); further, these tend to use various fertirrigation methods, predominantly hydroponics-based systems (Martí Rufí-Salís et. al, 2020).
This study applies a Life Cycle Assessment to analyze 03 different farm methodos in UA for lettuce under an experimental indoor space. Main goal was acquiring feasibility insights and primary data for LCA in order to evaluate metrics performance and propose strategies for mitigation of GHG in a corporate scenario.

Material and Methods: Lettuce specimens were cultivated in 50 day-period cycle groups using three of the most mainstream application forms in UA across the world: a deep water culture hydroponic system, a hydroponic tower system (also called aeroponic) and an artificial soil-bed mainly composed of peat moss, vermiculite, perlite and compost (Martin, M. et al., 2019; Shrivastava, A. et al., 2021; Wang, M. et al., 2019).
A photoperiod of 12 h was assigned for the specimens. Light was supplied by a chip-on-board LED linear system distributed for each cultivation track, subsequently after day 12 of trial, end of seedling stage, time got increased to 14 h/day, this based on the reviewed literature (Ahmed, H. A. et al., 2020; Chen, P. et al., 2020). Energy requirements of the system were managed by an independent timer manufactured for the research and consumption was allocated by following ratios of household consumption. Water consumption of each system was quantified.
The Life Cycle Impact Assessment (LCIA) was carried out through the software SimaPro 9.3 and, computed using the most updated ReCiPe midpoint method (Hierarchical approach) and primary data (Huijbregts et al., 2016). FU: 1 kg Lettuce (Lactuca sativa L).



Pictures of the experimental farm, energy self-made timer for each item and system boundary of the cultivation systems assess, based by Martin M. et. al, 2019

Results:
●Specimens got minior tip burns in some leaves and irregularities in the growth ratio of stem/leaves.
● A major contributor is artificial lighting, a consequence of its production-stage and energy. Raw materials of fertilizers are the second main contributor.
●Feasibility of production was proven with no sunlight from seed to harvest, and crops were perfectly consumable, in that sense, some specimens were
mature enough for an early
harvest after day 30.

Conclusions:

●Inconsistency in biomass and burdens per FU are linked to the scalability of the experimental approach, thus feasibility of cultivation (mostly any leafy vegetable) in an Urban Area as Lima was proven with a remarkable CO2 footprint driven by energy and fertilizers inputs.

●Modularity of inputs-outputs of the system should be a priority tier in any UA application in order to amend GHG.

●Holistic approaches of UA (e.g. hybrid of artificial/natural lighting) should be promoted for acquisition of primary data.

kg CO_2-eq per kg of lettuce - average biomass harvested

Overview of literature
FU: 1 kg of Lettuce (Lactuca sativa L.)

Production context	Climate Change Potential kg CO2-eq	Researcher
[UK] Peri-urban community farm to local market	0.32	M. Kulek et. al (2012)
[UK] Urban indoor hydroponic greenhouse to local retail	1.59	
[Sweden] Urban indoor hydroponic greenhouse to retail	0.51	M. Martin et. al (2017)
[France] Urban indoor hydroponic greenhouse with heater to retail	7.08	D. Romero et. al (2018)

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Evaluation of the environmental impacts of citrus management practices applying Life Cycle Assessment

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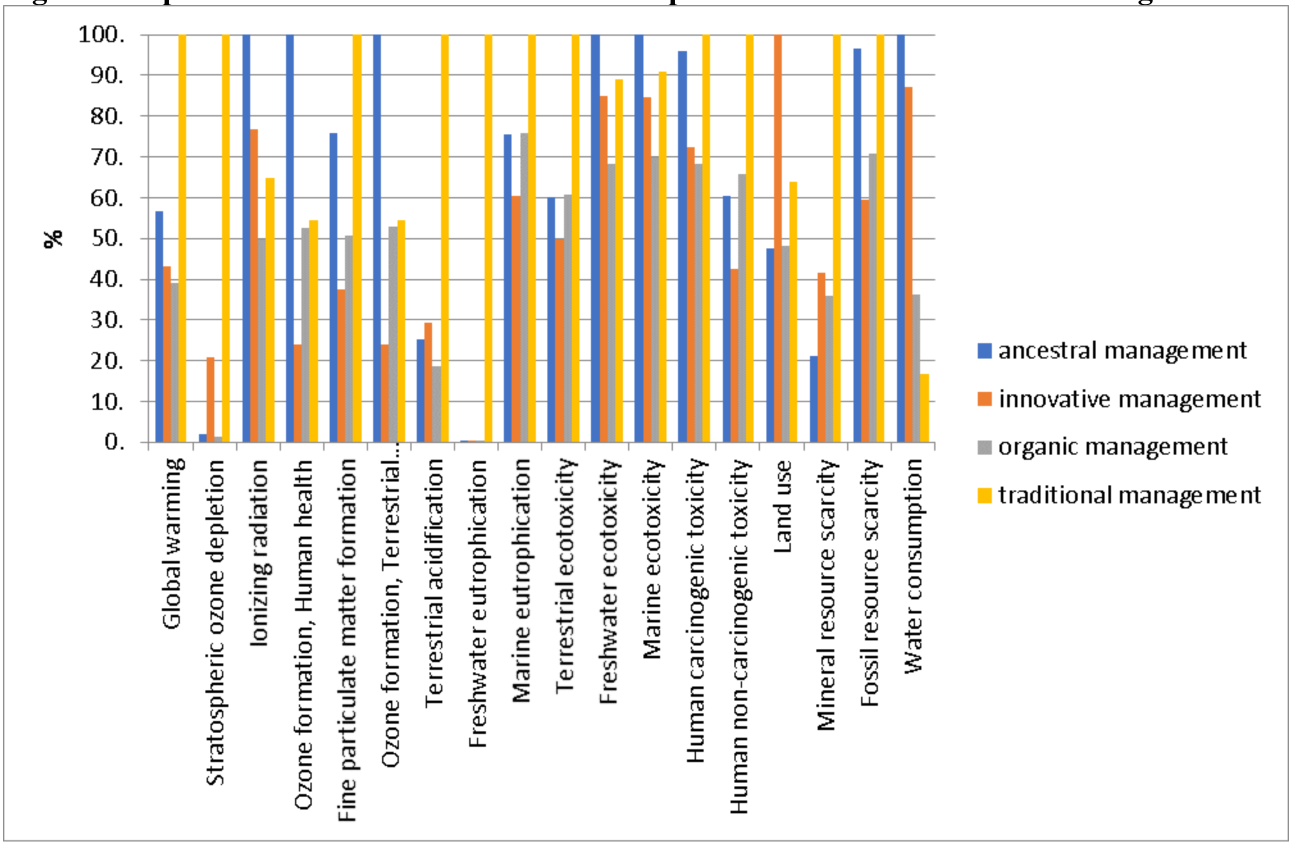
Citrus growing involves several countries and reveals a huge geographic dynamism, with an ever-changing role for each country during time, especially for the strong development this sector has experienced from last century. In view of this global upward trend citrus productions, there is the need of differentiating the production in terms of quality and geographic origin. In the Mediterranean basin, more specifically in Italy, the citrus sector is experiencing a dichotomous situation: on the one hand, citrus farming that is clearly in crisis and, on the other, efficient citrus farming with production models that tend towards quality and sustainability. The relentless negative effects of climate change, now more than ever, make it necessary to determine which cultivation method is less impactful on the environment and human health. For this purpose, a comparison of the different types of citrus grove management in different cultivation methods is proposed.
In Italy production is concentrated for 60% in Sicily. The pedoclimatic characteristics of this region make this land, particularly suited to citrus growing. Here the production of red oranges, are concentrated at the foothills of the Etna volcano (Pergola et al., 2013). Sicily is mainly characterised by four types of plantations: ancestral ones (heritage crops), characterised from very longevity plants and cultivation operations carried out almost exclusively manually; traditional ones, which are more widespread on the island and cultivated according to the conventional method; organic plants, which have become more widespread in recent decades; and innovative ones, following the principles of precision farming (Agriculture 4.0). The study is based on the application of the Life Cycle Assessmnet (LCA) methodology, which was chosen to highlight each life-cycle environmental hotspot and allow to design a more sustainable process based on its results (Falcone et al., 2016). The sample analysed consists of 40 farms specialised in citrus production, they were divided into four groups of 10 farms each, with each group characterised by a different citrus grove management. Orange production was the focus of the study and, in accordance with Li et al. (2022), with the system boundary extending from inputs including mineral and fossil-fuel extraction to yields at the farm gate after harvesting. The environmental impact was determined using 1 kg of oranges as the functional unit (FU) of analysis. The calculation method used instead is Recipe 2016 Midpoint in order to study 18 impact categories covering the environmental and human health dimensions. The LCA was carried out using primary and secondary data, the former collected directly in the field and the latter relating to the production of materials and fuels extrapolated from the Ecoinvent 3.6 (Wernet et al., 2016) database, available on the Sima Pro 9.1 software.
Table 1 and Figure 1 show the results of the comparison between the different citrus management systems adopted in Sicily.

Table 1 Comparative LCA of different management types in Sicilian citrus farms

Impact Category	Unit	ancestral management	innovative management	organic management	traditional management
Global warming	kg CO2 eq	0.08404	0.06370	0.05790	0.14813
Stratospheric ozone depletion	kg CFC11 eq	0.00000	0.00000	0.00000	0.00000
Ionizing radiation	kBq Co-60 eq	0.00570	0.00438	0.00283	0.00370
Ozone formation, Human health	kg NOx eq	0.00069	0.00017	0.00036	0.00038
Fine particulate matter formation	kg PM2.5 eq	0.00037	0.00018	0.00025	0.00049
Ozone formation, Terrestrial ecosystems	kg NOx eq	0.00070	0.00017	0.00037	0.00038
Terrestrial acidification	kg SO2 eq	0.00053	0.00062	0.00039	0.00210
Freshwater eutrophication	kg P eq	0.00003	0.00005	0.00002	0.00930
Marine eutrophication	kg N eq	0.00000	0.00000	0.00000	0.00000
Terrestrial ecotoxicity	kg 1,4-DCB	0.42896	0.35467	0.43352	0.71297
Freshwater ecotoxicity	kg 1,4-DCB	0.01416	0.01205	0.00968	0.01259
Marine ecotoxicity	kg 1,4-DCB	0.01752	0.01481	0.01227	0.01594
Human carcinogenic toxicity	kg 1,4-DCB	0.00362	0.00273	0.00258	0.00377
Human non-carcinogenic toxicity	kg 1,4-DCB	0.13172	0.09302	0.14358	0.21835
Land use	m2a crop eq	0.00296	0.00623	0.00300	0.00397
Mineral resource scarcity	kg Cu eq	0.00045	0.00087	0.00075	0.00210
Fossil resource scarcity	kg oil eq	0.02567	0.01577	0.01877	0.02654
Water consumption	m3	0.25218	0.21997	0.09120	0.04241

The analysis of the sample examined, representative of the Italian citrus production system, presents some very interesting and unexpected insights in relation to the nature of the sample. The choice of analysing only the management of the citrus groves allowed the impact linked only to the inputs and cultivation practices adopted, leaving out the entire life of the citrus grove and the management of a quantity of data that may lead to unreliable results with such large samples. Using the FU of 1 kg of oranges made it possible to highlight the production function and not the ecological function linked instead to a functional unit of area, also because as reported in the literature (Van Stappen et al, 2015; Tricase et al, 2018; Timpanaro et al, 2021), the less intensive methods that do not use chemicals (ancestral and organic) almost by definition have a lower impact per hectare in many of the impact categories analysed. This is also confirmed in the samples we analysed, which show significantly higher values per hectare for traditional farms, followed by innovative organic and ancestral farms. Our analysis referring to the production of 1 kg of oranges totally reverses the results. The sample of ancestral farms, which despite being characterised by the application of a reduced quantity of fertilisers, cultivation operations such as motor hoeing, and irrigation using the submerged-flow method, has a greater impact than the other samples due to the lower yield obtained (16,300 kg/ha). It should be considered that these farms have a marginal significance in the production context, and over time they tend to disappear in relation also to the age of the owners and their economic relevance. The organic production method, based on the application of organic fertilisers and natural plant protection products, had a lower impact than the traditional method but a higher impact than innovative systems. The analysis of the results shows that some of the greatest impact comes from soil tillage and organic fertiliser distribution, as well as lower yields compared to innovative systems (19,700 kg/ha). The traditional method characterised by nutrient management with chemical fertilisers, a lot of soil tillage, phytosanitary treatments with high-impact synthetic chemicals reports higher values both per hectare and per kg of product, making it an obsolete production model, even though it now accounts for more than 50% of Italian farms. Finally, we have the sample of innovative farms, which present better results in terms of environmental performance. They are characterised by the use of fractionated nutrition with micro-dose and with chemical and organic products, biostimulants, and the application of synthetic chemicals in low doses for crop protection. In this case, irrigation is micro-dose and in many cases with the application of water-deficit techniques. The innovative method overall is based on the application of Agriculture 4.0 techniques, which combined with the high yields (36,500 kg/ha) results in a sustainable management model.

Figure 1 Representation of the environmental impacts of four different citrus management



In conclusion, it can be said that there are two sustainable production models in Italy. The first is the one dictated by the standards of organic farming production, which also follows the directions of the Green Deal 2030 to lead us towards sustainable agriculture. On the other hand, an innovative model that, while departing from the green model, is sustainable due to both its high production yields, a not insignificant element with respect to the goal of reducing world hunger and increasing production costs, and the help of research that reduces its impact. Overall, based on the results obtained, it can be said that in the coming years we will be faced with a dichotomous scenario in which on the one hand the organic model will prevail, following the lines dictated by the Green Deal, and on the other hand the innovative model involving the use of new technologies aimed at limiting emissions. Which method prevails for citrus production will depend on the production contexts and the macroeconomic scenario that will also be defined by the de-globalisation we are currently witnessing, and the production or environmental priorities we will have in the near future.

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Defining a life cycle assessment framework for assessing toxicity-related impacts for livestock production systems: The case of Danish pork

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Introduction

Toxicity-related impacts are not fully modeled in life cycle assessment studies of livestock production systems. Commonly, the pesticide use in feed production and manufacturing of the inputs (such as mineral fertilizers, pesticides, and energy) are considered with regard to toxicity-related impacts. Aspects such as the use of veterinary pharmaceuticals, the use of cleaning agents, or heavy metals contamination because of the application of livestock manure to fields are often not included in assessments.

Therefore, a framework for assessing toxicity-based impacts was defined by using state-of-the-art methodology available based on the case of Danish pork. Furthermore, human toxicity (cancer and non-cancer) and ecotoxicity impacts were characterized for Danish pork. Finally, challenges and limitations were identified and suggestions for advancing toxicity modeling were discussed.

Methodology

Firstly, the life cycle of Danish pork was considered to identify chemicals used in the production at different stages (manufacturing of inputs, feed production, animal production at farm level, and slaughtering process). Then, the state-of-the-art methodology available was identified for these chemicals. In terms of emission modeling, the PestLCI Consensus (Dijkman et al., 2012; Fantke et al., 2017) and Nemecek and Schnetzer (2011) models were used for pesticides and heavy metals, respectively. For veterinary pharmaceuticals, a mass balance approach incorporating excretion routes in animals was defined. The USEtox model (Rosenbaum et al., 2008) was the consensus model regarding the impact assessment phase and thirty-five characterization factors were calculated.

To characterize human toxicity and freshwater ecotoxicity impacts for Danish pork, data regarding the use of chemicals in the chain were quantified. The functional unit used was 1 kg "meat" leaving the slaughterhouse, which was defined as the parts of the pig that are used for human consumption including fresh meat, bones, and edible offal. Challenges and limitations were identified based on the case study of Danish pork. Suggestions for improving toxicity modeling in livestock life cycle assessment studies were discussed based on literature review data.

Results

The main chemicals used in Danish pork production were quantified. Per kg "meat", 1.3 g a.i pesticides, 0.04 g a.i. veterinary pharmaceuticals and 0.12 g cleaning agents were used. These corresponded to the modeling of 107 pesticides, 21 veterinary pharmaceuticals, 7 heavy metals, and 5 cleaning agents. Furthermore, the use of cleaning agents and other inorganic substances could not be characterized with the existing models.

The toxicity results were presented separately for organic substances and metal-based substances. Feed production was the main contributor to all analyzed impacts for both categories of substances with pesticide use driving the impact for the organic substances and the heavy metals emissions related to manure application to fields driving the impact for metal-based substances. Copper and zinc emissions were dominant for freshwater ecotoxicity and human toxicity (non-cancer), respectively. The veterinary pharmaceuticals had a small contribution to freshwater ecotoxicity.

Discussion

Gaps and limitations were identified in relation to toxicity modeling for organic pesticides, veterinary pharmaceuticals, metal-based substances, and inorganic substances.

For organic pesticides, important challenges were the emission modeling approaches and the transformation of products. Regarding modeling approaches, primary distribution emission estimates from the PestLCI model were found to account for space-integrated emissions. The alternative could be the use of default emission distribution fractions developed by OLCA-Pest (2020). Furthermore, the model by Van Zelm et al. (2010) was suggested to account for impacts related to the transformation of products, which were found to be considerable, but very uncertain.

Additionally, the essentiality of zinc in modeling human toxicity (non-cancer) could be addressed by using nonlinear dose-response relationships as recommended by Fantke et al. (2018).

Data availability was a key factor regarding toxicity modeling for livestock production systems, thus, the recommendation to introduce digitalization approaches and establishment of better databases. These are further detailed by Fantke et al. (2021).

Conclusion

The life cycle assessment framework defined in this study for assessing toxicity-related impacts for livestock products included chemicals to be quantified and state-of-the-art methods to be used in modeling. Furthermore, useful information for improving the identified limitations and challenges was provided.

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Life cycle GHG mitigation potential of ICT-based precise water management for paddy rice production systems

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Background and Objective

Direct methane (CH_4) emissions from paddy fields contribute a large share of all greenhouse gas (GHG) emissions in agriculture. It is well known that water managements such as mid-season drainage (MD) and alternate wetting and drying (AWD) are effective in reducing CH_4 emissions (Kajiura et al., 2018; Tirol-Padre et al., 2018). In addition, precise water management extending the mid-dry period by about one week (EMD) suggested an additional 30% reduction of CH_4 compared to the MD management in Japan (Itoh et al., 2011). However, EMD management needs precise water management, which usually requires a great deal of labor, and it is highly inefficient to check water levels in all rice fields, especially in the case of large-scale cultivation farms. To solve this problem, automated water management systems utilizing information and communication technology (ICT) are expected. There is a strong need for a clear perspective of the environmental implications of such an ICT-based precise water management system.

This study aims to reveal the GHG reduction effects due to the adoption of ICT-based EMD management compared to MD. The co-benefit or tradeoff among various impact categories will also be discussed in the next step.

Methods

The targeted ICT-based EMD adopts an automatic water management system WATARAS (Kubota ChemiX Co., Ltd.), which can remotely and automatically manage irrigation and drainage of paddy fields and monitor water level using a smartphone or personal computer. The system mainly contains an electric actuator unit, which can operate over the Internet to open or close valves, and a communication repeater unit, which transmits user-made settings to the electric actuator via a radio broadcast (specific low-power) through cloud servers on the Internet.

The adoption of the system is expected to reduce direct CH_4 emissions and minimize the discharge of pesticides and nutrient loads into the surrounding environment due to changes in the water balance. To construct LCI data at the management practice level, we created a new LCI with SimaPro software for the manufacturing and operation (energy consumption, data transmission) of WATARAS. Changes in yield and direct CH_4 emissions due to adopting WATARAS will be observed directly. In addition, process-based models will be adopted to estimate pesticide emissions and fertilizer-derived nitrogen and phosphorus load from paddy fields.

The following summarizes the details for estimating only GHG emissions, as this study is still in progress. Direct CH_4 emissions for continuous flooding and MD were collected from the JAPAN National Greenhouse Gas Inventory Report (GIO, 2021). Because CH_4 emissions in ICT-based EMD have not yet been measured, we assumed a 30% reduction compared to MD based on existing literature (Itoh et al., 2011). The yield was assumed to be the same as that for MD. Other GHG emissions from the cultivation system were calculated based on a simplified agricultural LCA tool

(Kiyotada, 2011) with farm accountancy data in Tochigi prefecture.

Results

The results of climate change impact on three water management systems are shown in Figure 1. CH_4 emissions significantly affected up to 77% of total GHG in continuous flooding. The switch to MD resulted in a reduction in CH_4 emissions of approximately 31%. Furthermore, the adoption of ICT-based EMD resulted in an additional 21% decrease in total GHG compared to MD, considering changes in direct CH_4 and CO_2 emissions from WATARAS production. The result suggested that the increase in CO_2 emission due to WATARAS is slight, and therefore the contribution of the reduction of CH_4 derived from the introduction of ICT technology is significant.

As for the WATARAS system, the CO_2 emission due to data communication was small, and that from the production of circuit boards adopted in both units of electric actuator and communication repeater was the largest, accounting for about half of the total CO_2 emission.

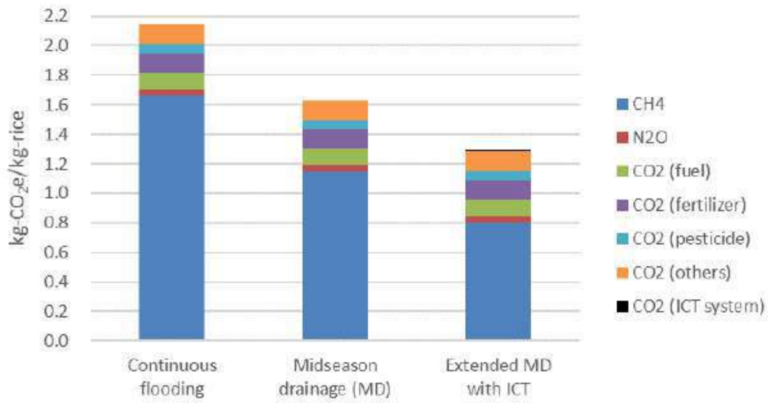

Fig. 1 Impact of climate change for three water management systems.

Discussion/Interpretation

In the next step, the GHG reduction effects of ICT-based precise water management against conventional AWD will be performed based on the above method. In addition, impacts other than climate change will also be assessed for the various water management methods. Finally, although it is beyond the scope of this study, in order to provide a comprehensive picture of the effects of ICT-based EMD, the effects of labor reduction should also be considered in addition to environmental impacts.

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Comparing the environmental impact of 45 artisanal French cheeses using two scenarios of ripening rooms

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Context: Cheese is a widely consumed product worldwide and it is particularly appreciated in France (La filière laitière française, 2013). A large number of cheeses varieties exist and they are known to have significant environmental impacts as animal products (Borges Soares, 2021). Most of the time, studies focus on the environmental evaluation of a single cheese. Yet the environmental impacts of the studied cheeses vary from one to another: for instance, hard cheeses seem to have a higher environmental impact than soft cheeses (Finnegan et al., 2018). Nevertheless, since these different cheeses were not studied in a same study, the variability observed in the literature can be the result of differences in the implemented models.

Objective: We wanted to study the variability of environmental impacts between a wide range of cheeses along three objectives: (i) To define the environmental hotspots of each of them; (ii) To determine the specificities of these hotspots relative to the characteristics of these cheeses; (iii) to make recommendations on what to focus on in order to improve their environmental profiles. We also wanted to identify the main factors responsible for the variations of environmental impacts between cheeses in order to make recommendations on what to focus on in order to reduce them.

Methodology: In order to study the environmental impacts of different cheeses, the LCA approach was followed.

Scope and goal

We have chosen to study the 45 French PDO (Protected Designation of Origin) cheeses. This allows us to compare cheeses produced by different technologies and from different milks (highland cow, lowland cow, goat and sheep). This choice has also a practical advantage since PDO cheeses must be produced according to very precise specifications available in free access, which allowed us to find a certain amount of information easily. The scope of the system we studied goes from the agricultural production of milk to the ripening step (included). The functional unit used is 1 kg of cheese after ripening. PDO cheeses can be produced in an artisanal or industrialized way. In this study, we focused only on artisanal production. Nevertheless, in order to study the influence of the ripening room on the environmental impacts of cheeses, two ripening room scenarios were explored: a small room scenario (commonly used in artisanal productions) and a large mutualized ripening room scenario.

Inventory analyses

The inventory data needed for the LCA were collected in different ways: information from the specifications, on-site measures (from previous INRAE projects), data from equipment technical sheets and expert estimates. From these documents the masses of co-products were also estimated for each cheese and impact allocation was assigned relative to the masses in dry basis between products and co-products.

Impact assessment

LCAs were conducted on SimaPro 9.1.0.11 software using the "EF 3.0 Method (adapted) V1.00 / EF 3.0 Normalization and Weighting Set" (Fazio et al., 2018).

Interpretation of the results

The results showed that the environmental impacts of cheeses vary widely between the studied cheeses, mainly due to differences related to milk and to ripening scenarios, while the cheese technology used doesn't. For example, the impact of the cheese with the highest impact on climate change is more than 3 times higher than the one of the cheese with the lowest impact.

Milk. For both scenarios, the agricultural production of milk is a major hotspot. The amount of milk needed to produce one kilogram of cheese is positively correlated to the global environmental impact of cheeses, and this correlation is much stronger for the large mutualized ripening room scenario than for the small ripening room scenario. The origin of the milk (cow (lowland or highland), goat or sheep) also has an influence on the magnitude of the cheese environmental impacts.

Ripening.The environmental impacts are higher for the small ripening room scenario than for the large shared room scenario, despite the increase in transport that the shared room scenario implies. In the small ripening room scenario, the ripening stage is a major hotspot for some environmental indicators. This poor performance of small ripening rooms is due to the electricity consumption, more optimized in large than in small rooms. The energy consumption is also strongly positively correlated to the time of maturation of the cheese.

Discussion/Conclusion: The results show that the environmental impacts of cheeses can be variable meaning that the consumption of these cheeses cannot be considered as similar from an environmental point of view. They also show that particular attention must be paid to the quantity of milk used. Therefore, reducing milk losses during processing, as well as reducing environmental impact of milk farming could be interesting levers for reducing the environmental impact of cheeses. Particular attention must also be paid to the cheese ripening step. Reducing the ripening time as well as optimizing the ripening room (by both improving the energetic performance of its equipment and its filling rate) are therefore interesting levers for reducing the environmental impact of cheeses. Nevertheless, the electrical consumption data used for the small ripening room scenario come from experimental rooms that are not necessarily as optimized as real ripening rooms. In any case, the huge diversity of existing ripening rooms is not represented in this study and we believe that a real effort should be made to measure the electrical consumption of a large number of ripening rooms in order to be able to refine the calculations of the environmental impacts of cheeses. Nevertheless, attempts to improve the environmental performance of the cheeses by improving the ripening rooms could be considered for further research, particularly for long-ripening cheeses.
These results may be of interest to cheese makers wishing to reduce the environmental impact of their products and to consumers wishing to learn about the impacts of their consumption choices.

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LCA of greenhouse gas mitigation measures of farms

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Keywords: global warming potential; emission reduction; climate protection measures; farm LCA.

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Introduction

To reduce the impact of farms on climate, one of the most important agricultural producer and distributor associations in Switzerland (IP-SUISSE) launched a point system that was developed together with Agroscope. For this point system, we identified and assessed greenhouse gas mitigation measures regarding their effect on global warming potential (GWP) of farms. Since 2021, it is mandatory for the approximately 10,000 IP-SUISSE farmers to implement mitigation measures, which they can freely choose from a catalogue, and with which they have to achieve an individually set mitigation goal. This article presents the list of identified greenhouse gas mitigation measures and their assessment results. Apart from the mitigation measures, the other necessary components of the point system and its design is described in detail in the LCA foods 2022 contribution by Bystricky et al..

Approach and methodology

Potential measures to reduce GWP on farms were identified in expert workshops according to their expected GWP reduction potential, reliability and feasibility. The measures selected for assessment were simulated on 4 model farms with different production focus: arable crops, milk, pigs and extensive cattle husbandry. For each model farm and measure, a full LCA was calculated using the SALCA methodology (Swiss Agricultural Life Cycle Assessment) in order to identify synergies and tradeoffs between GWP reduction and other environmental impacts.
Results with the measure applied were then compared to the results without the measure at farm level. When a measure had unfavorable effects on other impact categories, this was documented and the measure only recommended with caveats.
In order to transform the calculated GWP mitigations into the point system and thus onto the real farms, the GWP mitigations were set into relation with the quantities in which the measures were implemented on each model farm. The goal was to define the necessary amount per measure that relates to a mitigation of 1'000 kg CO2eq. When those amounts differed between the 4 model farms, the mean value of all 4 farms was used. This average mitigation per amount of measure was then used in the point system. Farmers fill out the point system with the measures they apply on their farm and the corresponding amounts. The system then calculates how many points a farm achieves based on that information, one point equaling 1'000 kg CO2eq mitigated.

Results and Discussion

The selected climate protection measures are categorized in the groups: energy consumption and heating, animal housing, crop production, and recycling. Table 1 shows the measures selected for the point system's catalogue. They enable a reduction of farm GWP, their feasibility was rated positive, and trade-offs with other environmental impacts were small. Mitigation measures in the category energy as well as technical measures in general have a low to medium reduction potential with relatively low uncertainties. Furthermore, there are only few tradeoffs and they show various synergies with other environmental impacts, in particular the use of non-renewable energy resources (Furrer et al., 2021; Alig et al., 2015).

Mitigation measures in the categories animal housing and plant production vary more in their results. For animal housing, covering of liquid manure stores show a particularly high reduction potential. Increasing the number of lactations of cows, too, allows a good reduction and shows synergies with many other environmental impacts. Conversely, the reduction potential of feeding of extruded linseed comes at the cost of various trade-offs originating from linseed cultivation. In the category crop production, the mitigation measures agroforestry and, to a lesser extent, application of biochar show high GWP reduction potentials, but there are still notable uncertainties, such as the extent to which the variability in practical implementation matches the conditions and assumptions in the assessment.

Table 1: measures in the point system climate protection with their reduction potential in points per amount. One point equals 1'000 kg CO2eq mitigated.

measure	**point value**
Purchase of green electricity	1pt. / 7'470 kWh
Photovoltaic production	1pt. / 7'470 kWh
Frequency converter in the milking system	1pt. / 350'000 kg milk
Heat recovery from milk cooling	1pt. / 130'000 kg milk
Heat recovery from animal housing (poultry/pigs)	1pt. / 3120 kWh
Wood heating (chips)	1pt. / 3.6 bulk cubic meter
Solar panel heating	1pt. / 6.3 m^2 panel area
Reducing fuel consumption through no-till seeding	1pt. / 10 ha
Reducing fuel consumption through ECOdrive	1pt. / 9.6 ha
Increasing the number of lactations of cows	1pt. / 1.8 cows*lactation
Linseed as feed for dairy cows	1pt. / 2'236 kg fed
Phase feeding in pig fattening	1pt. / 9.4 pigs fed
Covering of liquid manure stores	1pt. / 23 m^3 store capacity
Spreading of liquid manure with trailed hoses	1pt. / 770 m^3 spread
Recycling of silage films	1pt. / 300 kg recycled film
Replacement of mineral fertilizers through biogas digestate	1pt. / 28.5 t spread
Regular replacement of mower blades	1pt. / 350 ha mowed
Agroforestry (tree density: 50 trees/ha)	1pt. / 0.18 ha
Application of biochar on fields	1pt. / 810 kg biochar applied

Conclusion and outlook

All measures included in the catalogue for the point system have a positive effect on GWP. However, the amount of greenhouse gas emissions saved varies widely. Some measures with high GWP savings come with higher uncertainties or too many trade-offs with other impacts, or they would require more work or financial input from the farmers. Measures with low GHG savings, e.g. in the category energy consumption, are more robust. If implemented widely, they can still contribute substantially to a significant reduction of greenhouse gases. In the next two years, we will monitor the adoption rate of each measure on the IP-SUISSE farms and assess their impact at the level of the whole association.

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Environmental assessment of pea-barley intercropping in Denmark

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The transition towards sustainable crop production systems is key to feed the on-going growing population without threatening more the environment. In this regard, the agricultural practice of growing crops on the same field at the same time, known as intercropping, can play an important role. The most common intercropping is the combination of cereal and legumes. By taking advantage of the ability of legumes to get atmospheric N through biological nitrogen fixation (BNF), this cereal-legume intercropping may enhance crop yields, reduce chemical fertilization, which can be useful in low N availability systems (Bernas et al., 2021), as well as having other benefits, such as reducing pest and disease incidences (Mohler & Stoner, 2009).
While experimental fields have been studying the potential benefits, how to integrate intercropping is an on-going question within the LCA community. As reviewed by Costa et al. (2020), most of the LCAs on intercropping use a mass- or area-based functional units (FU), and most studies claim the need to use more than one FU when assessing multi-product crop rotations. The current study assesses the environmental benefits of cereal–legume intercropping systems and compare them with monocrops located in Denmark, using the field data from Cowden et al. (2020). The system boundaries of the study are from cradle-to-farm gate and two FU are used: yield, and land demand. Moreover, a money-based FU is proposed.

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Title: Environmental Performance and Circularity Improvement of Chicken Meat Packaging

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Keywords: Life Cycle Assessment; food packaging; circular economy; food loss; meat to packaging ratio

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Introduction: Food loss and waste is of great concern nowadays (FAO, 2015) and to prevent it, packaging plays an important role (Wohner et al., 2019). The primary function of packaging is to protect the product during distribution and storage (UNEP/SETAC Life Cycle Initiative, 2013). Packaging failures in the agri-food sector can lead to product damage and expose the food to oxygen, moisture, and microbes which may contribute to food loss and waste (Pauer et al., 2019). Moreover consumers, retailers and other stakeholders' expectations are increasing when it comes to the functionalities of packaging and its environmental impacts (UNEP/SETAC Life Cycle Initiative, 2013). To reduce the environmental impact of packaging while optimising their functions, sustainable packaging design has become very important (Yokokawa et al., 2021).

Objective: The aim of this study was to assess and improve the environmental performance and circularity of four conventional chicken meat packages. The characteristics of the four chicken meat-packaging systems are shown in Table 1.

Methods: Life cycle assessment (LCA) methodology (ISO, 2006a, 2006b) was used to evaluate the environmental performance of the packaging per kg of chicken meat consumed. Choosing this functional unit was important to include the packaging impacts due to food loss at retailer and consumer into the evaluation (Wikström et al., 2016). Hence all inventories accounted for in this study were calculated based on the reference flow associated with this functional unit (European Commission, 2017). Cut-off (recycled content) allocation method was used to model the end-of-life of the packaging systems. All the packaging raw materials (granulates) were assumed to be virgin. The modelling was done using GaBi software (Sphera, 2022). The environmental impact of the chicken meat-packaging system was assessed using EF 3.0 impact assessment method (European Commission, 2017). The EF 3.0 method consists of 16 environmental impact categories at the mid-point level.

Results: To select the most significant impact categories for the systems studied, the results were normalised and weighted into single scores using EF 3.0 normalisation and weighting factors available in GaBi. The most significant impact categories contributed cumulatively at least 80% (excluding toxicity-related impact categories) to the total environmental impact single score (European Commission, 2017). For this study, the most significant impact categories were climate change (CC), fossil resource use (RU_fossil) and water use (Water). Relative values for these three impact categories and seven others are presented (see Figure 1). PK1 (a PE bag) is the one performing better in all evaluated impact categories, while PK2

(PET tray and film) is the worst one in 70% of all impact categories presented. In addition, Meat (food)-to-packaging (MTP) ratios were also calculated (see Table 1) for all the packaging systems studied using the climate change impact category from cradle-to-gate. MTP ratios were calculated by dividing the impact of the meat by the impact of the packaging; a higher ratio means less impact of the packaging. These ratios guide the LCA practitioner/packaging designer where to focus their effort in improving the overall environmental performance of the meat-packaging system (Heller et al., 2019).

Table 1
Characteristics of four conventional chicken-meat packaging systems studied

Packaging		**Material type**				**Weight (g)**				**Results**
ID	Meat weight (g)	Tray	Film	Bag	MA (gas)	Tray	Film	Bag	MA (gas)	**MTP Ratio**
PK1	1880	-	-	PE	-	-	-	11	-	**194.0**
PK2	926	PET	PET	-	$O_2/CO_2/N_2$	22	5	-	~2	**38.6**
PK3	2810	-	-	PP+PA	-	-	-	38	-	**63.5**
PK4	1950	PS+PVC	PVC	-	-	22	5	-	-	**83.9**

MA: modified atmosphere; PK: packaging; PE: polyethylene; PET: polyethylene terephthalate; PP: polypropylene; PA: polyamide; PS: polystyrene; PVC: polyvinyl chloride; MTP: meat-to-packaging

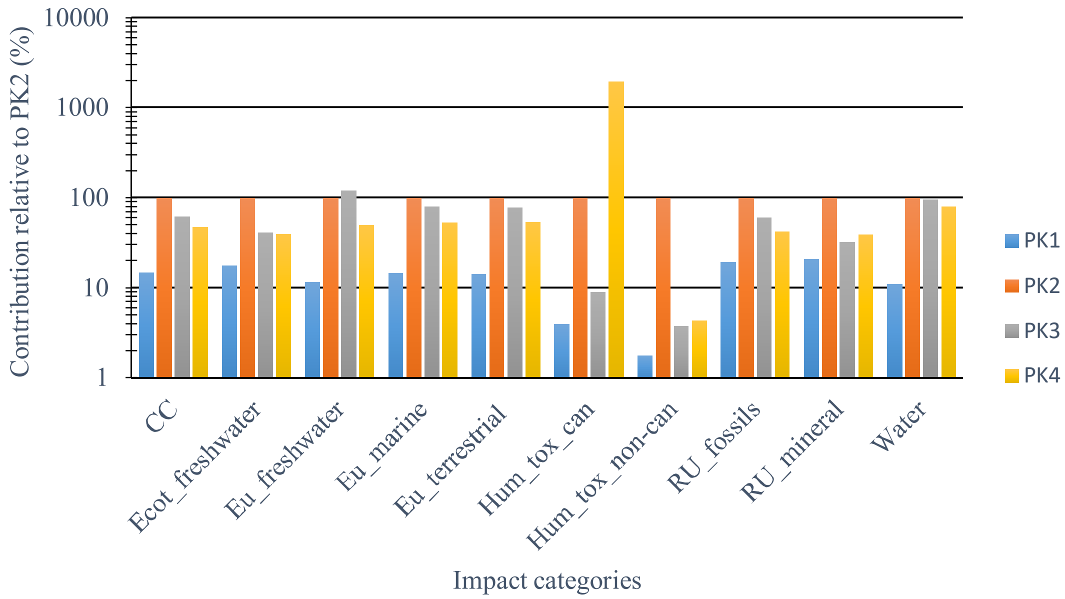

Fig. 1 Percentage contributions of each packaging to 10 impact categories (relative to PK2, which is 100%).

CC: Climate Change - total [kg CO2 eq.]; Ecot_freshwater: Ecotoxicity, freshwater - total [CTUe]; Eu_freshwater: Eutrophication, freshwater [kg P eq.]; Eu_marine: Eutrophication, marine [kg N eq.]; Eu_terrestrial: Eutrophication, terrestrial [Mole of N eq]; Hum_tox_can: Human toxicity, cancer - total [CTUh]; Hum_tox_non-can: Human toxicity, non-cancer - total [CTUh]; RU_fossils: Resource use, fossils [MJ]; RU_mineral: Resource use, mineral and metals [kg Sb eq.]; Water: Water use [m³ world equiv.]

Results of different packaging scenarios (assuming mono-layer packaging for all multi-layer packaging with the goal to improving their circularity) are also presented (see Figure 2) using the three most significant impact categories. A multi-layer plastic packaging is seldom recycled; this is the current situation in Spain (Lopez-Aguilar et al., 2022), where this study is carried out. Results show that for PK3, the best mono-layer material option according to CC impact is to use PP considering that raw materials production is the most contributing stage of the life cycle (see Figure 2).

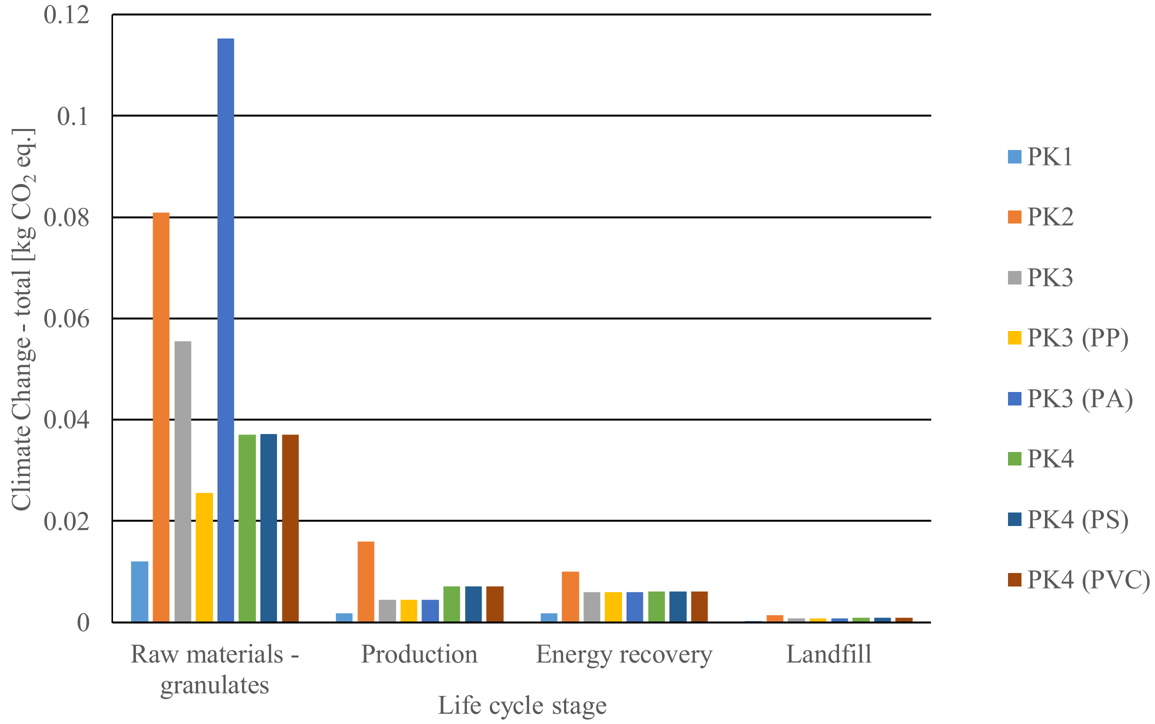

Fig. 2 Climate change results for base case (PK1, PK2, PK3 and PK4) and mono-layer scenarios for PK3 and PK4

Conclusions: Based on its MTP ratio and environmental performance, efforts should be directed at reducing PK2's environmental impact such as including recycled content, since it is a monolayer packaging with relatively good material recyclability in Spain (22.3% of all packaging materials of its type (Lopez-Aguilar et al., 2022)). For the multi-layer packaging (PK3 and PK4), efforts should be directed at improving their recyclability by using mono-layer materials. However, all these should be done taking into account their food loss/waste attributes and other sustainable packaging attributes such as safety and inertness of food-contact materials and consumer attitudes.

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2030 Outlook: Climate Impact of Danish organic tomatoes_poster

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Introduction.
The Danish production of organic tomatoes is an energy-intensive production due to use of climate control systems for heating and lighting in the greenhouse (Halberg et al., 2006) with up to 90% of climate impact from energy use (Golzar et al., 2019). However, legal bills for increasing the share of renewable energy in the electricity and district heating system towards 2030 have been passed in parliament. This is expected to have positive effect on climate impact from greenhouse production.
The aim of the present poster is to quantify the mitigation potential for a Danish organic tomato production in 2030 compared to present, by evaluating the expected technology development in the Danish energy supply.

Materials and Methods.
Danish electricity and heating production in 2019 was modeled based on statistics for fuel use at power plants, share of combined heat-and-power (CHP) production, electricity from non-combustible sources, net import/export from neighboring countries and transmission loss (Energistyrelsen, 2020). The Ecoinvent database was used for the specific energy production processes. Electricity from wind production was accounted for technology shares, grouped as corresponding to the four categories in Ecoinvent, based on the register of windmills in Denmark (Energistyrelsen, 2021b).
To model the climate impact for heat production based on the national gas grid, we assumed a linear increase towards 70 % biogas in 2030 (Energistyrelsen, 2021a), with datasets for natural gas from EcoInvent and biogas from a Danish life cycle inventory (Knudsen et al., 2014). For comparison between electric heat and heat from combustion of gas with electric production (CHP), we assumed coefficients of performance (COP) at the system-level from electrical heating up to 3.
The 2030 energy use was applied to present production data (2020) from a Danish organic tomato production system, to compare the current and future climate impact due to change in type of energy use. We also assumed a scenario where the amount of energy use was halved in 2030 compared to the present production system.
Characterization factors was based on IPCC (2013) methodology, incorporated in the ILCD impact assessment in the SimaPro software.

Results.
The 2030 energy mix with increased share of renewable energy will likely decrease the climate impact from heat with 77% and climate impact from electricity by 79 %, resulting in an overall reduction in carbon footprint of 62 % from production of one kg organic tomato. In the scenario with half amount of energy input in 2030, the potential reduction is 71 % of the climate impact of one kg tomatoes.
The impact from direct heating with electricity (COP: 1) was found to have an impact of 68% compared to the impact from heat produced from CHP combustion of grid-gas in 2030.

Discussion.
The expected increase of renewable energy will likely lead to a shift from CHP-based to electrical heating in greenhouses, if producers seek to lower their climate change impact from production. It is expected that a further increase in renewable energy shares (e.g. wind, biogas) and technological development (e.g. more efficient heat pumps, closed-system greenhouses, etc.) will further lower the climate impact of production.
The transition towards more renewable energy will increase the relative impact from other inputs and emissions, which might increase focus on e.g. nitrogen management in these system.

Conclusion.
The carbon footprint of organic tomato production in heated greenhouses in Denmark can be reduced by at least 71 % in 2030 compared to present production systems, by including the expected updated energy mix and the increased shares of renewable energy in the energy system.

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Environmental impact of the food waste utilization instead of raw material: the potential and limitations

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Background

With the global urban development, economies are expanding, and the amount of generated waste is increasing (Abdel-Shafy and Mansour 2018). A recent report by the United Nations Environment Programme shows that in 2019, a significant amount, i.e. 931 million tons, of food (from households, retail and food service industry) is wasted worldwide (United Nations Environment Programme 2021), thus leaving valuable resource without proper treatment and causing serious environmental problems. The main principle of the circular economy is that at the end of its life waste must be reintroduced into an industrial process as material or energy inflow complying with hygiene and safety requirements (Oliveira, Lago, and Dal' Magro 2021).

Waste Cooking Oil (WCO) is a food waste flow that is problematic regarding its recycling. We assessed environmental impact of the novel WCO utilization route, i.e. as a low-cost feedstock for production of microbial biosurfactants (BS) – an alternative to non-biodegradable synthetic surfactants synthesized from petroleum, a non-renewable source, through chemical synthesis routes that can be environmentally hazardous. Surfactants are one of the most important bulk chemicals that are used in almost every product of human daily life – cleaning products, cosmetics, food, pharmaceuticals, etc. In 2024, the global surfactant market is expected to exceed 41 billion euro. The main advantages of BS include their renewable origin, biodegradability, low toxicity, better foaming properties, and stable activity at a wide range of conditions. Considering their advantages microbial surfactants have a huge market potential, especially when produced from waste.

In this study, we performed Life Cycle Assessment (LCA) for sophorolipids (microbial surfactant) production process. To identify the potential and limitations of WCO a substrate in comparison to the same process with RCO as a substrate LCA was performed to all steps of production. The overall sophorolipids production process is the same for the WCO- and RCO-based processes and can be divided into three main steps – selection of the substrate for fermentation, production process itself, and product outcome regarding the substrate.

Pilot bioreactor (V=5L) is used to produce microbial biosurfactants sophorolipids using yeast *Starmarella bombicola* and WCO or RCO as a substrate. The LCA methodology is used to evaluate environmental impacts and avoided GHG emissions when microbial biosurfactants are produced from WCO instead of Raw Cooking Oil (RCO). Life cycle approach is one of the critical issues in sustainable development allowing to compare different products and processes from different perspectives.

This paper reports the preliminary results of the LCA study carried out for the project Waste2Surf Sustainable Microbial Valorisation of Waste Lipids into Biosurfactants (2020 – 2023). LCA methodology is used to evaluate environmental impact of the fermentation process, compare waste substrate to conventional raw substrate and optimize the process to obtain the most environmentally sustainable sophorolipid production process. Fermentation process is carried out by project partners

JSC BIOTEHNISKAIS CENTRS, who developed pilot plant and provided Life Cycle Inventory study with necessary data.

Objectives

This study aims to identify the potentials and limitations of using waste material instead of raw material. Three critical points were defined: environmental impact of the substrate, potential alterations in production process and environmental impact of the outcome variations due to biomass homogeneity.

Methods

The environmental impacts are calculated according the LCA methodology according to ISO 14040-44 (2006) standards. SimaPro 9.3.0.2. software by PRé Sustainability and ecoinvent database are used for the study. Geographic scope of the study is Latvia, Europe. Environmental impacts are estimated at endpoint levels according to the ReCiPe method.
To compare environmental performance of substrates, firstly, both substrates were compared, and afterwards different production outcome scenarios were used. It is assumed that produced sophorolipid outcomes are equivalent from both substrates. Environmental impact of the rapeseed oil was used from the LCA study carried out by A. Fridrihsone (Fridrihsone 2020). Rapeseed oil was used as a Raw Cooking Oil (RCO) to be compared with WCO. Simple cut-off or recycled content approach 100/0 was applied to recycling process.
Pretreatment of WCO was simulated by adding extra step between transportation and production process. It was assumed that popular oil cleaning method with bentonite was used to treat WCO before fermentation (Mannu et al. 2019).
Since the chemical composition of the WCO biomass can change regarding the source of the substrate, we assume that amount of the produced sophorolipids can change as well. Three outcome scenarios were applied with reduced outcome when WCO substrate was used.
This research has been developed in collaboration with a company JSC BIOTEHNISKAIS CENTRS, who developed fermentation technology and provided LCA study with necessary data.

Results and Discussion

At the resource selection stage, the biggest advantage of using the waste material is resource conservation that would otherwise be used to produce RCO. Recycling of the waste material reduce the need for primary production of materials, and this is resulting in an environmental benefit. We assume that by using WCO, it is possible to avoid RCO production for this purpose. Figure 1 display that usage of waste material instead of raw material has reverse proportional impact on environment – RCO has negative impact on environment while WCO, has positive impact from avoided usage of RCO.

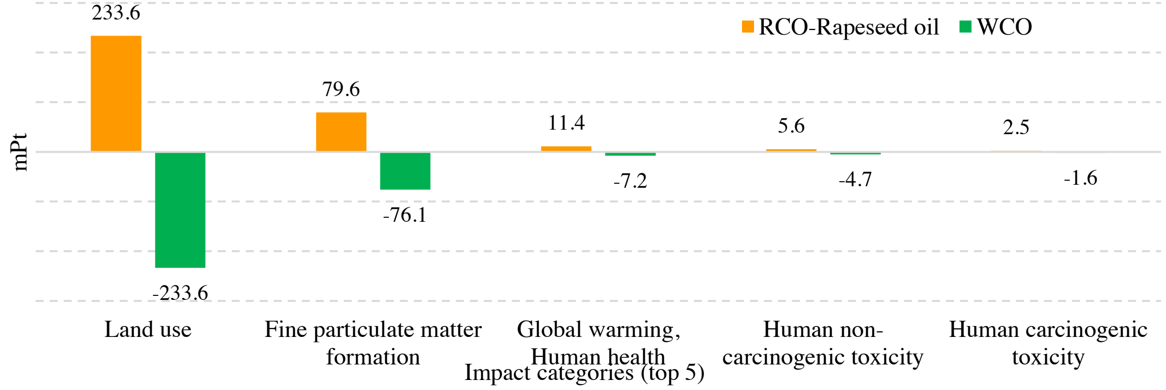

Figure 1 Comparison of environmental impact depending on substrate

By using waste material instead of raw material, it is possible to avoid negative impact on land use, fine particulate matter formation, global warming, and human toxicity.
Usage of waste material may cause problems in the production stage. During the cooking process food and used tools can enrich cooking oil with trace metals, salts, spices, and other organic molecules (Mannu et al. 2020). These additives can have a negative impact on the production process and final product application. Therefore, it is necessary to consider and implement the pretreatment stage. Adding a pretreatment method to the production process would increase the environmental impact, regarding the mechanical or chemical method is selected Figure 2.

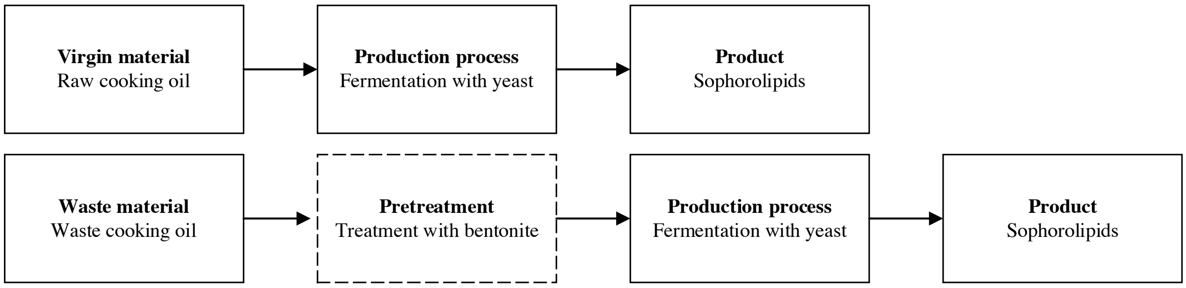

Figure 2 Production process

To evaluate environmental burden, caused by pretreatment process, we assumed that bentonite is used to remove pigments, oxidation products, trace metals and residual phospholipids. Life cycle assessment study showed that environmental impact of production process that includes the pretreatment is higher than WCO without pretreatment, but lower than usage of RCO (Figure 3). Hence, at the production stage, life cycle environmental impacts are caused not only by the selected pretreatment option, resource (energy and chemicals) consumption, but also by wear of equipment, that was not included in this study.

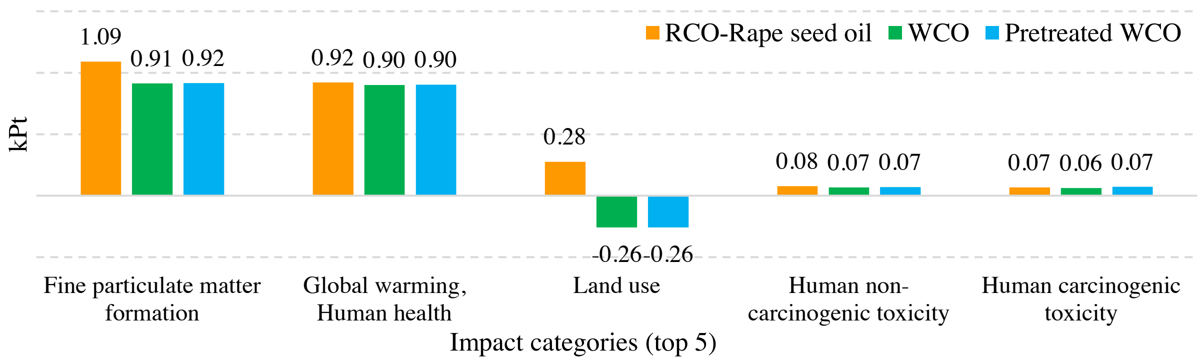

Figure 3 Comparison of environmental impact between production processes with treated and pretreated substrates

The substrate used for production may limit product application options. Even pretreated WCOs can contain some residues, and it can have an impact on the amount of the produced sophorolipids.

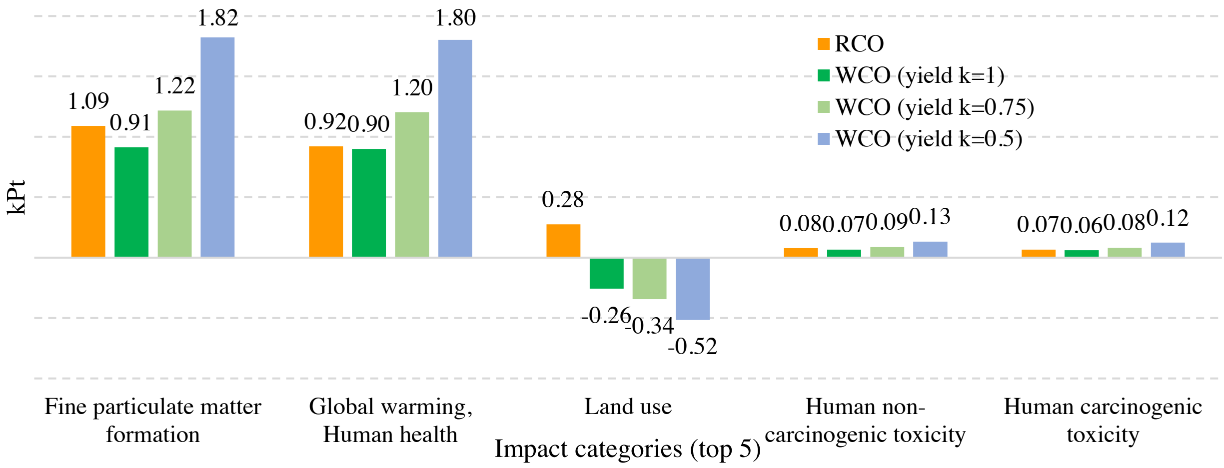

Figure 4 Comparison of environmental impact between processes with different sophorolipid outcomes

Results of the LCA show that usage of WCO instead of RCO cause lower environmental burden only in cases where both substrates give similar sophorolipid outcome (Figure 4). If sophorolipid outcome is by 25% lower, environmental impact is increasing by 30% and exceeds environmental burden caused by RCO in most cases.

Food waste as waste cooking oil can successfully replace raw material like rapeseed oil in sophorolipid production process. Waste material has a potential to avoid production of raw material or reduce demand for raw material and it is particularly relevant if the material can be used as food. Application of pretreatment to remove impurities from waste material didn't increase environmental impact higher than raw material. Lower production yield when using waste material can cause higher demand for material and production processes to achieve the same amount of the product and in this way causing hihger environmental impact that is higher than using of raw materials.

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Limiting the environmental impact of food waste: ecodesign of the reuse of unsold bread and spent grains in cookies making

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Keywords: LCA; recipe; food wastage; territory; social economy; SoliFoodWaste
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In France, food waste represents 10 million tons of food, or 150 kg per person per year (MAA, 2019). Its origins and solutions depend on the territory (Aphale *et al*, 2015). Donations to food aid associations are one of the solutions put forward. Depending on hygienic criteria, a part of food waste can be reused as ingredient for new food or feed in circular economy projects. These projects may contribute to the reuse of unsold food, the creation of new unrelocatable jobs (Collard, 2020) and territorial development (Torre and Dermine-Brullot, 2019). In bread food chain in France, 10 % of produced industrial bread is thrown away representing 1.340 million tons of wheat, 1,236 kt CO_2e (ADEME Carbon Base) and 2 billion €. These huge quantities and the reduced shelf life limit a direct consumption via donation. In parallel, spent grains are co-products of beer production (22 kg/hL of beer) with a limited shelf life. They can be used for animal feeding in the countryside but uses in towns are more limited. At the same time, in 2021 disabled persons, representing 4.06 % of French labor force, had 16% of unemployment rate, twice than able-bodied workers. Work Integration Social Enterprises (WISE) encounter some crisis, and they are looking for new activities. In this context, the association "Handicap Travail Solidarité" (HTS) has set up a social economy initiative to reuse food waste based on circular economy and working with the WISE: SoliFoodWaste (SFW). HTS is co-financed by the European Union program LIFE (LIFE18 ENV/FR/000029) to upgrade this initiative, to assess, to monitor SFW's rise and to enable its dissemination to other territories in Europe.

Objectives: This research aims to assess, using LCA, the environmental impacts of two recipes of cookies produced from unsold foods (bread and spend grain) in WISE or in supermarket with WISE's employees. As SFW is a social innovation initiative, a particular attention is also given to the social and economic impacts in the territory of implementation. Thereby, the objective is to present environmental impact associated with territorial impact.

Material and methods: This research-action is carried out within the framework of research intervention to support the establishment of this sector while measuring its environmental impacts. These impacts will be compared to the objectives of achieving environmental, social, and economic performance in order to replicate the model in different country. That is why particular attention must be given to territorial specificities. The support brought by researchers consists of:

- a territorial diagnosis of the local issues of unsold food in the territory of Nantes metropolis (Nantes Métropole, 2021). QGis software is used to create maps of deposits, actors, places of transformation and distribution of pastries.
- LCA of two recipes of cookies and two different production modalities (in supermarket or WISE). LCA is done in SimaPro software with EcoInvent V3.6 and Agribalyse V3 databases and ReCiPe 2016 (H) method. The functional unit is "produce 1kg of cookies". Bread and spent grain are collected, crushed, or dried. As waste, they have no impacts apart from their transport and transformation. Then these saved ingredients are incorporated into cookies dough, which is then shaped and cooked. The limits of the studied systems go from the collection of unsold foods to the production of the cookies without packaging. The foreground data come from recipes, observations, maps, and calculations.

Results: The mapping of initiatives and networks to fight against food waste on the territory of Nantes metropolis revealed many activities. The associations (eq. NGOs) are the main players involved in setting up the recovery circuit for unsold items and organic waste. In addition, many infrastructures exist to facilitate the development of SFW project. For the dissemination of SFW, actor mapping can be used as a decision support tool and to define the catchment area to reduce environmental impacts.

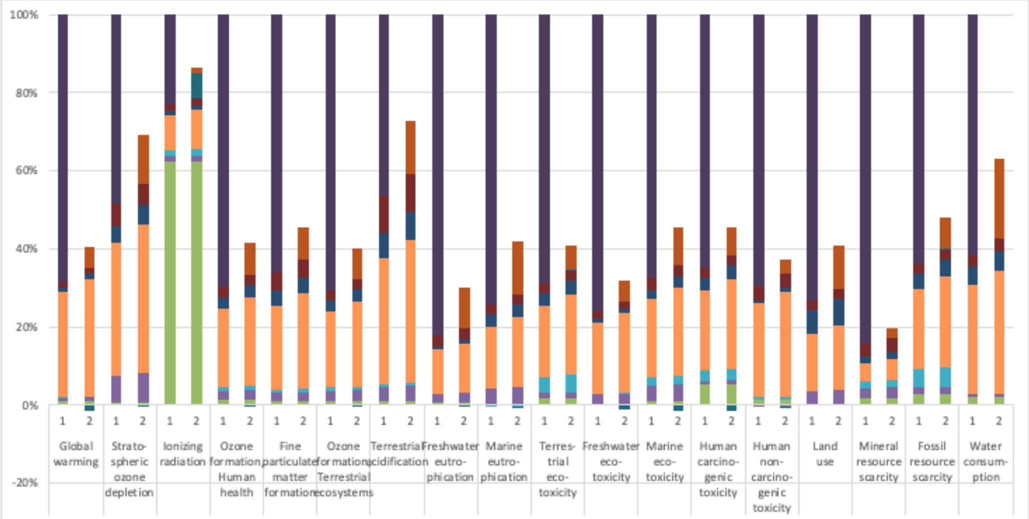

Figure 1: Comparison of impacts of SFW cookies made in WISE.
1: recipe with chocolate chunks
2: recipe with spent grain and hazelnuts.

The comparison of the impacts of two types of cookies produced in WISE (Fig.1) allows to identify the less impacting cookie (recipe 2) and the main contributors to the impacts: the bought ingredients. The main contributors for almost all impact categories are chocolate chunks and butter for recipe 1; butter and hazelnuts for recipe 2. The electricity has an important contribution in ionizing radiation. Among the solutions to ecodesign, the choice of ingredients for the future recipes is of huge importance: butter's substitution by sunflower oil can be interesting. The choice of unsold food is important: the reuse of unsold chocolate, even distant, is more crucial to avoid impact wastage than the reuse of local bread. In theory, production in supermarket with their own unsold food (no transport for bread) may seem more interesting, but impacts are reduced from 0% to 11.4% (linked to saved bread, Fig.1) and quantities of unsold food are more limited, more variable, more perishable, sales on site are not guaranteed and few WISE's workers are able to work in this context. Even if production in WISE is more intensive in transport for unsold supply, it is interesting for the production volume and the more inclusive activity. In 2021, SFW project recovered of 405 kg of bread and 192 kg of spent grains, produced of 2.62 tons of cookies, and gave 5,000 hours of work for 18 WISE's workers.

Conclusions: LCA allowed to evaluate the environmental impacts of SFW's products, even if some data (energy, distance) were difficult to estimate with precision (Notarnicola et al, 2017). The improvement in the completeness of inventory databases (Agribalyse, 2020) allowed to evaluate the environmental impacts with more accuracy. The current recipes were developed without the researchers' support. The design of future manufactured products should include the LCA in addition to sensory and economic criteria. The recipes of the future products should be developed with more unsold products (10-20% currently), with a long shelf life and with bought ingredients with less impacts. Since LCA requires expertise and a high degree of technicality, the development of simplified LCA tool to assess environmental impacts of developing recipes would be helpful for R&D teams (Thomas et al, 2020). Finally, Nantes metropolis is rich in food producers and associations fighting against food waste. The presented results are focused on the association of both territorial and environmental analysis and constitute a solid basis for the analysis. As SFW is a circular economy project that contributes to reuse unsold food and reduce unemployment of disabled workers, its impacts go beyond environmental impacts: they are also social and economic. As some environmental recommendations can have negative effects on social and economic aspects, it is therefore important to integrate all these dimensions into the impact measurement (Billaudeau et al, 2022).

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The potential impacts on climate change and farm scale economic sustainability from anaerobic digestion of manure

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Keywords: Biogas, manure management, LCA, economic sustainability

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Introduction

Economic sustainability for each actor in the value chain is necessary to obtain a change towards a net zero society. In Norway the agricultural sector has committed to reducing greenhouse gas (GHG) emissions by 5 million tonnes within 10 years. In the Agricultures Climate Plan (2021-2030) developed by the Norwegian Farmers association, better use of the manure resources and use of livestock manure for biogas production through anaerobic digestion (AD) are two of the eight proposed measures to obtain this. Currently only about 1% of the manure is treated in biogas plants (Lyng et al. 2019b).

Various definitions of economic sustainability of agricultural systems can be found in literature. Spicka et al. (2019) defined economic sustainability on farm level as "long term economic viability for the farm household". Lebacq et al. (2013) defined economic sustainability as the economic viability of farming systems. In this paper we define economic sustainability of a GHG measure as obtaining increase in profit or break even at the farm, compared with the current situation.

The purpose of this paper is 1) to assess the economic sustainability under the current framework conditions of farm scale and centralized biogas production from manure and 2) to document the GHG reductions that can occur not only on the farm, but throughout the value chain.

Methods

The study object is a typical Norwegian farm for combined meat and milk production. The farm scale biogas plant was assumed to generate heat on the farm, substituting electricity. The centralized biogas plant was assumed to co-digest the manure with other substrates and upgrade the biogas to be used as transport fuel, substituting diesel (Lyng et al. 2020).

The GHG emissions for farm based and centralized biogas production was calculated and compared with reference scenarios, using the BioValueChain model which is based on life cycle assessment methodology (Lyng et al. 2015). The functional unit was defined as treatment of the annual amount of manure available for AD (see Table 1), including the associated benefits.

Farm scale economic sustainability was based on (Lyng et al. 2019a), which calculated the annual economic results as alternative costs compared with the current situation for the two mitigation scenarios, as shown in Equation (1).

$$(1) \quad Annual\ economic\ results = (Income + Support + Avoided\ costs) - (OPEX + CAPEX)$$

OPEX are the annual operational expenditures and CAPEX are the annual costs related to capital expenditures. Income consist of avoided of energy and mineral fertilizer as well as economic support from the Norwegian Agriculture Agency per tonne of dry matter of manure used for biogas production.

Table 1 Amount of manure available for AD at the farm

	Number of animals	Manure for storage (excl. grazing)	Tonne manure (wet weight)	Tonne manure (dry matter)
Dairy cattle	35	84%	545	57
Suckling cows	23	69%	169	21
Bulls for slaughtering	39	69%	174	19
Total	97		889	97

Results

The results presented in Figure 1 show that centralized biogas production is the most preferred option both when it comes to annual economic results on form level and life cycle GHG emissions. These results are only relevant for farms that are located close to centralized plants.

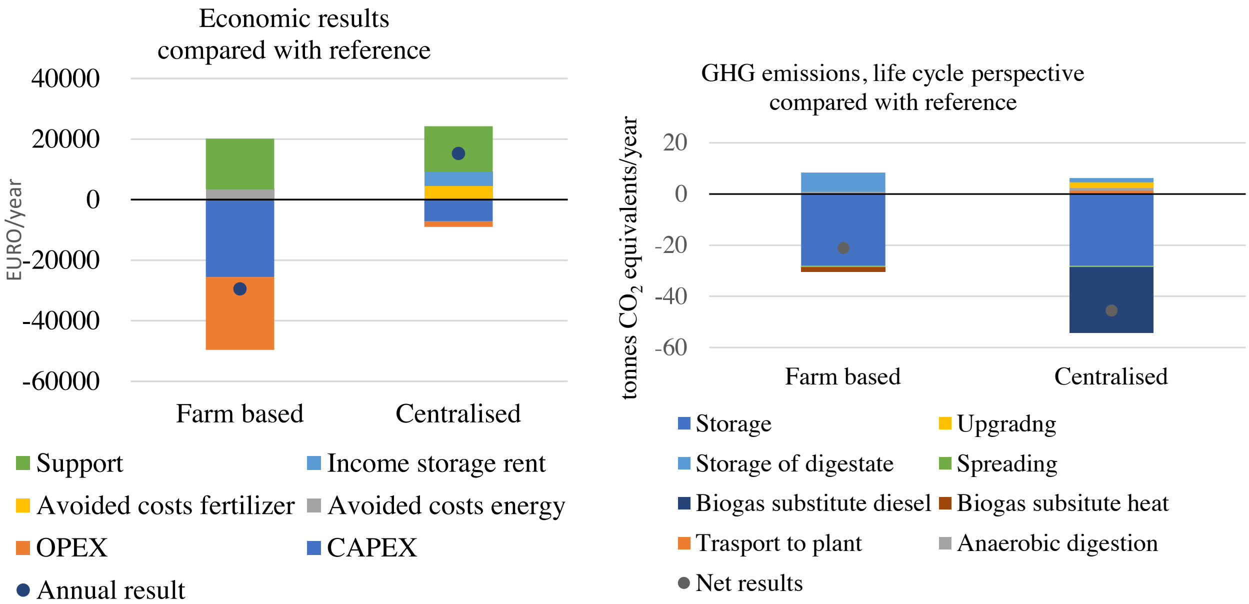

Figure 1 Farm scale economic sustainability and potential impacts on climate change

The farm scale biogas production is less economically sustainable for the farm under the current framework conditions, as the avoided costs from producing energy on the farm are not sufficient to cover the capital investments and operational costs. In both alternatives the current support system for manure to biogas production represent most of the income. The results are highly dependent on the agreement between the farmer and the centralized biogas plant regarding responsibility of transport and storage costs.

Results for potential impacts on climate change show that the largest difference between farm scale and centralized biogas production is the avoided emissions when biogas substitute other energy carriers or fuels. The centralized biogas plant alternative obtains the largest emission reduction as biogas is upgraded and used for transport, substituting diesel. These emissions do, however, occur outside of agriculture and will thus not be visible in their GHG reporting.

Conclusion

The results from this study show that to increase the amount of manure for biogas production and to obtain the largest emissions reduction, more centralized plants should be established in areas with a sufficient number of livestock farms. It also shows that maintaining or improving the current support system may be necessary to increase biogas production to obtain the goals of reducing GHG emissions from agriculture.

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Treating Food Waste: Need of Extension of Food Energy Input Calculations

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Keywords: *Food waste; Processing energy; Waste management; LCA; energy-food nexus*

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Rationale and objective of the work

Direct connection between energy and food is threefold: energy necessary to provide food, energy provided by eaten food to humans, and energy required by uneaten food for waste processing. Food waste accounts for 30 - 40% of overall food production (around 1.3 billion tons) (Noleppa and Cartsburg 2015.) and should be considered in estimations of energy required to provide food. However, waste treatment system is complex, as food waste collection, separation and treatment differ a lot from case to case, depending on the type of food and available waste treatment infrastructure. This research aimed to identify energy of food waste treatment and compare it to energy needed to supply food to consumers.

Approach and methodology

Depending on the source and methodology, amounts of food yearly wasted in Germany range from 10.9 to over 13 million tons (Noleppa and Cartsburg 2015.). Overall amount of food waste in German production and supply chains was estimated to about 3.6 million tons, of which about 1.4 million tons were associated with primary production losses and about 2.2 with processing and manufacturing losses, but food waste at the German retail (including other distribution of food) and consumer levels, was estimated to 9.1 million tons (Leverenz et al., 2021).
On the other hand, energy required to provide food, especially if including cooking, varies hugely, going from just over 1 MJ/kg for honey to an extreme of 220 MJ/kg for shrimps without shells (Carlsson-Kanyama et al., 2003). Unsurprisingly, animal products typically require more energy. Yet, the leading four food groups accounting for as much as 68% of food waste in Germany, fruits (20%), vegetables (18%), cereal products (16%) and potato products (14%) (Noleppa and Cartsburg 2015.), are all of plant origin and typically, despite large variations depending on transport, growing and cooking technique, do not require large amounts of energy (3.5-115, 3.7-66, 1.0-26, 4.6-60 MJ/kg, respectively) (Carlsson-Kanyama et al., 2003). However the full picture can only be obtained if waste treatment would also be included.
To do that, a scenario typical for Germany was assumed. This meant including 4 waste treatments (anaerobic digestion, composting, wastewater treatment and incineration) and 5 sources of waste (primary production, processing and manufacturing, retail and wholesale market, restaurants and food services and households) (Leverenz et al., 2021). Primary production losses were not treated while the remaining food wastes were treated as shown in table 1. The underlying energy of food waste treatment was calculated from ecoinvent 3 (ecoinvent, Zurich, Switzerland) database in the software SimaPro 9.3.0.3 (PRé Sustainability B.V., Amersfoort, The Netherlands) and followed the standard LCA approach (ISO 14040, 2006 and ISO 14044, 2006). The methodology of the life cycle impact assessment was Cumulative Energy Demand V1.11 (Frischknecht et al., 2004).

Main results and discussion

Predominant treatment of food waste in Germany was anaerobic digestion, followed by incineration, composting and wastewater treatment (Table 1)

Table 1: Amounts and energy required per food waste treatment

Treatment	Amount of food waste (ton)	Energy of food waste treatment (MJ/ton)
Anaerobic digestion	4 145 800	660
Incineration	3 451 000	380
Composting	1 663 200	360
Wastewater	1 654 000	6500
Pet food	353 000	50
Not treated	1 360 000	0

On average, 1221 MJ of energy was needed for treatment of 1 ton of food waste. So, to account for the overall energy necessary to provide, per example, 1 ton of fresh bread from local bakery, we need to account for these losses as well. If we assume that above mentioned 16% of cereal products waste applies also to this bread, then it is necessary to produce 1.19 tons per 1 ton eaten. As 8.9 MJ/kg are needed for production of this bread (Carlsson-Kanyama et al., 2003), for production of eventually wasted 190 kg, 1695 MJ of energy are needed. Further, the waste needs to be processed, on average requiring additional 231 MJ. So, providing 1 ton of consumed fresh bread from local bakery requires 10826 MJ, of which over 2% accounts for waste bread processing. This energy is over 20% higher energy requirement compared to originally estimated 8.9 MJ/kg. Therefore, LCA studies should consider specific data of food waste processing energy use instead of generalized assumptions common in practice.

Conclusion

In simultaneous energy and climate crisis that we are experiencing, energy necessary for waste processing must not be overlooked. This is particularly true for food waste which is generated in large amounts, and which is in some cases, even with our best efforts, unavoidable. Therefore, LCA studies, as well as other food waste, circularity or similar studies, should include specific data of food waste processing energy use into energy requirement estimations.

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Environmental assessment of combustion and micro-cogeneration innovative units for poultry manure valorization

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Introduction

The poultry sector is the second largest producer, after pork, of meat worldwide (FAO, 2019). In Spain, the sector is increasing the production every year due to growing demand of chicken and turkey meat, as well as eggs. However, this demand is triggering serious environmental issues since poultry sector is responsible for the generation of large amount of waste and emissions (Billen et al., 2015). In this sense, it can be remarked the generation and management of poultry manure which is stored and used as fertilizer in farm's field. In this sense, the environmental impact of manure management depends highly on the storage time, the nitrogen content, and the excessive application on field —which may lead to greenhouse gas (GHG) emissions and eutrophication of land and/or water reservoirs due to the nutrient's leakage.
Attending to the GHG emissions, the poultry sector accounts by 8% of GHG emissions of livestock sector — 8 million tons of CO_2 eq. Concerning the hotspots for poultry production, the largest impact contributor in terms of GHG emissions is the feed production followed by manure management and energy consumption in the farm (FAO, 2016).

Methodology

The project AVIENERGY develops an alternative and innovative solution to deal with environmental issues derived from poultry manure management. The project promotes on-site energy valorization of manure —by means of combustion (with a specially designed burner) and a micro-cogeneration unit— as alternative fuel to fossil fuels. Consequently, the farm not only reduces the amount of manure to be stored and applied to fields, but also decouples the farm's energy supply –in terms of heating (e.g., natural gas) or electricity– from fossil fuels (Figure 1).
The environmental profile of the innovative solution proposed is evaluated throughout Life Cycle Assessment (LCA). In this regard, two scenarios were evaluated: i) the traditional scenario (i.e., with no changes for manure management; and ii) the AVIENERGY scenario (i.e., with the implementation of the proposed solution for manure valorization).

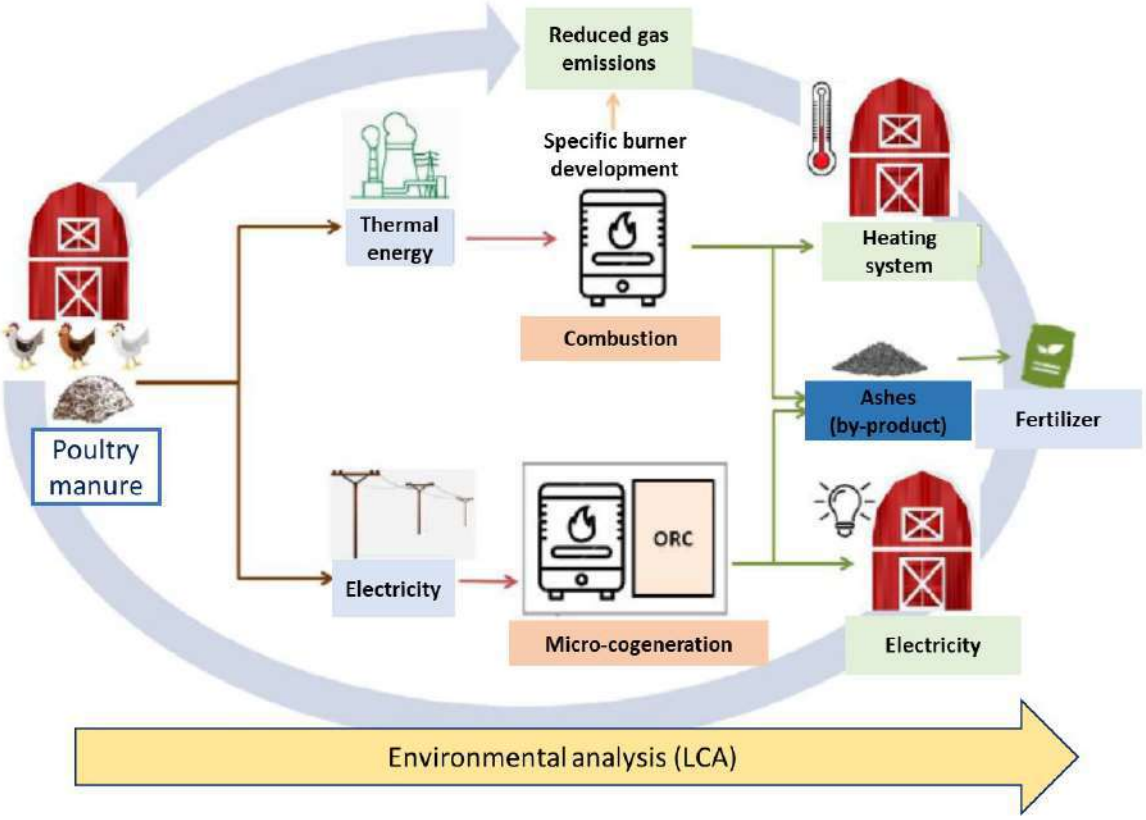

Figure 1. Schematic representation of the innovative solutions proposed in AVIENERGY.

Results

The results obtained showed that poultry production for AVIENERGY scenario attained significant impact reduction when benchmarking with traditional scenario due to the following:

- Lower necessities of field for manure spreading.
- Lower emissions from manure management.
- Lower electricity requirements from the grid.
- Lower fossil fuels consumption for heating.

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Conceptualization of ecodesign for food products

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Keywords: *Ecodesign; Design for X; Sustainable product development; Sustainability; Circular economy; Recycling*

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Objective:
The current food system is unsustainable, causing a lot of damage to the environment (Poore & Nemecek, 2018). While increasing food production for growing population is important, the generation of food waste should not be left aside. Food waste has been under close attention because it keeps rising in both developed and developing countries. Food loss and waste along the chain is around one-third of all the food produced currently (FAO, 2011), and it releases 8% of Greenhouse Gas emissions (GHGs) (FAO, 2015). It is vitally important to find efficient ways to produce more food while, at the same time, decreasing resources' expenditure and the environmental impact of the production. This work aims to conduct an extensive literature search and **identify conceptual ecodesign approaches**, which can be applied to the specifics of perishable products of the agri-food system. Identification then follows with the establishment of a conceptual framework of food products ecodesign applicable for further practical and theoretical testing.

Approach and methodology:
The concept of ecodesign takes into consideration the combination of different environmental aspects into product design and development to reduce harmful environmental impacts throughout a product's life cycle (ISO, 2020). The objectives of this concept are in line with sustainability, as described by (Biron, 2018). The available literature shows that the application of this concept can be done through different methodologies (Rossi et al., 2016), such as "Design for X". The review was conducted using the Google Scholar database. Here the following keywords were used "ecodesign", "design for x" and "food", yielding a total of 246 results. Further analysis and refinement narrowed down the results to 28 articles.

Main results and discussion:
It is known that the biggest improvements to the impact of a product is at the design stage (Basbagill et al., 2013). After an extensive literature search, it was found that the implementation of this concept can reduce: (1) The impact of current diets by 20-40% by decreasing animal protein consumption by 25-50% (Notarnicola et al., 2017); (2) Around 30% in current emissions when applying mitigation strategies in animal protein production (Gerber et al., 2013); (3) Between 22-29% in GHGs' release, when changing from the current diets towards plant-based diets (Sabaté & Soret, 2014); (4) Inefficacy per hectare of food production (93%) and increase water use efficiency, soil health, fertility and pest control by shifting from current cultivation systems to alternative ones (Machovina et al., 2015); (5) The amount of avoidable food waste at consumer point that could potentially result in the reduction of GHGs of 800–1400 kg/tonne of food waste (Schott & Andersson, 2015); (6) Resource consumption with the use of new technologies and processes (Rohn et al., 2014): up to 30% in water use; between 6-25% in fuel use; and between 11-90% in herbicide, pesticide or herbicide use, and others (Liu et al., 2019).

Conclusions:
The implementation of the "Design for X" methodology of ecodesign on the development of food products to the most environmentally taxing parts of the life cycle of a product – material sourcing,

processing stage and end of life – we combine three design dimensions: "*Design for Sustainable Sourcing*" (DfSS), "*Design for Optimized Resource Use*" (DfORU) and lastly "*Design for Reuse*" (DfR). With this it is possible to reduce the environmental impact of food products at different levels according to the stage of the value chain: 20-30% at the farming stage, around 5% at the transformation stage, and 15-20% at the end-of-life stage. With this is will help fulfil different SDGs.

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REVALIM, a French network for the environmental assessment of agricultural and food products

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The French national research institute for agriculture, food and environment INRAE, the French environmental agency ADEME, and the French networks for agricultural and food technology institutes ACTA and ACTIA launched a Scientific Interest Group (GIS) in September 2021, called REVALIM ("Réseau d'EValuation environnementale des produits agricoles et ALIMentaires", for agricultural and food products environmental assessment network). It follows an informal partnership on the AGRIBALYSE program that pre-existed since 2009. The four members integrate de facto 11 technical institutes specialized in agricultural or food sectors. REVALIM's main objective is to develop new methodologies for the environmental assessment of agricultural and food products and to expand the AGRIBALYSE reference database on the environmental impacts of these products. Today, AGRIBALYSE faces major challenges related to the sharp increase of expert and non-expert users, the updating and development of transparent and high-quality data over time. This issue is particularly important as recent legislation prepares an environmental labelling scheme for food products consumed in France and given the development of the Product Environmental Footprint (PEF) framework at European level. The government, society stakeholders and the scientific community therefore want to quantify the environmental impacts of agri-food products using science-based environmental assessment methods. We present the REVALIM 2022-2025 roadmap. We discuss in more detail the work planned to expand and improve the AGRIBALYSE database and environmental assessment methods, in particular Life Cycle Assessment (LCA).

REVALIM members have drawn a roadmap defining actions to address issues and limitations identified in the current AGRIBALYSE database and in the impact assessment methods used for food and agricultural products. REVALIM identified one-time actions, background actions and methodological projects.
Regarding one-time actions, a major task is the updating of the agricultural production life cycle inventories (LCIs), which are based on data for the 2005-2009 reference period. Agricultural production systems have evolved in terms of farmer practices, pesticides used, yields, etc. Another key action is to develop the database by introducing LCIs for new food products or new production modes (organic, certified …) AGRIBALYSE now integrates all stages of the food chain: REVALIM plans to improve the accuracy of the post-farm stages, particularly with regard to industrial transformation processes, the use phase and packaging.

Background actions will take place over several years. As an example, data quality procedures will be set up to ensure and maintain the quality of the AGRIBALYSE LCI database. Other background actions as the integration of the most consensual agricultural emission models, the articulation with international databases to ensure the harmonization of the work or the continuous updating of LCIs are also essential for the quality of the database.
In addition to these actions, REVALIM focuses on data and methodological issues concerning biodiversity, pesticides and soil carbon sequestration in LCA. On these issues, dedicated work sessions have been conducted to share knowledge between members, to discuss scientific questions and to prioritize the tasks at hand.
As some methodological tasks require fast action, REVALIM proposes a two-stage approach: the first interim level provides a basic but rapid solution, the second level provides a more detailed and scientifically robust solution.
Regarding pesticides in LCA, REVALIM has identified several tasks regarding the LCIs, such as updating pesticide use, correcting negative metal emissions, and considering the evolution of ionic forms of metals. On the impact assessment step, REVALIM will propose an "adapted Environmental Footprint" method to correct some characterization factors, to allow the assessment of metals with a 100-year horizon, and potentially the assessment of impacts of pesticide residues in food products. In a more distant future, REVALIM will analyze and test the methods recommended by the Global Guidance on Environmental Life Cycle Impact Assessment Indicators (GLAM) initiative regarding pollinator impact assessment and terrestrial and marine ecotoxicity for integration in AGRIBALYSE.
Regarding soil carbon sequestration, REVALIM will address three key questions linked to land use and land use change. As a first level, REVALIM will use literature values to take into account the trend in soil carbon sequestration linked to the type of land use (arable versus permanent grassland). The second level will replace this interim approach by using a tool developed to assess direct land use change. This tool combined with an appropriate land use dataset with sufficient spatial accuracy will address soil carbon dynamics due to Land Use Change. Finally, the carbon sequestration linked to specific practices (e.g. introduction of cover crops) will be integrated on the basis of literature values or using more accurate models.
Regarding biodiversity in LCA, REVALIM aims to consider "local" biodiversity linked to farming practices. REVALIM will focus on the first driver of biodiversity loss, which is land use. After a quick review of the available methods based on international state-of-art, REVALIM will select the most promising methods. In order to identify whether a method can meet the expectations and needs for the biodiversity impact assessment, REVALIM will test and compare them regarding scientific robustness and their compatibility with data available in the AGRIBALYSE LCIs. The results may allow AGRIBALYSE to integrate a biodiversity assessment method that can better distinguish agricultural intensities and practices.
This roadmap affirms the will and ambition of REVALIM to improve and enhance the AGRIBALYSE database, but also to better assess the diversity of today's farming practices by relying on robust and consensual scientific results. This roadmap is a strategic steering tool that will be updated regularly.

Dairy sheep simplified LCA: comparison and evaluation of different tools to estimate carbon footprint across Europe

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Keywords: *Milk, meat, enteric methane, Green Sheep LIFE*

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Rationale and Objective LIFE Green Sheep (LIFE19 CCM/FR/001245) has been targeting a common Carbon Footpritnt (CF) assessment methodology at European level. In order to simplify the life cycle inventory, tools to estimate CF in dairy and meat sheep farm have already been developed in European countries such as France (CAP'2ER), Spain (ArdiCarbon) and Italy (Carbonsheep), and Irelanad (Sheep LCA). Nevertheless, they are specifically adapted to local production systems in terms of collected inputs and algorithms used in the impact assessment. Consistent data inventories and shared plans of mitigation for sheep production farming at European level requires aligned approaches and tools. The objective of this study was to compare 3 tools, already available in Europe, to estimate the carbon footprint of dairy sheep farming systems.

Approach and Methodology The 3 compared tools were: CAP'2ER (C2E; "Institute de l'Elevage, France); ArdiCarbon (AC; Neiker, Spain); and CarbonSheep (CS; Univ. of Sassari, Italy). For the comparison in this study all tools were set at level 1 of model detail for simplified estimates, based on aggregate inputs from farms. Collected inputs and model impact assessments were based on customized algorithms and emission coefficients of IPCC (2019) for animal and farm emissions, to increase the tool flexibility at country level. Algorithms and equations to estimate animal requirements, food intake and excretion, coefficients adopted to calculate emissions from each hotspot or emission source and allocation formulas were not modified before the comparison. The LCA boundaries of the analysis were from cradle to farm gate. The comparison was performed collecting data from 3 sheep farms in France, Spain, Romania and Italy (n=12). Basic inputs required to run each tool (82 for C2E, 83 for AC and 52 for CS) were collected from the 12 farms copying the life cycle inventory of flock consistency, crops and pasture areas, fertilizers, purchased feed, fuel and electricity, and farm outputs of milk and meat. The model runs enabled assessment of aggregated emissions from the following categories: CF 100% allocated to milk, enteric methane, manure management, crops and fertilizers, feed purchased, electricity, fuel and other purchased inputs. Emissions were expressed per kg of CO_2eq./kg of fat and protein corrected milk (FPCM). A total of 36 estimates were obtained running each tool with inputs from the 12 farms. The model evaluation was performed from differences between C2E vs. AC, C2E vs. CS and AC vs. CS analysed as mean bias and the root mean square error of prediction (RMSPE) (Tedeschi, 2006).

Results and Discussions Collected inputs proceeded from a broad range of farm conditions. The farms involved in the study had 499±123 ewes, 187±118 ha, and produced 87.2±87.8 tons of milk per year. Most of the farms had semi-extensive farming systems with animals having access to pasture. The estimated of CF, mean bias of differences and RMSPE of the 3 models were presented in Table 1. The mean farm CF for the 3 tools was 3.57, 3.75, and 4.85 kg of FPCM for AC, CS, and C2E, respectively. Big differences were observed in the allocation percentage, which ranged from 67% of C2E to 94% of CS. All tools reported high incidence of animal emissions (enteric methane and manure) on the total CF in line with the literature evidences. The lowest emissions were observed for electricity and other purchased inputs, which was resulted higher in AC than in C2E and CS. The differences in CF expressed as mean bias were higher than 1.0 kg of FPCM between C2E-AC and C2E and CS, but was very small for AC-CS, and similar proportions were also observed for the allocation percentage and other emission sources. It indicates that values predicted by one tool e.g., AC, were on average highly accurate when compared with CS but showed large underestimation when compared with C2E. But in this sense However, the mean bias does not allow to have a clear picture of the tool performance at farm level, since average values compensate by the negative and positive differences. When differences were evaluated as RMSPE, it was higher than the mean bias, and indicated that CF predicted by C2E was 1.7 kg of FPCM higher than AC and CS but also AC predictions were 1.2 kg of FPCM higher than CS. Large differences were also observed among tools for within each hotspot. When the RMSPE of each hotspot were expressed as percentage of the RMSPE of CF (Table 3) it was possible to observe that differences were due to enteric methane (67% of RMSPE for AC-CS), and to manure management (62% of RMSPE for C2E –AC). In particular, the highest differences were due to methane emission factor and animal excretion predictions considered by each tool for sheep categories, since the 3 tools adopted values customized at country level. Other detected differences relies on emission coefficients adopted for crops and feed purchased and on allocation formulas.

Table 1. Estimated of Carbon Footprint performed with CAP'2ER/DEO (C2E), ArdiCarbon (AC) and CarbonSheep (CS), mean bias of differences and root square error of prediction (RMSPE),

	CF predicted values			Mean bias			RMSPE		
Variable	C2E	AC	CS	C2E-AC	C2E-CS	AC-CS	C2E-AC	C2E-CS	AC-CS
Carbon footprint, kg FPCM	4.85	3.57	3.75	1.28	1.11	-0.17	1.71	1.72	1.19
Allocation for milk, %	67%	89%	94%	-22.8%	-27.8	-5.0	24.2	29.5	6.2
Enteric methane, kg/kg FPCM	2.04	1.68	1.87	0.31	0.17	-0.19	0.64	0.52	0.80
Manure, kg/kg FPCM	1.36	0.36	0.71	1.02	0.66	-0.36	1.07	0.71	0.48
Crop and fertilizers, kg/kg FPCM	0.40	0.58	0.16	-0.15	0.24	0.41	0.70	0.32	0.74
Feed purchased, kg/kg FPCM	0.83	0.45	0.50	0.42	0.35	-0.05	0.58	0.61	0.31
Electricity, kg/kg FPCM	<0.01	0.04	0.03	-0.04	-0.03	0.01	0.05	0.04	0.03
Fuel, kg/kg FPCM	0.22	0.33	0.24	-0.10	-0.01	0.09	0.21	0.11	0.15
Other purchased, kg/kg FPCM	< 0.01	0.07	<0.01	-0.07	< 0.01	0.07	0.14	< 0.01	0.13

Conclusions The comparison indicated that algorithms and emission coefficients used in the 3 tools, especially for methane emissions and manure management, need a careful alignment before run common estimates at European level.

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Towards environmental labelling of food products in France

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This paper outlines the main aspects of a more detailed article (Hélias et al. 2022). The French government has enacted legislation to create an environmental labelling system for food products. During an experiential phase in 2020-2021 involving numerous stakeholders, many of whom proposed labelling systems, a multidisciplinary scientific council (SC) was set up to support the process. The SC addressed several issues related to the data and methods to be used, the environmental impacts to be considered and the label design to summarise all of the aforementioned aspects in a simple, informative and useful way. We present the main outcomes of the SC's reflections (Soler et al, 2021), and conclude that operational and massive environmental labelling of food products is possible. The feasibility, stakeholder agreement and compliance with international recommendations were the basis for answering six questions.

What environmental issues should be considered? Most environmental labelling systems implemented to date have focused on climate change, however, other environmental issues have become more acute, leading amongst others to a multicausal decline in biodiversity. Human health is not explicitly mentioned in the French law enacted in 2021, but is a major concern for consumers and citizens for which two domains must be distinguished. The exposure of populations to pollutants emitted into the environment should be included in the environmental labelling scheme. Health impacts associated with contaminants (e.g. pesticide residues) in food relate to food safety, which is regulated by the food legislation in the European Union (EU), including these health impacts in environmental labelling could prove incompatible with EU regulations and raise significant risks of legal challenge.

What objectives should be targeted? Environmental labelling can act in two ways: highlighting the differences in impact within each food category, and between food categories (e.g., between animal and plant-based products). Determining the extent to which environmental labelling should focus on one or the other, or on both of these levers is a major issue in the choice of a labelling system. We consider that both should be encompassed.

What data should be used, and by who? An intermediate pathway is possible between low-cost creation of generic data and the creation of more specific data at higher cost. Implementing a "semi-specific" approach would involve complementing the generic data with data for a range of high-impact action levers e.g. recipe, transport or packaging. Different types of stakeholders – companies and digital app providers – can then attribute environmental impact values to products on the market. Collective rules must be defined. In all cases, evaluations should be part of a coherent and compatible methodological framework, be transparent and traceable to allow external verification or an institutional validation process.

What methods for assessing environmental impacts? The European Commission has proposed the "Product Environmental Footprint" (PEF) method, for assessing the environmental impacts of products. For food labelling, improvements to the method and associated current data can be proposed. (1) LCA has to account for variations in soil carbon stocks in agro-ecosystems resulting from a change in practices or in land use. Taking these stock variations into account is legitimate and desirable in an environmental label, and French data are available. (2) Toxicity and ecotoxicity indicators are the subject of numerous debates by stakeholders. PEF uses an infinite time horizon. Given the need to aggregate the information into a single indicator, modulating the PEF with a 100-year horizon would allow a better balance between the impacts of organic molecules and trace metals. (3) The relationships between agricultural practices and biodiversity are complex. Several proposals have been made but they have not yet been included in the PEF. A possible and rapidly operational solution would be to add a new impact category "field-level biodiversity" in the LCA framework. It would require defining two parameters: a coefficient expressing biodiversity benefit associated with various types of labels, and the weight given to this impact category, which is a matter of societal arbitration that needs to be made explicit.

Which environmental scores should be chosen? LCA is mainly used in multicriteria comparative approaches, but for environmental labelling the information is aggregated in a single score expressed in millipoints. This scale can be changed for two reasons: (1) To express the impact of a food product relative to other foods and not in absolute terms, in order to facilitate comparison between products. (2) To introduce a non-linearity between the single score scale and the labelling scale, so that the latter can be fully used (with values all along the variation range and not only at the extremes). When changing scale, special attention must be paid to the equation (introduction of non-linearity) and to the bounds used (construction of the reference), scale changes must be transparent and argued.
Modifying the environmental scores by introducing additional indicators may distort the food-environment relationship established in the basic framework, and thus risk losing scientific rigour in order to gain on other dimensions. However, this may be acceptable to better highlight the benefits of actions that are consistent with public policy priorities (like in the EU 'Farm-to-Fork' strategy). These elements raise important strategic questions to be considered when thinking about complementary indicators, but their justifications are not only scientific but also political.

What label format should be proposed? A label format refers to the visual that is presented to the consumer. An effective format must attract attention and have salience. For this, it is preferable that it be standardised, hence the importance of having a unique, immediately recognisable format, located in an expected place on the packaging. For salience, it is preferable that it be in colour. An effective format for changing behaviour must be synthetic. This can nevertheless be complemented by an analytical part, based on a sub-score decomposition or a numerical value revealing the actions of producers in a more detailed way than the aggregate score.

Through the existence of the PEF, the life cycle inventory data in the Agribalyse database and the answers to the above questions, the LCA framework can be operationalized and adapted for environmental labelling. Informing consumers about the environmental impacts of food products is therefore possible and is certainly a step forward in minimizing the human impact on nature.

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Carbonsheep: una herramienta SIG para simplificacion de analysis de ciclo de vida para comparar y espacializar la huella de carbono de explotaciones ovinas

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Keywords: ARCGIS, ovino lechero, metano, mitigacion,

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Intoduccion y Objectivos Los inventarios del ciclo de vida para estimar la huella de carbono suelen ser muy detallados, requieren mucho tiempo en la toma de datos y en los cálculos del impacto, por lo que sólo un número limitado de explotaciones puede caracterizarse con este enfoque. El desarrollo de herramientas de soporte a la toma de decisiones para evaluar la eficiencia técnica y ambiental de las fincas es por otro lado fundamental para mejorar el uso sostenible de recursos naturales. La herramientas simplificadas de análisis de ciclo de vida pueden ayudar a extender la cuantificación de las emisiones de gases de efecto invernadero a muchas explotaciones y planear la mitigación a nivel territorial.

En el proyecto Europeo LIFE Forage4Climate (F4C; LIFE15CCM/00039) se ha desarrollado una herramienta para estimación simplificada de huella de carbono llamada CarbonSheep y basada en un numero mínimo de datos de la finca para un análisis de impacto rápida aplicable a un numero muy elevado de granjas ovinas de leche en el área de producción Mediterránea. El modelo de calculo se implementó directamente en un sistema informativo geográfico (SIG) para visualizar mapas de impacto generado por las explotaciones. El SIG estaba incluido en ARCGIS Online, una plataforma cartográfica y analítica de Esri Italia s.p.a. (Roma, Italia), accesible tambien desde moviles, y que permite: i) recopilar los datos esenciales de las explotaciones; ii) mostrar los resultados del LCA simplificado; iii) mostrar mapas de estadísticas descriptivas de las explotaciones registradas; iv) comparar el FC de las explotaciones con los valores de referencia territoriales (Figura 1). Con acciones de networking, a continuación del proyecto F4C, el modelo se ha incluido en los proyectos LIFE Sheep To Ship (StS; LIFE15CCM/00123) and Green Sheep (LIFE19 CCM/FR/001245) para comparación con otros modelos Europeos (Abstract 153 y 154). Este trabajo tenia el objectivo de evaluar la CF del modelo simplificado CarbonSheep vs. Las estimaciones conseguidas con el estándar de análisis de ciclo de vida detallado y completo según la normas ISO internacionales.

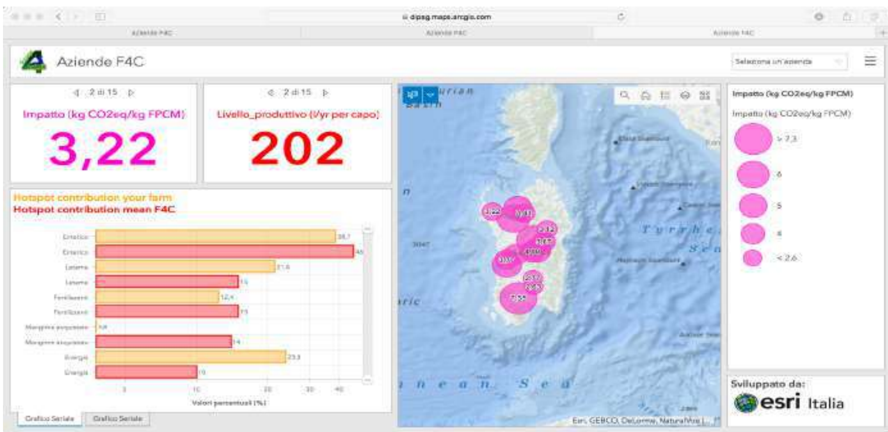

Figura 1. Resultados graficos en Sistema Informativo Geografico (SIG) de la herramienta Carbonsheep-

Aproche y método Para la evaluación se han considerado datos de 32 fincas lecheras de Sardinia (Italy) (promedio de 355 ovejas y 170 L/ano de leche per oveja). Una completa LCI se ha llevado a cabo con encuesta al ganadero y toma de datos de la finca. Los datos incluyan las categorías de ovejas, el tipo de establo, cantidad de leche y carne producidas, piensos y forrajes comprados, fertilizantes consumidos y rendimiento de cultivos, la energía y el combustible gastados. Los datos se analizaron i) con CarbonSheep (CS) y ii) según los estándares ISO 14040, 14044 y 14067 (ISO) con el software SIMAPRO®. CarbonSheep ha estimado la huella de carbono con solo 40 datos esenciales para describir el ciclo productivo anual. El modelo se desarrolló en Excel® inspirado por el nivel 2 del IPCC (2019), modificado con ecuaciones especificas para ovino de leche (ingestión de materia seca, excreción de N, etc) y coeficiente de emisiones en estudios de la misma área (Serra, 2014). Como unidad funcional fue considerando el impacto para unidades de leche estándar (LN: kg de CO2eq./kg de leche con 6.5% grasa y 5.8% proteína). La evaluación se llevó a cabo con análisis de error medio y error cuadrático medio (RMSPE) y su descomposición (Tedeschi, 2006)

Resultados and Discusiones Las estimaciones CS vs. las de ISO completo realizadas con el software SIMAPRO® fueron iguales a 3.89±1.01 vs. 4.22±1.2 kg CO2/kg de LN, con un error promedio CS-ISO de -0.56±0.43. La regresión de ISO vs. CS fue igual a $y = 1.07*X + 0.09$ $R^2 = 0.77$ (Figura 2) con RMSPE igual a 0.47 ±0.48 kg CO2/kg de LN, debido por el 26% a error medio, 1% a error de regresión y 73% a error casual.

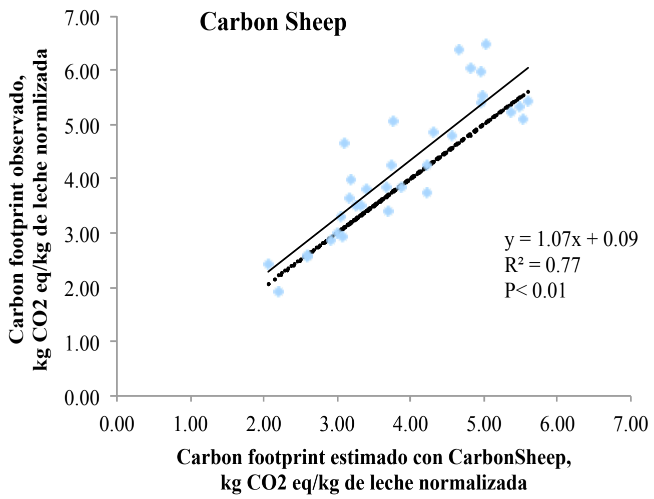

Figure 2. Valores observados de la huella de carbono determinados en 32 explotaciones de ovino de leche de Sardegna (Italia) con análisis ciclo de vida completo (ISO) frente a los valores previstos determinados con el Carbon Sheep. La línea de puntos indica la equivalencia y=x.

Conclusions Carbonsheep puede considerarse una herramienta eficaz para seleccionar las explotaciones lácteas con alto potencial de huella de carbono candidatas a planes de mitigación y mostrar las emisiones de gases de invernadero in mapas territoriales.

Aknowledgments The work was supported by European Community, LIFE PROGRAM for Climate Change mitigation, projects: LIFE Forage4Climate (F4C; LIFE15CCM/00039), LIFE Sheep To Ship (StS; LIFE15CCM/00123) and Green Sheep LIFE (LIFE19 CCM/FR/001245).

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Environmental assessment tools make LCA knowledge accessible and actionable

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Keywords: *LCA-tools; environmental assessment tools; global food supply chains.*

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Rationale

Companies and other actors operating in food supply chains are becoming more and more involved in environmental impact assessments. This trend is necessary to overcome the initial evaluative and small-scale application of LCA and unlock its real potential. A proven option to accelerate this trend is to develop LCA-based tools that companies can use independently. Blonk (Blonk Consultants and Blonk Sustainability Tools) has been actively engaged in numerous collaborations focusing exactly on tool development. A successful example is the work that Blonk has been doing for IDH, The Sustainable Trade Initiative (IDH) and for the Floriculture Sustainable Initiative (FSI).

Approach

IDH is an organization (Foundation) that works with businesses, financiers, governments, and civil society to realize sustainable trade in global value chains. In several food crops and ingredients industries, IDH convenes actors in sector initiatives around common sustainability agendas and ambitions. IDH undertook the path of environmental assessments and LCA together with Blonk about 3 years ago, for several of its sector initiatives, starting with the fruit & vegetables sector, and since then continuing with spices and, in collaboration with FSI, flowers & plants in 2020, and aquaculture in 2021. These projects have enabled IDH (and FSI) members to better understand the environmental impact of their supply chains and make real positive change.

After an initial trajectory focusing on raising awareness on key environmental issues, Blonk developed tools based on LCA methodologies for all the sectors mentioned above. The tools enable the user to collect data and calculate the environmental impacts of a certain supply chain. Currently, the environmental impact categories climate change, water scarcity, eutrophication, and ecotoxicity are included. Food losses are also accounted for as a key additional indicator.

All tools satisfy certain fundamental requirements: user friendliness, completeness, consistency with existing LCA standards, and coherence with the supply chain. The tools are built in Excel as it is widely available globally and does not require any specific software or knowledge to use. The tools consist of two separate files. The Input Sheet file allows the user to collect data throughout the supply chain. Data is then imported into the Tool file, where calculations occur and results are displayed. This split between the data collection and the results files has the advantage of allowing to store data from hundreds of supply chains and aggregate and compare results relatively to important parameters such as the type of product or the year of production. This same structure applies for all tools and is adapted and modified where necessary thank to a process of dedicated pilots in the specific sectors. Piloting the tools with actual companies ensured that the requested data was realistic and easy to understand.

The tools are based on the same key LCA methodologies but are adapted to the specific characteristics of the sectors they apply to. The underlying methodologies are: the ISO 14040/14044 (ISO, 2006a, 2006b), the Product Environmental Footprint Category Rules (European Commission, 2017), the Flori-PEF (draft, to be published in 2022), the Hortifootprint Category Rules (Helmes et al., 2020). Background data is extrapolated from LCI databases such as Ecoinvent (Wernet et al., 2016) and Agri-footprint (Van Paassen et al., 2019). Primary data is collected for every stage of the supply chain, from cultivation up to retail. The stages in between slightly vary as the sectors have different supply chain characteristics. For example, the tool developed for the spices sector, has a drying and processing stage both at the country of cultivation and at the country of import, as such activities might occur at different moments.

Results

Through a set of comprehensive dashboards, the tools enable companies to get insights into the environmental footprint of their products, as well as their entire product portfolio. Next to the total footprint of a product, the tools provide insights into how the different stages contribute to this footprint, as well as what are the main contributing factors to each of these stages. This enables users to identify the hotspots in their value chain and stimulate collaborative action to reduce the footprint. The progress of these reduction strategies and targets can be measured and tracked within the tool. Based on initial use of the tool, several of IDH's sector initiatives have adopted reduction targets for different sectors, and companies are now measuring progress towards these targets for a number of key commodities.

Conclusion

This series of tools shows the potential of making LCA knowledge and approach available to a wide range of stakeholders in international value chains. This allows stakeholders to take ownership of their environmental impact and act accordingly. Instead of using LCA as a one-off method to determine the environmental impact of a product at a certain moment in time, these tools make LCA knowledge accessible and actionable, and serve as a driver of change towards more sustainable food chains.

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Rapid environmental footprint calculation of animal production using the new APS footprint tool

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Keywords: *Animal production systems, Feed, Software.*

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Abstract

Animal production systems are a significant source of environmental impacts. The impacts can be substantially mitigated through various interventions such as system management changes, technical and feed improvements. Due to the diversity of animal production systems, it is challenging to determine the overall impact of various interventions. To facilitate the assessments and communicate impacts of animal derived protein including interventions along the value chain we developed the Animal Production Systems footprint tool (APS-footprint) to facilitate the establishment of LCAs of animal derived footprint at farm level. Here we present a case study of Beta carotene supplementation on an average dairy farm in The Netherlands. This shows that overall footprint can be reduced by 1-2% in various impact categories. The results presented here demonstrate that the APS-footprint tool can model complex interventions where multiple factors within an animal production system change simultaneously. The case of Beta Carotene shows that the APS-footprint tool can provide insights into the trade-offs associated with an intervention.

Introduction

Animal production systems are essential for global food security. At the same time, they are a significant source of environmental impacts such as global warming, land use (water use, eutrophication, and acidification). The impacts can be substantially mitigated through various interventions such as system management changes, technical and feed improvements.

Due to the diversity of animal production systems, it is challenging to determine the overall impact of various interventions. Life Cycle Assessments can be used to assess the environmental performance of these interventions. However, LCAs require specific knowledge about emission modelling and assessment standards. To facilitate the assessments and communicate impacts of animal derived protein including interventions along the value chain we developed the Animal Production Systems footprint tool (APS-footprint) to facilitate the establishment of LCAs of animal derived footprint at farm level.

Methods

The APS-footprint tool calculates impacts according to well-defined LCA standards and guidelines regarding methodology and data APS footprint consists of several so called APS protocols. An APS calculation protocol is a combination of an LCA standard, an emission model, a background database and an LCIA method. The APS protocols are defined per animal production system and are based on specific guidelines (table 1). Within these systems it is possible to model the effects of farm management interventions such as different feed, feed additives, efficiencies, herd management and other characteristics. Here we present the case of Beta Carotene as a feed additive applied to the average dairy farm in the Netherlands as an example. Beta Carotene improves fertility, as a result dairy cows live longer with shorter dry periods between lactations. Consequently, the amount of replacement animals, youngstock, and output of dairy cows to slaughter is reduced on the other hand dairy cow feed intake increases.

The effect of Beta Carotene was modeled as an increase in milk production (+0.73%), feed consumption (+0.3%) and a decrease in animals to slaughter (-11.7%) and replacement animals present at farm (-15%).

Table 1: Elements of the APS-footprint protocols[2]

<table>
<tr><th>Module</th><th>LCA-methods</th><th>Emission model</th><th>Background database</th><th>LCIA method</th></tr>
<tr><td>Dairy[3]</td><td>PEFCR dairy</td><td rowspan="3">IPCC 2006 & EMEP/EEA 2016</td><td rowspan="6">Agri-footprint 5.0</td><td rowspan="6">EF 2.0</td></tr>
<tr><td>Pig[4]</td><td rowspan="2">PEFCR red meat</td></tr>
<tr><td>Piglets[4]</td></tr>
<tr><td>Broilers[5]</td><td rowspan="2">LEAP guidelines elaborated by Blonk</td><td rowspan="2">LEAP 2016 & IPCC 2006 & EMEP/EEA 2016</td></tr>
<tr><td>Layers[5]</td></tr>
<tr><td>Feed</td><td>PEFCR feed</td><td>n.a.</td></tr>
</table>

Cultivation		IPCC 2006, EMEP/EEA 2016, PAS 2050, PEFCR guidance 6.3, GFLI methodology, AFP		

Results

The reduction of replacement animals results in a reduction of direct emissions and feed related emissions of the youngstock. This is partially counterbalanced by the increase of dairy cows' feed consumption and by reduced output of dairy cows to slaughter. The overall results show a reduced impact, in a range of 1.1 up to 2.2 % (Figure 1). Beta Carotene addition has a stronger effect on respiratory inorganics, because this impact category is more dependent on youngstock because of their relatively higher contribution to this impact category.

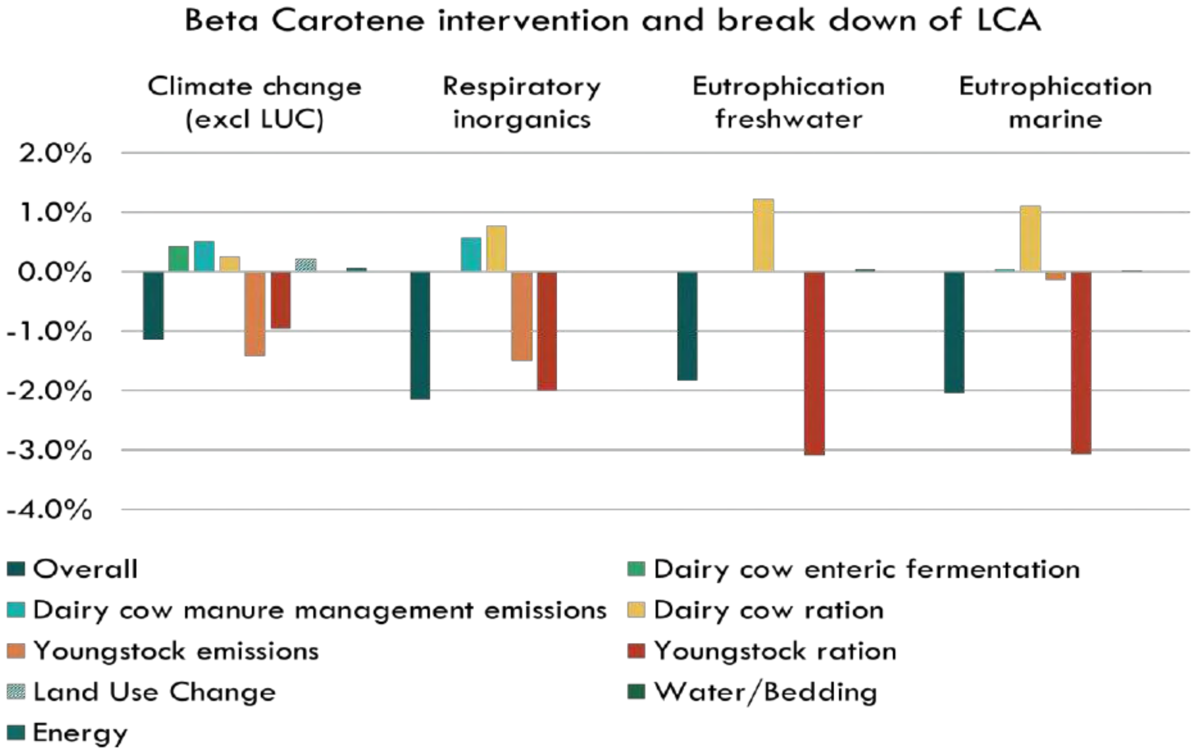
Discussion

We presented the APS-footprint tool in which various animal production systems can be modeled. Unlike other tools. the APS footprint tool can not only be used to assess the existing situation, but also to assess the effect of interventions applied to the system. Where many existing tools for environmental assessment of animal production systems focus on a limited set of impact categories or on specific regions or countries, the APS-footprint tool provides full LCA results giving a more comprehensive picture of the environmental impact of an animal production system. In this way trade-offs in environmental footprint can be captured. However, effectively using the tool still requires some detailed knowledge about animal production systems and how an intervention will (indirectly) affect the system.

Conclusion

The main advantage of the APS-footprint tool is that it enables users with limited specialized (LCA) knowledge to conduct detailed and consistent assessments. In addition, it is relatively easy to do scenario analyses, using the intervention mechanism. The results presented here demonstrate that the APS-footprint tool can model complex interventions where multiple factors within an animal production system change simultaneously. The case of Beta Carotene shows that the APS-footprint tool can provide insights into the trade-offs associated with an intervention.

Figure 1: Intervention results for Beta Carotene intervention for the average dairy farm in the Netherlands for selected impact categories.



A Life Cycle Toolkit for Food Packaging Design

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Keywords: *Toolkit; packaging; food; life cycle; design; method.*

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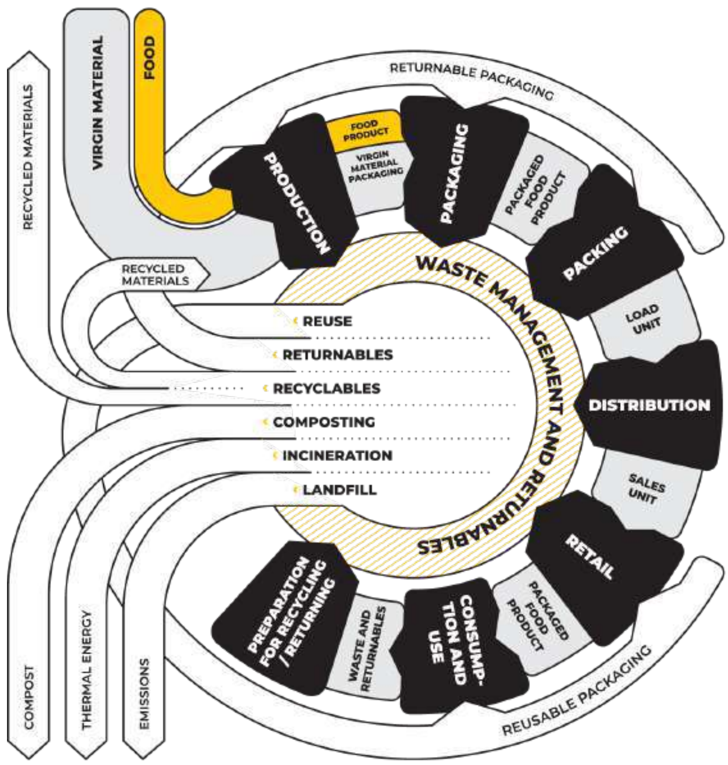
Rationale and Objective of the Work

Food packaging serves multiple functions within the food industry. Packaging provides the functions of product protection, promotion, information, convenience, unitisation, and handling (Consumer Goods Forum, 2011a). The functions of protection, unitisation, and handling are relevant, mostly for the food producer, since they enable the delivery of a product in perfect condition, from factory gate to point of sales. On the other hand, promotion and information serve mostly from sales to consumers, while convenience and information are aimed mostly at the consumer. Besides the virtues of packaging, it brings considerable environmental impact, of which maybe most notorious is packaging waste. But the impact is derived, not just from packaging waste, but from all life cycle stages of a packaged product (see Figure 1).

Figure 1
Packaged food product life cycle diagram



Note. The diagram depicts a generic packaged food product's life cycle, showing life cycle stages, main material flows, waste and returnables management, reuse, recycling, final disposal scenarios and byproducts. Source: Huerta, O., Melo, C. & Rubio, M. (2021). Method for strategic design in the food packaging system. The 10th International Conference on Life Cycle Management. 05-08 September, Stuttgart, Germany.

While extended producer responsibility legislation (EPR) addresses the end of life stage of packaging, significant impact is derived from all life cycle stages. In order to minimize and mitigate packaging life cycle impacts, some existing approaches can be used in packaging design.

Ecodesign provides guidelines to minimize a product's life cycle environmental impact (White et al., 2013). Being packaging itself a product, ecodesign can be used for packaging design. Specifically, packaging ecodesign aids in minimizing its environmental impact while facilitating downstream compatibility with end of life processes for EPR compliance (IHOBE, 2017). On the other hand, the Global Protocol on Packaging and Sustainability provides guidelines to help improve packaging sustainability, addressing its environmental, social and economic performance (Consumer Goods Forum, 2011b). While appropriate and useful, the focuses of these approaches are general, not being specific to food packaging or any particular food product. Moreover, they do not necessarily help meet environmental or sustainability features together with traditional food packaging concerns and requirements.

The multiplicity of functions that food packaging must fulfill calls for interdisciplinary work during packaging decision making, planning and design. This can enable incorporating the information and requirements that are appropriate as inputs for food packaging design. Also, while abundant information exists that is applicable in packaging design for better functionality and environmental performance, there is no specific tool to do this for food packaging design.

The objective of the work reported in this article was the creation of a toolkit that can help in food packaging decision making, planning and design processes, enabling it to fulfill both traditional food packaging functional requirements, and environmental performance characteristics and requirements.

Approach and Methodology

A research and development project was conducted during thirty months, with the objectives of understanding and describing the complexities of food packaging systems in Chile, and creating a method to aid in decision making, planning and designing food packaging with a systemic approach (Huerta, Melo & Rubio, 2022).

The project had two phases. Phase one consisted of a qualitative study within the packaged food industry in Chile. This study comprised interviews with experts, on-site observations, and qualitative analysis of relevant documents. Phase two consisted in the creation of a method and toolkit for food packaging design. The results of phase one were inputs to the work performed on phase two.

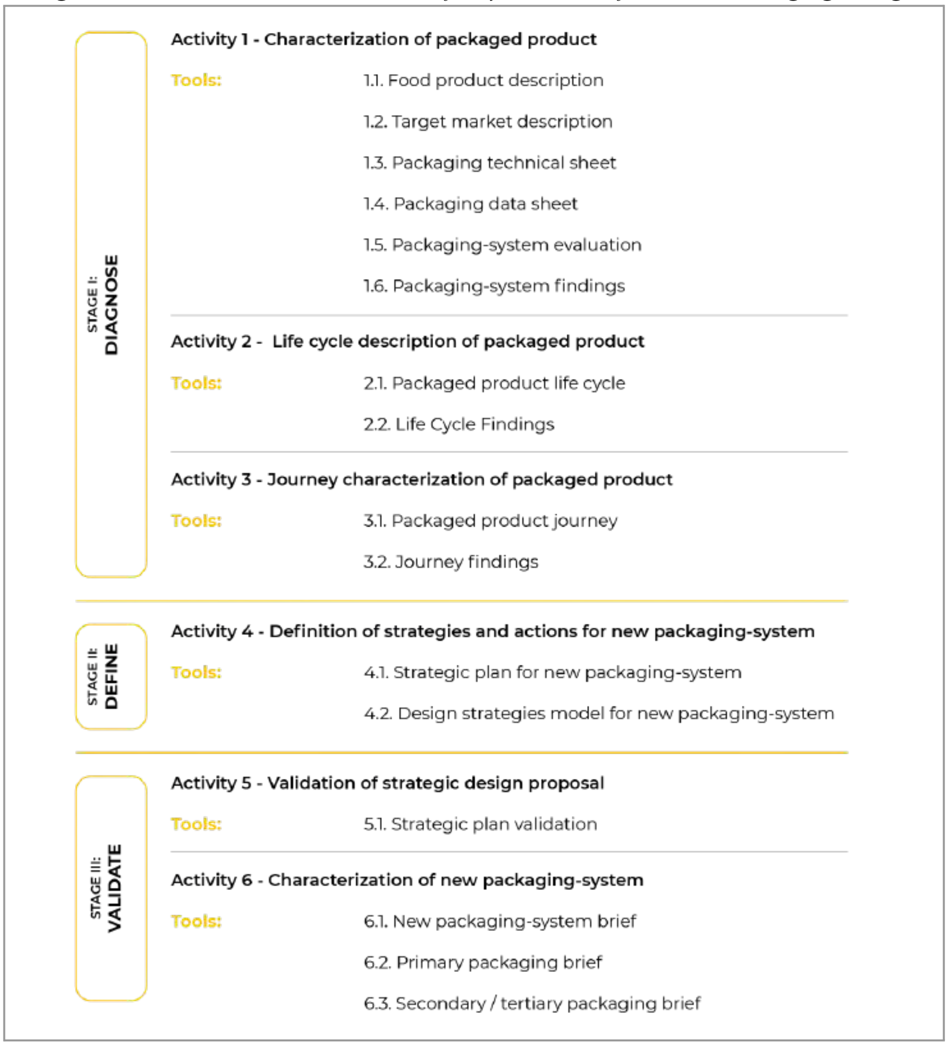
During the development of the method and toolkit, several versions of the toolkit were produced. Multiple formats were explored, with varying sizes, including sets of cards and other kinds of printed material. Mockups and prototypes of the tools were tested with users for several food products, either individually or in interdisciplinary teams, depending on the tool.

Main Results

After testing the earlier versions of the toolkit, several things were found. It was found that interdisciplinary work proved to be much appropriate in order to provide complete and timely information to use the toolkit during food packaging decision making and design processes. The experience of test-driving the tools allowed fine-tuning the information needed as inputs and the fields to be completed for their use. The use of cards was considered not to be a good idea, because too many different cards should be used, which were difficult to search for and required considerable time. The use of color in the mockups proved not to be very useful and made the printing of the material expensive and difficult to reproduce by the users.

Based on the experience gained, a newer version of the method and toolkit were developed. These took shape in a manual with book format to be printed in black and white and using standard size formats. The manual contains an introduction to food packaging systems and explains how the method is and how to use it. It also contains a set of sixteen tools to be used within the method. These tools are displayed in Figure 2. The tools exist as detachable sheets of paper printed in black and white, on sizes A4 and A3, so it can be easily printed or photocopied for working sessions. The tools are intended to help collect and display relevant information for food packaging projects, and to help planning and briefing within these projects. Some tools can be used by individuals, and some must be used by interdisciplinary teams of experts in relevant areas for a project.

Figure 2
Stages, activities and tools within the Life Cycle Toolkit for Food Packaging Design



Note. Figure 2 shows the sixteen tools that comprise the Life Cycle Toolkit for Food Packaging Design. These tools are to be used within six activities, which can be clustered into three stages: Diagnose, Define and Validate.

Discussion, Conclusion and Next Steps

Activities from 1 to 3 of the method focus on gathering relevant information, about an existing food product, for a food packaging project. Its aim is to describe and characterize a packaged food product, its market, its life cycle, and the journey it travels from the moment the food is packaged until it is sold to the consumer or returned to the producer before the expiration date. These three activities comprise the use of ten tools, each of which asks for information related to the product system. The tools can be thought of as questionnaires and diagrams to be completed by the users. At the end of each activity, a specific tool helps users to gather the findings per activity. Activities from

4 to 6 focus on defining strategies and actions to implement for the design of new packaging with a systemic approach, validating such decisions, and briefing solutions for a new packaging-system.

The information required to answer the questions and complete the data that the tools ask for, should be complete and detailed, and may not be readily available for the users of the method. It may take some time to gather the information requested, but it is worth it in order to get the most out of using the method. In order to complete the information requested, people that are knowledgeable about the packaged product must be involved. Many times the producer is the one who knows best the packaged food product, and may be able to complete some of the information. However, since the approach of the method is systemic, upstream and downstream information is needed, as well as specifics about packaging, distribution, and waste management. It is then necessary to work in interdisciplinary teams of experts in different areas of the packaged food product system to use the toolkit properly.

The next step forward is to publish the proposed manual, including the newer version of method and toolkit in book format. Even though there have been several iterations of use and redesign of the method and tools during their development, the newer version is yet to be formally tested in use. So another next step would be to test the newer version of method and toolkit with users for real food products, in order to understand the nuances of their use, assess their functionality, and to enable their further refinement and redesign.

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Environmental schemes for the dairy sheep sector. Category rules for hard cheese from sheep milk developed within the Product Environmental Footprint EU initiative.

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Keywords: *Product Environmental Footprint; eco-schemes; category rules; dairy sheep sector; hard cheese.*

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Introduction

Within the general debate and effort to improve agrifood systems sustainability, which resulted in the development of multiple frameworks, conceptual approaches and methods to capture the complexity of this challenge, environmental schemes for food products play a relevant role supporting the properly ecolabelling and reward of green products by the market (McLaren et al., 2021). In fact, the misleading communication of environmental performance causes asymmetric distribution of information that affects both producers, generating in addition economic barriers for accessing to competing labels and certification schemes, and consumers, which, often disoriented by the excess of environmental schemes and labels, tend to lose trust in these claims (Delmas and Burbano, 2011). Therefore, in 2013 the European Commission, with the Recommendation 2013/179/EC, launched the Product Environmental Footprint (PEF) scheme, aimed to harmonize the assessment and communication of the environmental impacts of products using a life-cycle approach. Italy is a leading global agri-food products exporter, with Made in Italy, Protected Designation of Origin (PDO) and Protected Geographical Indication (PGI) labels recognized worldwide as high-quality standards with elevated reputation profile (Bonaiuto et al., 2021). This paper presents the elaboration process and main results of the product environmental footprint category rules (PEFCR) for the hard sheep milk cheeses, developed within the PEF scheme. In particular, the paper is focused on the preliminary PEF study (screening study) implemented on the Pecorino Romano PDO, which is considered the most representative product of the whole hard sheep milk cheese category. Pecorino Romano is a sheep milk cheese among the most exported in the world (Pirisi and Pes, 2011).

Methodology

The PEFCR for hard sheep's milk cheeses were developed within the LIFE MAGIS - Made Green in Italy Scheme (LIFE18 GIE/IT/000735) project, aimed at launching and disseminating the PEF method and the recently introduced PEF-based "Made Green in Italy" scheme. The PEFCR were intended as an integration to the already existing "PEFCR for Dairy Products" v1.0 (EDA, 2018). In particular, the integration consisted in the inclusion of the product sub-category "hard cheese from sheep milk", and the related representative product. The structure and content of these PEFCR have been developed in line with the "PEFCR for Dairy Products" but it differs in those parts characterizing sheep milk production and processing and which are not covered by the existing PEFCR that only includes raw milk (and its derived dairy products) produced by cattle. In general, sheep milk farming is characterized by more extensive and pasture-based farming techniques, with lower animal productivity levels, compared to the dairy cow sector. Therefore, a specific LCA model is required. The representative product was defined as "Pecorino Romano PDO" (the second exported Italian cheeses in the world and the best-known Italian dairy product obtained from sheep milk) which is cooked, made with fresh or thermised whole sheep's milk, derived exclusively from farms located in the regions of Lazio, Sardinia and the province of Grosseto in Tuscany. A preliminary PEF study was carried out on the representative product with the aim of identifying the most relevant life cycle stages, processes, elementary flows, impact categories and data quality needs to derive the preliminary indication about the definition of the benchmark for the sub-categories in scope, and any other major requirement to be part of the final PEFCR. This screening study involved 18 sheep farms (data refer to 2016/2017) representing the main Italian sheep farming systems and 4 dairy sheep plants producing 23% of the total "Pecorino Romano PDO" production (data refer to 2019/2020). LCA calculations were made using EF version 2 (Fazio et al., 2018) impact assessment method. The following main limitations that are particularly relevant to the sheep dairy sector were considered: i) The benchmark is related to a representative product produced in Italy. Therefore, it can be used to compare PEF study results of products in the PEFCR scope. In particular, the profile of sheep milk production is representative of the Italian conditions in terms climate, soil, and technology, and differences could be expected from sheep farming systems of other geographic areas; ii) This benchmark is intended to be used by other companies belonging to the Pecorino Romano Consortia as reference to the PEF profile of their products; iii) Sheep milk production datasets were specifically developed based on background data from Ecoinvent Centre v3.6 (Moreno Ruiz et al., 2019) and Agri-footprint 4.0 (2017).

Results and discussion

The functional unit and its reference flow (Figure 1) was defined as 10 g dry matter equivalent of cheese, fit for human consumption and considered from milking to consumption up to the expiration date. The system boundaries include 7 life cycle stages: a) "Raw milk", b) "Dairy processing", c) "Packaging", d) "Distribution", e) "Use" and f) "End-of-life", and the main cut-off rules concern i) cleaning agents and refrigerants at farm, ii) transportation of input products to the dairy unit accounting for less than 1% in mass and solid waste at dairy plant stage, and iii) capital goods.

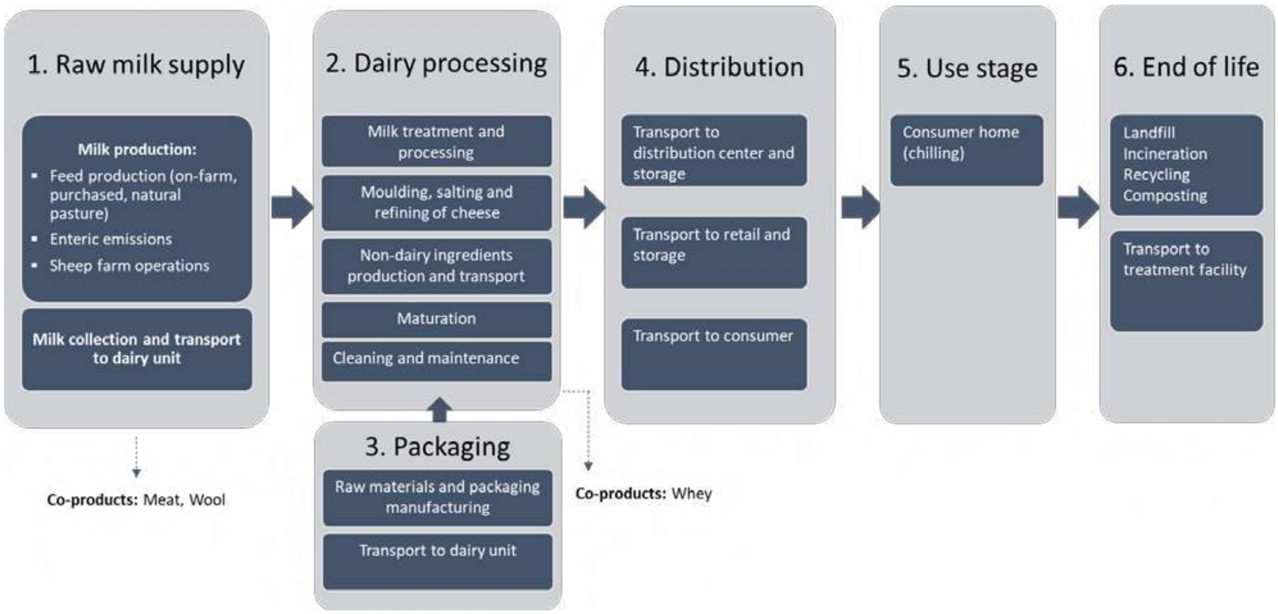

Figure 1. System boundaries diagram for hard cheese from sheep milk.

The most relevant impact categories, identified considering those that cumulatively contributed to at least 80% of the total environmental impact (excluding toxicity-related impact categories), were 1) Climate change (CC) (25.2%), 2) Water scarcity (WS) (23.3%), 3) Land use (LU) (22.3%) and 4) Resource use mineral and metals (RU m&m) (10.2%). For all the most relevant impact categories, raw milk supply was the most relevant life cycle stage (contribution above 94%), followed by dairy processing as additional relevant life cycle stage (Table 1).

Impact category	***Raw milk***	***Dairy processing***	***Packaging***	***Distribution***	***Use***	***End-of-Life***
Climate change	95.51%	2.93%	1.17%	0.01%	0.01%	0.37%
Land use	99.45%	0.09%	0.16%	0.29%	0.00%	0.01%
Water scarcity	99.21%	0.37%	0.21%	0.13%	0.00%	0.08%
Resource use, mineral and metals	94.95%	2.22%	1.62%	1.06%	0.01%	0.14%

Table 1. The most relevant life cycle stages of hard sheep's milk cheese, calculated as the life cycle stages that together contribute to at least 80% of any of the most relevant impact categories previously identified. Functional unit:10 g dry matter; impact assessment method: EF v.2 (Fazio et al., 2018).

Impact categories as Eutrophication and Acidification, considered among the most relevant in PEFCR dairy, do not appear very significant in Pecorino Romano PDO manufacturing. That is probably due to less critical issues related to manure storage and disposal and feed production and supply in sheep farming systems compared to dairy cattle ones.
Benchmarks were provided as characterised results (Table 2), normalised results and weighted results (Figure 2).

Impact category	***Unit***	***Life cycle excl. use stage***	***Use stage***	***Total***
Climate change	kg CO_2 eq	1.64E-01	2.03E-05	1.64E-01
Land use	Pt	6.75E+01	2.99E-04	6.75E+01
Water scarcity	m^3 depriv.	5.52E-01	1.61E-05	5.52E-01
Resource use, mineral and metals	kg Sb eq	1.36E-06	9.12E-11	1.36E-06

Table 2. Characterised benchmark values (most relevant impact categories) for hard sheep's milk cheese. Functional unit:10 g dry matter; impact assessment method: EF v.2 (Fazio et al., 2018).

Normalized and weighted impact values for CC, LU, WS and RU m&m in Pecorino Romano PDO were higher than the corresponding values reported in PEFCR dairy for cheeses (EDA, 2018). This result has been widely expected and can be easily explained considering the above mentioned technological and management differences between dairy cattle and sheep milk production systems.

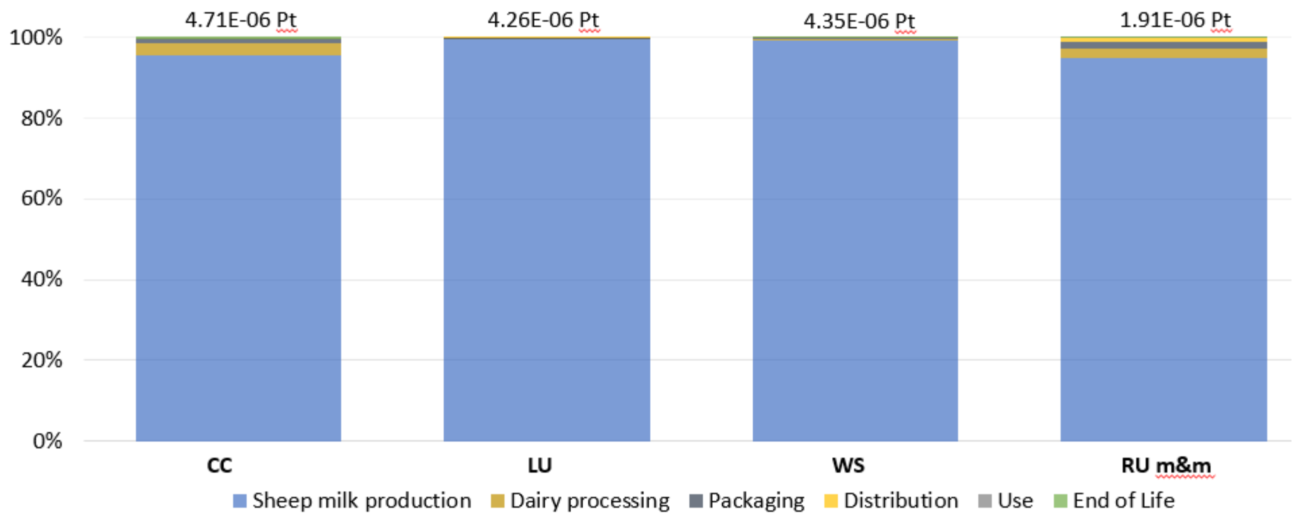

Figure 2: Normalized and weighted values (Pt, points) and life cycle phases contribution of Climate Change (CC), Land Use (LU), Water Scarcity (WS) and Resource Use mineral and metal depletion (RU m&m) for 10 g dry matter equivalent of Pecorino Romano PDO cheese, calculated using the EF method 2.0 (adapted) (Fazio et al., 2018).

Conclusions

PEFCR for hard sheep's milk cheeses were developed as an integration of the already existing "PEFCR for Dairy Products". In particular, specific rules for sheep milk production modelling were included (production systems of sheep and cattle differ largely for both productivity levels and animal nutrition management). Screening study indicated Climate change, Land use, Water scarcity, Resource use minerals and metals as the most relevant impact categories of the environmental footprint of Pecorino Romano PDO supply chain, with a very large contribution (around 94%) derived from milk production phase. The main differences among cattle and sheep systems' PEFCR consist in the most relevant impact categories list and in the benchmark values.

Acknowledgments

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Which models to predict SOC changes in LCA?

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Carbon modelling in LCA context is gaining momentum, notably in the context of refinements to the estimation of impacts on the climate change impact category (e.g. Albers et al. 2019; Bessou et al. 2019). Particularly in bioeconomy and biomass-oriented LCA (crops including perennials, grasslands, forests, biofuels stock, etc.), C exchanges between the biomass system and the environment take multiple forms, including sequestration in biomass and/or in soil, and releases associated with practices.

When building inventories of agricultural systems, for instance, the practitioner must chose an approach for estimating the sequestration of C in biomass (above- and below-ground), at least when perennial species (perennial grasslands, trees, bushes, etc.) are present in the studied system. This is relatively simple, as the biomass accumulation dynamics of most plant species are known. Even the biomass inputs to soils can be easily estimated, by considering management inputs (organic fertilisers, plant residues, etc.). The challenge arrives when trying to estimate the evolution of soil organic carbon (SOC) of the studied system. The main reason for that is that there is a wide and confusing universe of SOC modelling approaches, which include

- "empirical" models (e.g. IPCC stock-difference approaches, or very simple models based on the seminal Hénin-Dupuis model (Hénin & Dupuis, 1945)),
- "soil" models that add complexity and consider key factors and mechanisms (such as the pools-based commonly used RothC or CANDY), and
- fully-fledged "ecosystem" or "agro-ecosystem" models that simulate soil-plants interactions (such as DNDC, DAISY or STICS) (FAO, 2019).

Most LCA practitioners are likely to use IPCC-style models, but we affirm that the best suitable models in LCA contexts are intermediate models, not too simplistic nor too demanding in terms of expertise and data, such as soil models. This rationale applies as well when estimating direct field emissions (Angel Avadí et al., 2022). For instance, a relevant compromise between nitrogen modelling extremes in agricultural LCA lies in the development of operational models using a restricted number of parameters and input variables, as reviewed by Buczko and Kuchenbuch (2010).

We propose the coupling of an intermediate soil model (featuring a monthly time-step) coupled with a simple erosion model for LCA purposes, be it at the system level or at larger scales. We illustrate the usability of the proposed approach by two case studies: estimation of SOC turnover in Ecuadorian cocoa systems (at the system level, Figure 1) (A. Avadí et al., 2021) and estimation of SOC turnover in bioeconomy-interesting crops on (global) marginal lands (Albers et al. under review). For both cases, we combined an R implementation of RothC (RothC - A Model for the Turnover of Carbon in Soil. Model Description and Users Guide (Updated June 2014), 2014; Sierra et al., 2012) with a model for SOC erosion (Lugato et al., 2016) based on the RUSLE2 soil erosion equation (Foster, 2005). The combination of these models is sensitive enough to represent certain agricultural practices/management strategies.

A direct comparison of the validity of predictions by different models was not performed to justify the proposed approach, but based on an extensive literature review —presented in (Albers et al. under review) and its Supplementary Material, available as a preprint—, we were able to compare the "cost-benefit" for an LCA practitioner of deploying some 20 different models. Our proposed approach offers a good trade-off between operability and acceptability of predictions, a common challenge in LCA (Avadí et al. 2022; Bockstaller et al. under review).

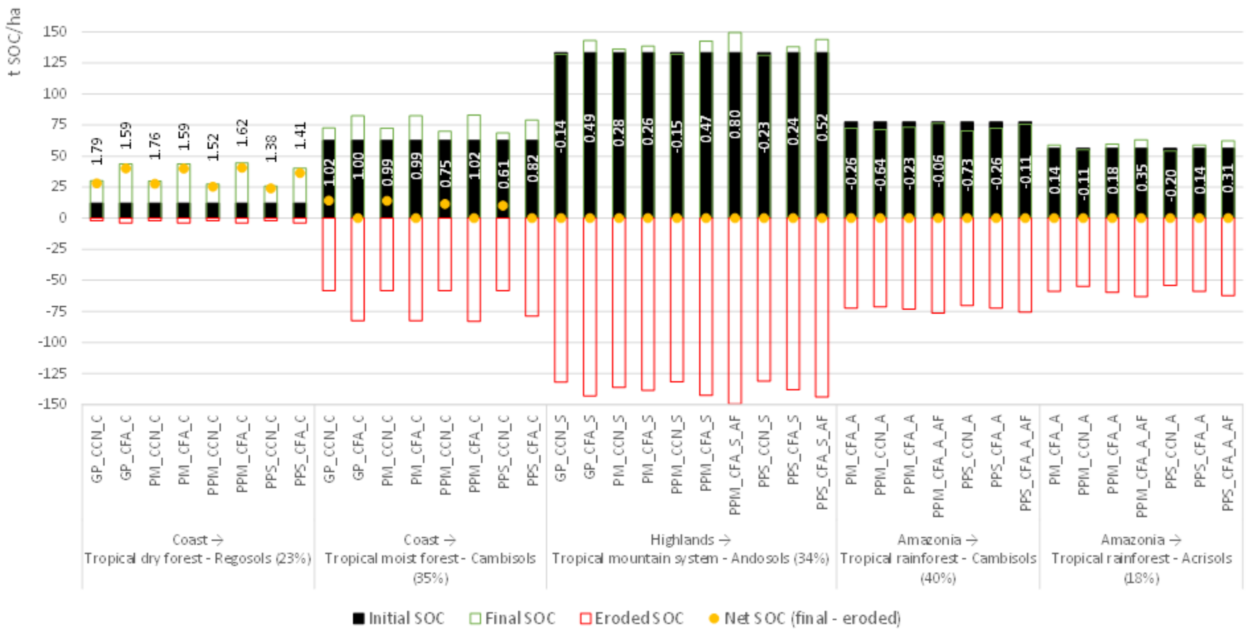

Figure 1. Sequestration of SOC with respect to the initial SOC of Ecuadorian cocoa systems, by type of producer (GP: large producer, PM: medium producer, PPM: small micro-entrepreneur producer, PPS: small subsistence producer), variety (CCN: CCN-51, CFA: Cacao Fino y de Aroma) and region (coast, highlands, Amazonia). Agroforestry systems are identified with "AF". Labels represent sequestration rates (t SOC/ha•year)

Our proposed approach represents a good-enough choice for LCA practitioners, when they happen to be non-experts in SOC dynamics or C modelling in general.

This work will be published as Albers et al. (under review). The Ecuadorian cocoa case study has been submitted to the International Journal of Life Cycle Assessment Special Issue associated with LCA Foods 2022 (https://www.springer.com/journal/11367/updates/20266956).

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Global warming potential and soil organic carbon stock change of three cattle silages in the boreal region

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Keywords: *Forage crop; Silage production; Cattle feed; Forage maize; SOC modelling; Life Cycle Assessment.*

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Introduction

In the boreal region, dairy cattle feeding is based on grass silage (Virkajärvi et al., 2015). However, interest of the farmers in high-yielding forage maize (*Zea mays* L.) cultivation has increased markedly (Mussadiq, 2012). Although forage maize is still a marginal crop in the boreal region, its cultivation area has increased rapidly in recent decades. The high hectare yield of maize may lead to decreased greenhouse gas (GHG) emissions per unit of silage produced compared to grasses as observed previously in Denmark (Mogensen et al., 2014) in the continental region (EEA, 2017). However, the global warming potential (GWP) of forage maize production has not been studied previously in Finland and the whole boreal region. Investigation of GWP of silages is important since feed production is the second greatest GHG emission source (total of 36% of GHG emissions) of milk production (Gerber et al., 2013).

Material and methods

This study aimed to estimate the 100-year GWP (kg CO_2 equivalents) of different silages produced in the boreal region including forage maize (shortened as maize), perennial timothy-meadow fescue grass (grass), and whole crop cereal (cereal).

The method used was life cycle assessment (LCA) with a scope from the cradle-to-farm gate. The functional units of the study were 1 hectare, 1 megagram (Mg) dry matter (DM) of harvested silage yield and 1 megajoule (MJ) of harvested silage yield. Data about forage maize yield and input use was collected from a 3-year field experiment conducted in Helsinki and Maaninka, Finland (Table 1). The data was supplemented with data from literature and agronomy experts. Data about grass and cereal yield and input use was collected from Finnish and Scandinavian literature and agronomy experts (Table 1). Metabolizable energy (ME) contents for different silages were collected from Natural Resources Institute Finland statistics to calculate the ME yields (MJ/ha).

Table 1. Dry matter (DM) and metabolizable energy (ME) yields, and the main cultivation inputs of forage maize (maize), timothy-meadow fescue grass (grass) and whole crop cereal (cereal).

	DM yield	ME yield	Nitrogen fertilization	Fuel consumption in field work
	Mg/ha	MJ/ha	kg N/ha	l/ha
Maize	16.2	181 440	140	98
Grass	10.7	113 671	200	75
Cereal	9.2	89 127	90	73

On-field N_2O emissions and CO_2 emissions of liming were calculated according to IPCC (2019) Tier 1–2. GHG emissions from fuel consumption were calculated according to the Lipasto database of the Technical Research Centre of Finland. GHG emission released in the production of cultivation inputs was modelled by using Ecoinvent 3.7 and Agrifootprint 5 databases. The LCA modelling was conducted with OpenLCA 1.10.3. software and ReCiPe 2016 Midpoint (H) method.

Annual soil organic carbon (SOC) stock change in 1 m soil layer was modelled with the Yasso model (v. Yasso20; Liski et al., 2005, Viskari et al., 2021). The annual C input to the soil from above-ground crop residues, root biomass and rhizodeposition was calculated according to method by Bolinder et al. (2007). The harvest indexes (averaged from several scientific publications) used in the modelling were 0.95 for maize, 0.84 for grass and 0.75 for cereal. Root:shoot ratios (averaged from several scientific publications) used were 0.17 for maize, 0.67 for grass and 0.18 for cereal. All crop residues and roots were assumed to have a C content of 45%. The rhizodeposition was calculated as root C input × 0.41 (Palosuo et al., 2016). The annual C input was divided into AWENH fractions according to Palosuo et al. (2016). The weather data used was Finnish Meteorological Institute data on mean monthly temperature and mean annual rainfall in Southern and Central Finland from 1961 to 2021.

The SOC stock change was modelled with a 100-year time horizon. The initial SOC stock was 55 Mg C/ha in 1 m depth based on long-term farm-level grass cultivation with high cattle manure application. The annual SOC stock change was calculated as: (initial SOC stock – SOC stock after 100 years) / 100 years. The annual SOC stock change was converted into CO_2 and included in the GWP results.

Preliminary results

At the hectare level, the GWP was highest for maize and lowest for cereal (Table 2). However, per Mg DM of harvested silage, the GWP was somewhat higher for grass in comparison to maize and cereal (Figure 1). As the ME content of silages was considered, the highest GWP per MJ was observed for grass and the lowest for maize (Table 2). The lower GWP (per Mg DM and MJ) of maize compared with grass was related to the high DM yield of maize and the relatively low nitrogen (N) fertilization rate of maize. Although grass had a negative emission from SOC stock change indicating net C sequestration to the soil, the GWP of grass remained highest due to N_2O and other GHG emissions related to abundant N fertilization.

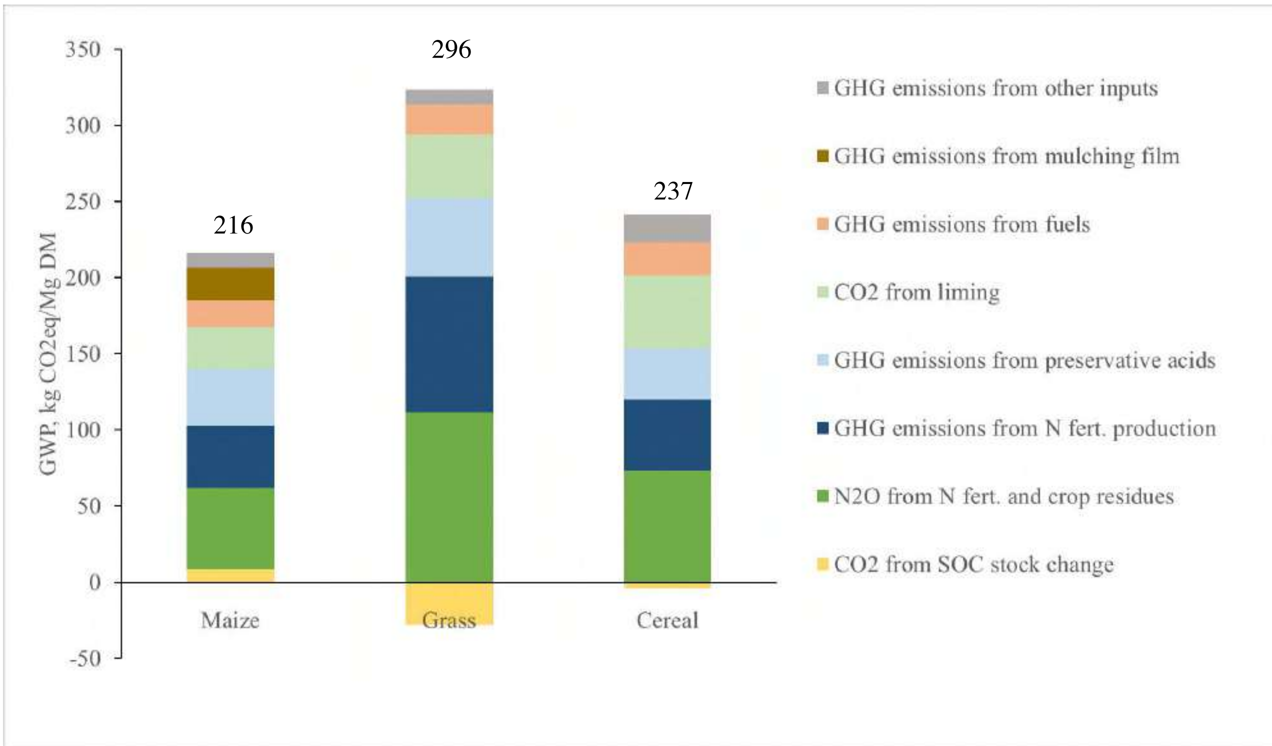

Figure 1. Global warming potential (GWP) of forage maize (maize), perennial timothy and meadow fescue grass (grass) and cereal whole crop silage (cereal), and the greenhouse gas (GHG) emission sources. Net GWPs are marked above the bars.

Generally, the most substantial GHG emission source was N_2O emission related to N fertilization and crop residues (~32% of total GWP) followed by GHG emissions from N fertilizer production (~24%; Figure 1). GHG emissions from preservative acid production and CO_2 emissions from liming caused both ~16% of the total GWP. Fuel combustion accounted for ~8% of the total GWP. For maize, the production of mulch film accounted for 10% of the total GWP. The effect of CO_2 from SOC stock change on the total GWP of silages was relatively marginal (from -9% to +4%) with the initial SOC stock and the C input rates used in the modelling.

Table 2. Global warming potential (GWP) of forage maize (shortened as maize), perennial timothy and meadow fescue grass (grass) and whole crop cereal silage (cereal).

	Global warming potential	
	CO_2 eq/ha	CO_2 eq/MJ
Maize	3501	0.019
Grass	3153	0.028
Cereal	2172	0.024

Discussion

The GWP of silage production may be reduced if the DM yield rate is increased and abundant N fertilization is avoided. The GWP of maize was somewhat lower in comparison to grass similarly to observations by Parajuli et al. (2017) and Mogensen et al. (2014), although maize cultivation reduced the SOC stock. However, the DM yields and silage quality vary markedly under boreal conditions, especially for forage maize. Hence, sensitivity analysis and Monte Carlo analysis need to be done to the results before the final conclusions of the study. Additionally, we will include clover grass in the model to assess, how biological N fixation and reduced N fertilization affect the results. The effect of SOC stock change on the GWP of silage production was observed to be marginal in the preliminary results. Nevertheless, in future, we will test different initial SOC stocks, C input calculation methods and SOC modelling tools to conduct a further assessment of the effect of SOC stock modelling on the GWP of silages. We are also researching the climate impact on milk production level to assess, how silage choice affects the GWP of milk.

Conclusions

In terms of GWP of harvested yield, forage maize does not seem to cause more GHG emissions in comparison to perennial timothy and meadow fescue grass. Nevertheless, grass cultivation seems to increase C sequestration to soil compared with forage maize. However, the results are preliminary, and the research is ongoing.

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Integration of socio and environmental LCA using same LCI: Application to dejection treatment in agriculture

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1. Introduction

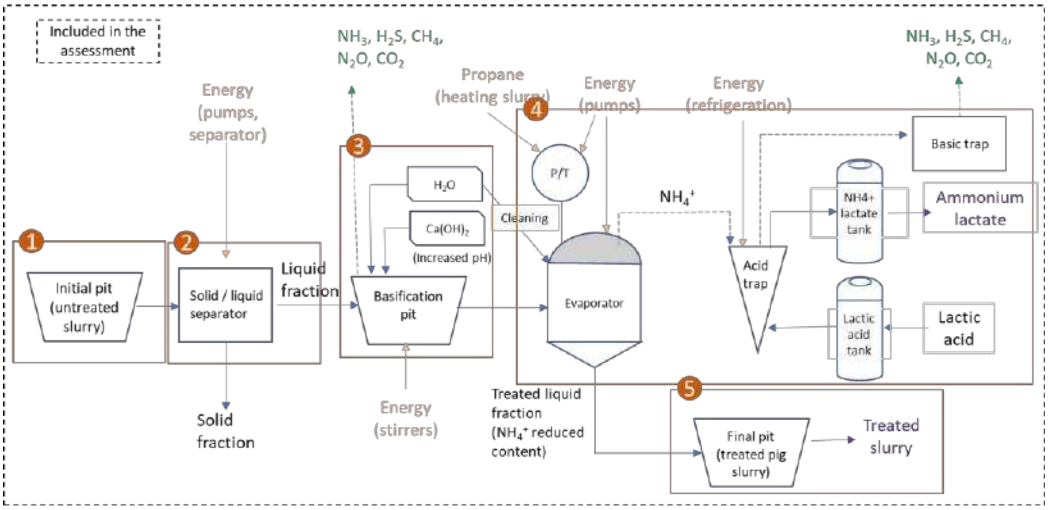
Agriculture contributes to 90% of the total ammonia emitted in the world, and 50% of the livestock ammonia emissions in Europe come from cattle, 30% from pigs and 20% from poultry (IIASA, 2017; EEA, 2018). Aiming to improve sustainability in livestock, several technologies for waste management have been developed to reduce nutrient losses, specially, nitrogen emissions to the air, water and soil (Xia et al., 2020). Anaerobic digestion is a widely used technology for the treatment of this kind of waste stream, converting organic nitrogen and phosphorus to ammonia and phosphate, but has no impact in modifying the nutrient content. Several inputs (e.g. water, electricity, machinery, acid, infrastructure) and outputs (e.g. air emissions, treated deject) of these technologies have potential to cause environmental and social impacts. Thus, it is essential to assess those impacts, to avoid harmful trade-offs in the system.
Life Cycle Assessment (LCA) is a widely spread tool used to assess social and environmental impacts of several value chains, including, agricultural products and novel technologies (Igos et al., 2019). However, dealing with both aspects, social and environmental, is still a challenge for LCA. Therefore, the goal of this study is to advance on the integration of simultaneous social (S-LCA) and environmental (E-LCA) life cycle assessments. Thus, in the present study, we have conducted a case study focusing on a novel technology to treat livestock dejections.

2. Methods

2.1 Technology 'Low temperature ammonium-stripping using vacuum'

The technology selected removes nitrogen from pig slurry using vacuum stripping and the final products are ammonia salt solution that can be reused as a fertiliser, and organic fertilizer with less nitrogen content, which in turn improves further management of nutrients, and facilitate final disposal of the treated slurry. A farm scale pilot system (maximum capacity 6.4 m3) with a treatment capacity of 10 m3/day is operating in a sow farm of Navàs (Catalonia, Spain). The system is composed of a solid-liquid separator, a closed raft, an evaporator, a vacuum pump, an acidic trap, and a basic trap (Figure 1). At the end of the cycle, processed livestock manure is obtained, with lower nitrogen content. On the other hand, an ammonium lactate solution is produced, which can be used as a fertiliser.

Figure 1. Flow chart of the technology 'Low temperature ammonium-stripping using vacuum'



Legend: P/T = pressure/temperature

2.2 Environmental and social life cycle assessment

The functional unit of the system is 1 m^3 of treated slurry, and the impacts were assessed from cradle-to-gate in both environmental and social assessments. A 10-year life span was used for machinery; a 20-year life span, for the concrete pit. The impacts were using OpenLCA v1.10.3.

Inventory was collected in the field, and costs of the inputs required for the technology and social flows from Product Social Impact Life Cycle Assessment (PSILCA) database (Maister et al., 2020) were used to estimate the social impacts caused by the technology. The methodology adapted in the current study is similar to the Serreli et al. (2021), in which the inputs to the system were used in PSILCA as economic values. It is important to highlight that in this work we assess the social impacts of producing and using the technology in a country-level since PSILCA provides sector and country-level data.

Environmental footprint (EF) impact categories (EC-JRC, 2012) and EF 3.0 normalization and weighting set (Sala et al., 2018) were used to calculate environmental impacts, and the Social Impacts Weighting Method from PSILCA was used to estimate technology's social risks. 45 social impact subcategories from PSILCA, for the stakeholders: workers (WK), society (SO), local community (LC) and value chain actors (VCA), were selected in this study.

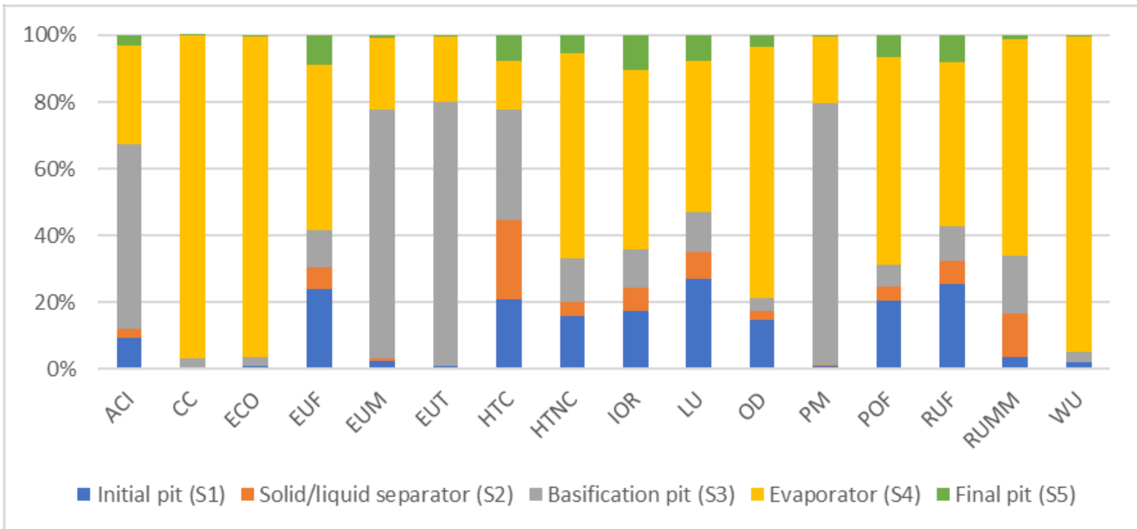
Following Werker et al. (2019), since it is provided a detailed account of the environmental implications of the the technology, eleven of the impact categories with a more environmental focus are excluded from this analysis. Such exclusion of indicators aims to avoid double-counting effects that can lead to serious errors when large interconnected systems are analyzed or when results are placed into broader contexts (Lenzen, 2008). For instance, 'industrial water depletion' is better described with the E-LCA impact category "water use" and the AWARE method (Boulay et al., 2018) that accounts for water depletion and relates it to its regional scarcity. Another example is the 'pollution level of the country' which is a qualitative indicator in PSILCA, and in the E-LCA is assessed in the two areas of protection 'human health' and 'ecosystems' and their associated impact categories covering the diverse types of pollution that can occur in a country (Werker et al. 2019).

3. Results and discussion

3.1.1 Environmental LCA

Overall environmental impacts of the technology are presented in Figure 3. S4 has higher contribution to eleven out of sixteen impact categories (69%), highlighting more than 90% of the impacts in the impact categories 'climate change' – mainly due to the methane emitted -, 'ecotoxicity, freshwater' – mainly due to 'lactic acid production' and 'market for steel, chromium steel 18/8' processes – and 'water use' – due to 'market group for tap water' and 'lactic acid production' processes. Stage 3 has higher contribution of impacts in the impact categories 'acidification', 'eutrophication, marine', 'eutrophication, terrestrial' and 'particulate matter' due to ammonia emitted in the stage. The impact category 'human toxicity, cancer' has more balanced impacts (21% S1, 24% S2, 33% S3, 15% S4 and 8% S5). The highest contribution to impacts of S1 was in 'land use' due to the process 'market for concrete, normal'; S2 in 'human toxicity, cancer' due to the carcinogenic emissions in the process 'market for concrete, normal'; S5 in 'ionising radiation' due to the emissions in the process 'market for steel. Chromium steel 18/8, hot rolled'. Regarding the E-LCA, 51% of the normalized impacts are attributed to 'climate change' (0.12), 33% to 'ecotoxicity, freshwater' (0.08) and 6% 'particulate matter' (0.01). As in Van Zelm et al. (2020) several impacts of the process to recover ammonia from digestate came from the acid needed to produce the fertilizer and the direct nutrient emissions during the process.

Figure 2. Environmental impacts of the novel technology for ammonia recovery of livestock dejections

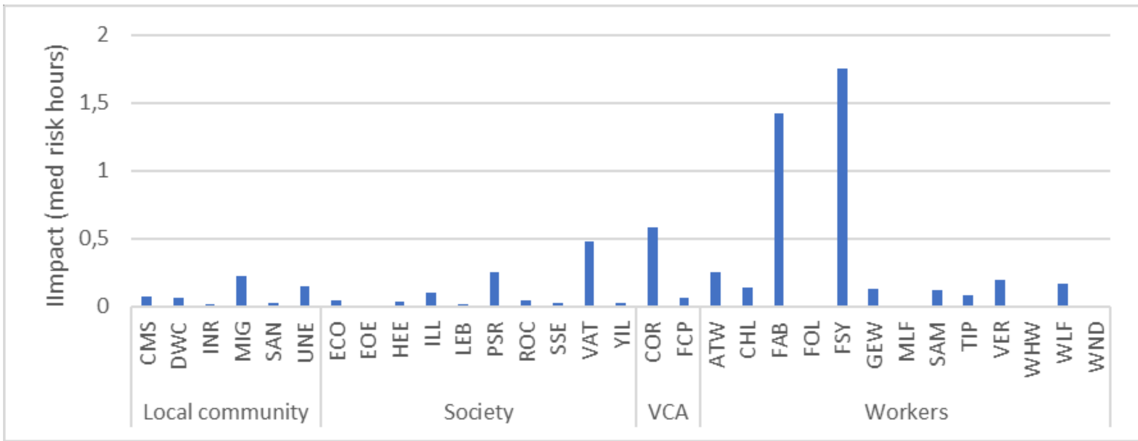


Legend: ACI: acidification, CC: climate change, ECO: ecotoxicity freshwater, EUF: eutrophication freshwater, EUM: eutrophication marine, EUT: eutrophication terrestrial, HTC: human toxicity cancer, HTNC: human toxicity non-cancer, IOR: ionising radiation, LU: land use, OD: ozone depletion, PM: particulate matter, POF: photochemical ozone formation, RUF: resource use fossils, RUMM: resource use, minerals and metals, WU: water use

3.3.2 Social LCA

For the S-LCA, 65% of total impact, measured in medium risk hours, is concentrated in four impact categories, 27% were found in 'fair salary - WK' (1.76), 22% in 'freedom of association and collective bargaining - WK' (1.42), 9% in 'corruption - VCA' (0.58), and 7% 'value added (total) – VCA' (0.48) (Figure 5).

Figure 3. Overview of results for stakeholder group and indicators for the novel technology for ammonia recovery from livestock



Legend: ATW: accidents at work, CHL: child labour, CMS: Certified environmental management system, COR: public sector corruption, DWC: drinking water coverage, ECO: contribution of the sector to economic development, EOE: expenditures on education, FAB: freedom of association and collective bargaining, FCP: fair competition, FOL: forced labour, FSY: fair salary, GEW: gender wage gap, HEE: health expenditure, ILL: illiteracy, IMS: international migrant stock, INR: indigenous rights, LEB: Life expectance at birth, MIG: migration, MLF: men in the sectoral labour force, POL: pollution, PSR: promoting social responsibility, ROC: risk of conflicts, SAM: safety measures, SAN: sanitation coverage, SSE: social security expenditures, TIP: trafficking in persons, UNE: unemployment, VAT: value added (total), VER: violations of employment laws and regulations, WHW: weekly hours of work per employee, WLF: women in the sectoral labour force, WND: workers affected by natural disasters, YIL: youth illiteracy; VCA : Value chain actors

Main processes responsible for impacts in 'fair salary' were related to the high risk of living wage in the flows 'manufacture of machinery and equipment' - representing all equipment used in the technology - and 'computer and related services' - used to represent plant automation. The impact caused in 'freedom of association and collective bargaining' is also mainly due to 'manufacture of machinery and equipment' and 'computer and related services', in this case, the very high risk is in the trade union density. The impact category 'Corruption', represented by the subcategories 'active involvement of enterprises in corruption and bribery' and 'public sector corruption'. In the first, the processes 'construction' – used to represent the infrastructure – and 'other land transport; transport via pipelines' have a very high risk; in the second, the processes 'manufacture of machinery and equipment' and 'computer and related services' is the one with a high risk. Finally, the very high risk in the processes 'metal products' and 'metallurgy products' were the main responsible for the impact category 'value added (total)'. Lowest impacts (in medium risk hours) were found in 'men in the sectoral labour force - WK' (6.89E-04), 'fatal accidents – WK' (2.90E-04) and 'frequency of forced labour – WK' (2.14E-04).

4. Conclusions and future work

With the methodology adopted, environmental and social aspects of the process could be measured using the same inventory but adapting to the intended conditions, using a sector and country-specific database and monetary flows. The study conducted allowed us to identify the needs and challenges conducting, simultaneously, social and environmental assessments, in our case for a relevant area such as livestock management. However, it is worth to mention that PSILCA provides country-specifics sectors datasets based on country statistics, thus a more detailed regional and sectorial information is probably the cornerstone for the assessment in future studies. Finally, we would like to encourage to advance on the inclusion of social assessment in sustainability studies, which will help to better improve the databases and methods for such assessments. For future work, further investigation on weighting social and environmental indicators in simultaneous assessments is essential to compare or aggregate results from the two dimensions.

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Integration of environmental assessment, eco-efficiency and carbon sequestration as a strategy for identifying good practices in Spanish extensive dairy farms

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Introduction

The livestock sector plays an important role providing food such as milk, cheese, or derivatives for society. Global milk production reached nearly 906 million tons in 2020, of which approximately one third is produced in Europe, being the second largest region in the World (FAO, 2021). In the European context, Spain accounts for nearly 7 million tons per year ranking eighth (Augère-Granier, 2018; Ibidhi and Calsamiglia, 2020). In Galicia (Northwest of Spain), the dairy sector has shown a significant growth in the last decades, increasing on average by 75%, positioning this region with 39% of the Spanish raw milk production in 2020 (Ministerio de Agricultura, 2020). This growth has been accompanied by an increase in livestock density and milk production per hectare, and expansion in production for larger farms, and a decrease in the production of smaller farms. In this context, the assessment of both production efficiency and environmental performance of Galician dairy farms allows the identification of eco-efficient practices that allow reducing both their current level of resources and environmental impacts.

Bringing safe food of livestock origin to consumers starts with on-farm production and is strongly related to feeding activities and animal welfare, as well as the management of associated environmental impacts. Livestock within the food sector have been identified as playing a prominent role in anthropogenic GHG emissions (Cortés et al., 2021). However, this generic statement should not apply to all types of farms, as depending on their management regime, some livestock farms can be identified as benchmarks of good practices in their aim to reduce associated environmental impacts and consume resources rationally. Examples of these practices are formulating diets based on sustainable feeds (van Boxmeer et al., 2021), increasing access to technical support for management practices (Vogel and Beber, 2022), agricultural practices that promote carbon (C) sequestration (Vogel and Beber, 2022), among others. Therefore, it is pertinent to identify eco-efficient dairy farms that can be considered benchmarks in the sector, focusing not only on production concerns, but also on associated environmental burdens.

Eco-efficiency has been promoted as an appropriate methodology to analyze production and environmental impacts associated with production systems. In this context, the joint use of Life Cycle Assessment and Data Envelopment Analysis (LCA+DEA method) appears as a suitable methodology for the evaluation of eco-efficiency (Vásquez-Ibarra et al., 2020). LCA is a methodology to assess the environmental impacts of products or services during their entire life cycle (ISO, 2018), being the carbon footprint (CF), the best known environmental indicator. On the other hand, DEA is a linear programming tool to determine the relative efficiency of a set of homogeneous units, called DMUs (Decision Making Units), which use multiple resources (inputs) to produce multiple outputs (Cooper et al., 2007). Previous studies have considered the joint application of LCA+DEA to assess the eco-efficiency of dairy farms (Vásquez-Ibarra et al., 2020). However, in this context, there are no previous studies that consider the potential of carbon sequestered on-farm due to the cultivation of crops for cow feed. Therefore, the main objective of this study is to evaluate the eco-efficiency assessment of dairy farms and to determine the carbon sequestered for those growing cover crops. In this way, this study can be considered as a starting point for developing a novel framework that considers operational resources, environmental impacts, and carbon sequestration in the agricultural and farming activities.

Methodology

This study analyzes the raw milk production of 50 Spanish dairy farms using the three-step method of the LCA+DEA methodology originally proposed by Lozano et al. (2010). This methodology was performed according to the following steps:

i) Data collection: Operational data were collected to assess environmental impacts and perform the DEA model. Since the farms grow feed for cows and produce milk, two main stages are identified: fodder crop farming and milk production. Therefore, the data collected in this study were mineral fertilizers, pesticides, cow feed, bedding material, electricity, water, diesel, cleaning products and disinfectants. In addition, field emissions from agrochemicals (mineral fertilizers and pesticides) were calculated. Field emissions of mineral fertilizers were estimated using IPCC (IPCC, 2019) and Nemecek et al. (2015) guidelines, while pesticide emissions were calculated using PestLCI Consensus model (Fantke et al., 2017). A statistical summary of the input and output variables is presented in Table 1.

Table 1. Statistical summary of the input and output variables of raw milk production.

	Bedding material (ton)	Diesel (kg)	Electricity (kWh)	Cow feeds (ton)	Water (m^3)	Fertilizers (ton)	Pesticides (l)	Cleaner and disinfectant products (kg)	Raw milk (m^3)
Average	84.2	6,639.5	38,568.6	568.3	691.6	18,7	48.1	1,066.5	1,016.2
Maximum	1,000.0	16,523.8	243,946.0	7,941.9	2,655.4	132.0	355.2	7,020.8	5,289.3
Minimum	1.8	1,360.9	12,603.0	111.4	306.6	0.3	3.0	286.8	359.7
Standard deviation	147.8	3,619.6	34,453.4	1,120.5	365.0	20.6	60.8	958.0	945.1

ii) CF assessment: The CF indicator was evaluated using the LCA methodology and considering a cradle-to-gate approach for the functional unit (FU) of 1 L of raw milk. The life cycle impact assessment methodology used was ReCiPe 2016 Midpoint (H) v.1.04, while the background data were extracted from Ecoinvent database (Wernet et al., 2016). In addition, since there are two outputs obtained from dairy farms, a mass allocation is conducted to evaluate the environmental impacts associated with the raw milk production.

iii) *Eco-efficiency assessment*: In this step, the DEA model was performed focusing on the reduction of operational resources consumed and their environmental impacts while maintaining production values. Thus, an input-oriented DEA model, particularly the BCC, was used (Cooper et al., 2007). Consequently, the inputs are bedding material, fertilizers, pesticides, water, cow feed, electricity, diesel, cleaner and disinfectant products, and CF while the output is the raw milk produced.

Finally, once the DEA was performed, the CO_2 sequestered was calculated and reported separately following ISO guidelines (ISO, 2018). This procedure was conducted for those farms that cultivate crops. In this case study, 11 dairy farms reported their own crop cultivation, for those the calculation of CO_2 sequestered was performed, as they have direct control over these agricultural management decisions. To determine the CO_2 sequestered, factors from previous studies with similar crops and soil and climatic conditions were used, due to the lack of field data from the farms. In this regard, the following factors for CO_2 sequestration were considered: for straw 961 kg $CO_2 \cdot ha^{-1} \cdot yr^{-1}$ (Petersen et al., 2013), for grass 1.8 kg $CO_2 \cdot ha^{-1} \cdot yr^{-1}$ (Madigan et al., 2022) and for spring vetch (*vicia sativa*) 6530 kg $CO_2 \cdot ha^{-1} \cdot yr^{-1}$ (Galantini and Sá Pereira, 2018). Then the total CO_2 sequestered by a farm is determined by multiplying the surface of crop i by the CO_2 sequestered factor associated with the crop i.

Results and discussions

Results show that the dairy farms analyzed produce 1,016 m^3 of raw milk on average, ranging from 360 m^3 to 5,289 m^3. Regarding the CF (see Figure 1), farms generate 1.30 kg $CO_{2\text{-eq}} \cdot FU^{-1}$, ranging from 0.8 to 4.24 kg $CO_{2\text{-eq}} \cdot FU^{-1}$. It is interesting to observe that farms 16 and 49 generate the largest CF (3.8 and 4.24 kg $CO_{2\text{-eq}} \cdot FU^{-1}$, respectively), mainly due to the field emissions of the agrochemicals used and the cow feeds. On the contrary, farm 5 presents the smallest CF (0.8 kg $CO_{2\text{-eq}} \cdot FU^{-1}$), mainly due to the lower impacts of the cow feeds.

Focusing on the main contributors to CF, on average field emissions account for 62%, while cow feed totals on average 28%. Regarding field emissions from fertilizers, farmers mainly use NPK fertilizers. The average amount of fertilizer applied per season is 18.7 tons (see Table 1). However, farms do not report the use of techniques to determine the optimal amount of fertilizer to be applied to the soil. Consequently, the total amount of fertilizers used might not be adequate, leading to the loss of the amount of nutrients applied and, therefore, to an environmental impact. As for cow feeds, farmers produce their own feed (mainly maize, and grass), but they also buy fodder consisting mainly of additional corn, soy, rapeseed, barley, and wheat (Rebolledo-Leiva et al., 2022). This different composition of cow feeds could induce differences in the CF generated by each farm.

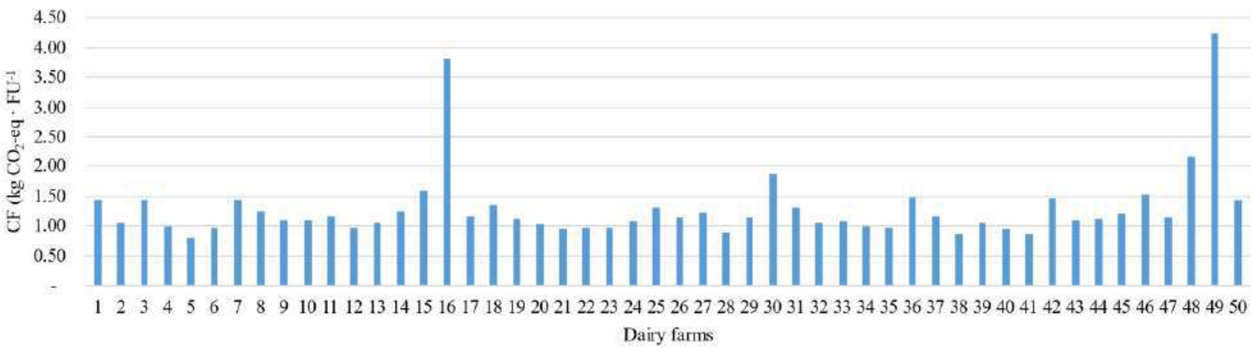

Figure 1. CF per L of raw milk generated by the dairy farms analyzed.

When the BCC input-oriented DEA model is applied, a total of 35 farmers are identified as efficient, while the rest are classified as inefficient. For the inefficient, an average efficiency of 86% has been determined, ranging from 67% to 98%. In addition, DEA provides targets for inefficient farmers in order to use resources efficiently. According to these targets, the main average reductions are cow feed (44%), fertilizer (39%), diesel (38%) and pesticides (36%). As can be seen, farmers should pay special attention to the use of agrochemicals and feed, as these inputs present the highest demand reductions and at the same time are the main contributors to environmental impacts.

When it comes to comparing eco-efficient and eco-inefficient farmers in terms of raw milk production, eco-efficient farms produce on average 18% more raw milk than inefficient ones. On the other hand, comparing the amount of resources, efficient farms consume more cow feed, bedding material and electricity than inefficient farms during the season (67%, 24% and 11%, respectively). However, efficient farms consume less fuel, water, agrochemicals, cleaning products and disinfectants (24%, 10%, 22% and 11%, respectively). Furthermore, when comparing the ratio of resource to liter of milk produced from efficient and inefficient farms, similar results are obtained. Consequently, this could imply that efficient farmers focus mainly on raw milk production activities rather than on agricultural activities for growing feed crops, which could lead to better environmental performance.

Finally, once the eco-efficiency performance is determined, the sequestered C is analyzed. It is estimated that a total of 11 farms sequester an average of 2.1% of the CO_2 emitted. This sequestration is associated with the agricultural stage during the cultivation of cow feed. The highest amount of CO_2 sequestered is reported for farm 49, with 90 tons of CO_2. However, it is important to consider that this farm generates 1,730 tons of CO_2 and consequently, the amount of CO_2 sequestered represents a small part of the total: 5.2%. This variation between emitted and sequestered CO_2 is similar for other dairy farms.

Conclusions

The LCA and DEA study of the 50 dairy farms identified significant variations among them. In terms of resources used, efficient farms consume more cow feed, bedding material and electricity, but less fuel, water, agrochemicals, cleaning products and disinfectants, than inefficient ones. In particular, two resources are key to improving the eco-efficiency of the dairy farms analyzed: agrochemicals and cow feed. Therefore, some management practices can be adopted in relation to these two inputs. For example, it is advisable for farmers to conduct a soil analysis to determine the current level of crop nutrients. In this way, they can use the correct amount of nutrients required by the soil. In addition, farmers could select forage with lower environmental impacts. In addition, it has been identified that farmers who grow their own feed for cows have the potential to sequester CO_2. Although the estimated value of CO_2 sequestration using cover crops represents on average a low percentage (2.1%). Therefore, further studies could focus on additional methodological options to integrate carbon sequestration into the LCA + DEA framework.

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Expansion of the Land Suitability Rating System Model for Pulse Crops to Enable LCA of Alternative Agricultural Land Use Scenarios in Canada

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Background and rationale: For the world to eat a "healthy" diet, as per USDA guidelines, an additional gigahectare of land (about the size of Canada) is necessary (Rizvi et al. 2018). However, agriculture already occupies 35-40% of terrestrial surface area, with limited potential for expansion (FAO 2013) and at high anticipated cost to biodiversity. At current levels of production, food systems are responsible for 70-90% of freshwater consumption (Jägerskog, A., Jønch Clausen 2012), 95% of nitrogen pollution (Bodirsky et al. 2014) and 30% of greenhouse gas (GHG) emissions (Hallström et al. 2017). This leaves little room for expansion of the current methods and distribution of food production. At the same time, poor dietary quality contributes to the rising prevalence of both malnutrition and obesity (and related diseases) (Kelly and Bateman 2010; Asif et al. 2017). It is therefore imperative to improve the nutritional quality, environmental sustainability, and production efficiency of food systems.

In Canada, field crops make up a significant portion of the agricultural sector, accounting for more than half the agricultural land use (Statistics Canada 2020). There is room for improvement in the current allocations of Canadian agricultural lands to grow different field crops, due to the significant degree of variability in environmental impacts and nutritional quality of the food products produced. In addition, there is increased awareness and adoption of plant-based diets, resulting in changes in production and allocation of crop products (Medical Letter on the CDC & FDA 2020). For example, the dried pea market is currently experiencing growth which is expected to continue due to the consumption of pea protein as a meat substitute (Hexa Research 2019).

Market demand currently dictates which and how much of each crop type are produced, regardless of nutritional and environmental sustainability outcomes. However, when agricultural land use policy does address these objectives, different crop types cannot simply be substituted in all agricultural soils because different areas are better suited to specific types of crops due to climate, soil, and management factors, as well as the agronomic needs of the crops (Agronomic Interpretations Working Group 1995). These factors must be considered when designing alternative patterns of agricultural land use, and life cycle assessments (LCA) to assess their sustainability. On this basis, the Land Suitability Rating System (LSRS) for Agricultural Crops was developed for Agriculture and Agri-Food Canada (AAFC) (Agronomic Interpretations Working Group 1995). This model ranks the suitability of agricultural lands for specific crops and management practices based on the agronomic requirements of the crops. Currently the LSRS includes models for suitability of soils for spring-seeded small grains (wheat, barley, oats), alfalfa, brome, timothy, canola, corn and soybeans.

Pulses are nitrogen-fixing legume crops which may serve to improve both the environmental sustainability and nutritional quality of the Canadian food system. Therefore, the benefits of increasing land use for pulse cultivation should be assessed using LCA scenario modelling. However, the LSRS does not currently include a pulse model, thus LCA scenarios cannot currently be designed to take into account the suitability of different agricultural lands for pulse production.

Objectives: The purpose of this study is to expand the LSRS to include factors for pulses, which can be used to conduct LCAs of agricultural land use scenarios in Canada that include expansion of the current pulse-growing regions.

Methods: Data on the agronomic requirements of pulse crops (dry peas, dry beans, faba beans, and chickpeas) were collected from an expert stakeholder panel made up of members from Canadian provincial pulse growers' associations, government, and academia. In addition, provincial pulse associations' websites were consulted (Saskatchewan Pulse Growers 2022; Alberta Pulse Growers 2022; Manitoba Pulse & Soybean Growers 2022). Specifically, the model includes metrics for climatic factors such as moisture and temperature; soil factors such as water supplying ability, structure, organic matter content, depth of topsoil, pH, salinity, sodicity, drainage, temperature and nutrient content; and landscape factors such as landform rating, stoniness, wood content, landscape pattern and flooding (Agronomic Interpretations Working Group 1995).

First, the optimal climate, soil and landscape factors for each pulse crop were determined. Then, the model was developed to include point deductions for non-optimal conditions based on regression curves and expert judgement from the stakeholder panel. This information was then used to create numerical rating systems from 1 to 100 for each factor, to rate the suitability of agricultural lands in Canada for growing pulses, based on their climate, soil, and landscape characteristics. These ratings were used to give each region a suitability class that indicates how severe the limitations are to growing each pulse crop in that region (ranging from unsuitable to no limitation). This information is combined with GIS climate, soil, and landscape data to determine the suitability of agricultural lands for pulse production.

Results and discussion: The LSRS model was expanded to include pulse-specific rating systems. These can be used to assess the feasibility of LCA scenarios in which pulses are grown in regions of Canada where other crops are currently grown, in order to assess the environmental and nutritional impacts of these scenarios. The updated LSRS model will also be made publicly available by AAFC in order to facilitate further research on the suitability of agricultural lands for pulses, which can be used for a variety of sustainability, policy, and education purposes.

Conclusions: Pulses are nutritionally and environmentally beneficial crops, and the expansion of pulse-growing regions in Canada can potentially serve to increase the nutritional quality and decrease the environmental impacts of the food system. Coupled with the LSRS model, LCA can then be used to assess the environmental impacts of different agricultural land use scenarios including pulse crops. In order to determine the feasibility of such land use scenarios, the LSRS model was expanded to include suitability ratings of Canadian agricultural soils for pulse crops. This was done by consulting pulse agronomy experts to determine the optimal soil, climate, and landscape factors for pulses, as well as point deductions for non-optimal conditions. The new pulse LSRS model can be used to design LCA scenarios that include the optimal locations for pulse growth, in order to maximize and quantify the nutrition and sustainability gains. The results of these LCAs can be used to inform agricultural policy to improve the sustainability and nutritional quality of the Canadian food system.

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Expanding the perception of LUC impacts beyond GHG emissions: A case study for a Brazilian scenario.

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Rationale and objective: In 2018, Brazil was responsible for emitting about 1 billion tons of greenhouse gases (GHG), which represents about 2% of total global emissions (WORLD BANK, 2022). Of that 1 billion, about 44% are associated with Land Use Change (LUC) (NATIONAL GEOGRAPHIC, 2020). In Brazil, LUC processes take place mainly for the expansion of the agricultural frontier, once Brazilian agriculture is important to the world's food production, with emphasis on soybeans and livestock. In the 2020/2021 harvest, for example, the country was the second largest producer of soybeans, reaching 137 million tons, which represented 37.63% of the total world production (SOPA, 2022). In parallel, in 2020, Brazil was responsible for the largest livestock in the world, with 217 million cattle, which contributed to 14.3% of the world's production (EMBRAPA, 2021). With these results, the agriculture sector plays an important role in the country's economy, accounting for 6.8% of Gross Domestic Product (GDP) in 2020 (SEBRAE, 2022). Nevertheless, in addition to GHG emissions, the expansion of agricultural frontiers, associated with increased production of soybean and livestock, has the potential to cause several negative impacts, such as soil and water contamination due to the use of pesticides, soil impoverishment, and deforestation caused by poor management and/or expansion of the agricultural frontier. Considering that the agriculture sector continues to expand in Brazil, this paper aims to evaluate the repercussions on the environmental profiles of production systems (soybean/livestock) associated with the expansion of the agricultural frontier in the country.

Approach and methodology: The life cycle assessment (LCA) methodology was used to evaluate the repercussions on the environmental profiles of production systems (soybean/livestock). The data on the expansion was obtained for the years 2000, 2010, and 2018 (Table 1). Based on the expanded area and considering the evolution of productivities for soybeans and for livestock, the total productions were extrapolated for the analyzed years. These data were used to model the soybean and livestock production datasets obtained in ecoinvent® database® 3.7.1, forming the life cycle inventory (LCI). The life cycle impact assessment (LCIA) was performed with the OpenLCA® 1.10.3 using the ReCiPe 2016 method for the following impact categories: freshwater ecotoxicity (FEX), freshwater eutrophication (FEU), global warming (GW), terrestrial acidification (TA), terrestrial ecotoxicity (TEX) and water consumption (WC).

Table 1 – Evolution of soybean production and livestock.

Land use		2000	2010	2018	Source
Soybean	Area (ha)	13,970,000	24,182,000	35,876,000	CONAB (2022)
	Productivity (t/ha/yr)	2.75	3.11	3.21	Calculated
	Total production (t/yr)	38,433,000	75,323,000	115,030,000	CONAB (2022)
Livestock	Area (ha)	88,518,600	109,903,100	112,519,400	IBGE (2022)
	Productivity (t/ha/yr)	0.045	0.06	0.066	IBGE (2022)
	Total production (t/yr)	3,983,337	6,594,186	7,426,280	Calculated

Main results and discussion: The analysis of the evolution of land use in Brazil shows that from 2000 to 2010 there was a 24% increase in the area destined for pasture management, and from 2010 to 2018, the increase was 2%. At the same time, productivity in pasture management increased by 33% and 10%, respectively. This resulted in an increase in total production (t/y) of 66% in the period from 2000 to 2010 and 13% in the period from 2010 to 2018. Through the LCA, it was possible to trace the environmental profile of the expansion of livestock production (Table 2). In the FEX, FEU, TA, TEX and WC categories, the impacts in 2018 were 2.01 Mt 1,4-DCB, 0.0049 Mt P eq, 0.519 Mt SO_2 eq, 38 Mt 1,4-DCB and 244 hm³ respectively, from 2000 to 2018, the impacts increased in orders close to double from the beginning to the end of the period studied. In the GW category, impacts rose from 107 Mt CO_2 eq in 2000 to 200 Mt CO_2 eq in 2018, representing 42% and 79% of impacts in 2000 and 2018, respectively.
Regarding the area destined for soybean planting, it is possible to observe that there was a growth of 73% from 2000 to 2010, and 48% from 2010 to 2018. Productivity increased by 13% from 2000 to 2010 and 3% from 2010 to 2018. Hence, the observed increase in total production was 96% from 2000 to 2010 and 53% from 2010 to 2018. The environmental profile of the expansion of soybean production, in the same manner as the livestock production, was traced through the LCA (Table 2). In the FEX category, the impacts represented 1.77 Mt 1,4-DCB in 2018, in other words, they increased from 20% in 2000 to 88% in 2018. In the FEU, GW, TEX and WC categories, impacts in 2018 increased fivefold compared to 2000, and for 2018, the impacts were 0.0851 Mt P eq to FEU, 253 Mt CO_2 eq to GW, 174 Mt 1,4-DCB to TEX and 377 hm³ to WC. In the TA category, impacts rose from 0.0595 Mt SO_2 eq to 0.261 Mt SO_2 eq, in other words, the impacts increased from 11% to 50% in 2000 and 2018, respectively.
From the data presented, it is possible to verify that the development of new techniques and the advancement of technologies make it possible to increase productivity, and therefore reduce the need for expansion to new areas. When analyzing the environmental profiles traced for both productions, it is possible to observe that the impacts of soybean production increased more, from 2000 to 2018, in all categories, in relation to livestock production. This may be related to the fact that the area destined for soybean production had a significantly greater increase than the area destined for livestock production during the analyzed period.

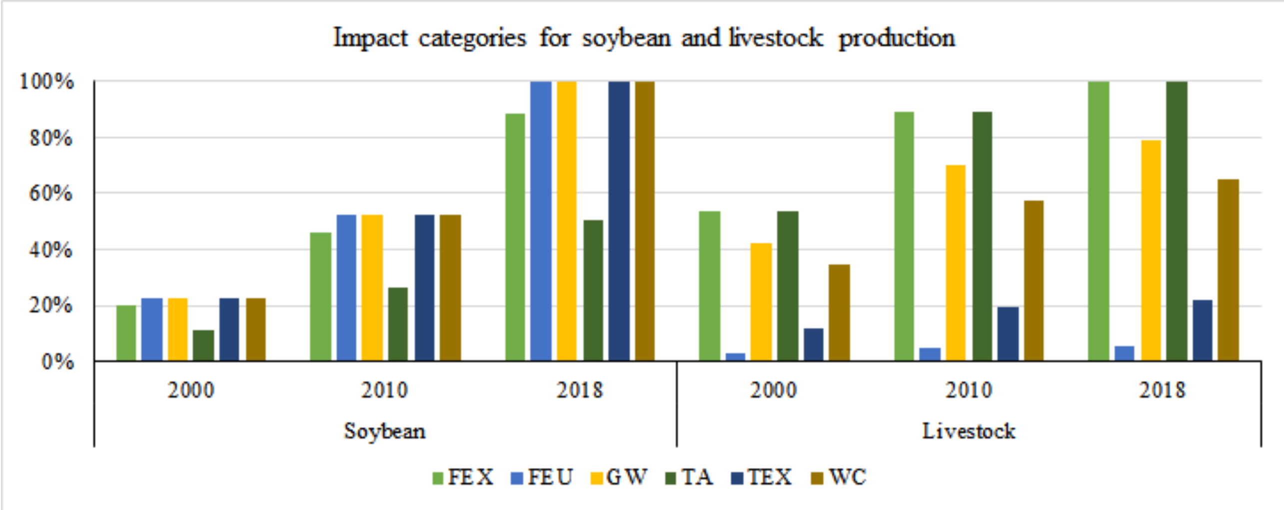
Table 2 – LCIA for soybean production and livestock.

Indicator	Soybean		Livestock	
	2000	2018	2000	2018
FEX (Mt 1,4-DCB)	0.404	1.77	1.08	2.01
FEU (Mt P eq)	0.0194	0.0851	0.0026	0.0049
GW (Mt CO_2 eq)	57.7	253	107	200
TA (Mt SO_2 eq)	0.0595	0.261	0.278	0.519
TEX (Mt 1,4-DCB)	39.6	174	20.4	38
WC (hm³)	86	377	131	244

Source: Authors, 2022.

From the internal normalization (Figure 1), it was possible to observe that for some categories, the impacts of the expansion had significant differences comparing the productions of soybean and livestock. In 2018, FEU and TEX were more impactful in the case of soybeans than in livestock (7% and 27% respectively). In the TA category, for the same year, the relationship reverses, representing 41% for soybean. These differences can be explained by the specificity of each production. The intensive use of agricultural fertilizers and pesticides in soybean production may be responsible for causing greater freshwater eutrophication and terrestrial ecotoxicity. Previous work developed by Kulay et al. (2017) showed that the dispersion of agrochemicals in soybean fields was responsible for contributing to several categories of impact on LCA, including eutrophication. In addition, the use of chemical fertilizers in soybean plantations contributes to terrestrial ecotoxicity, due to heavy metals present in their composition (SILVA et al., 2010). On the other hand, the high terrestrial acidification in livestock production may have, as one of the causes, the nitrogen fertilization used in the production of pastures, and to a lesser extent manure (WILLERS et al., 2017).

Figure 1 - Results of impact categories for soybean and livestock production after normalization.



Source: Authors, 2022.

Conclusion: Currently, the deserved attention is given to GHG emissions from different sectors, and the Brazilian agricultural sector is no different. However, this focus ends up overshadowing other impacts resulting from productive activities, especially those that are expanding. This work sought to analyze the environmental repercussions resulting from the expansion of the agricultural frontier for other categories of impact, in addition to climate change. Representative contributions to eutrophication impacts were associated with soybean cultivation, while acidification impacts were identified in pasture management for livestock. It is important to point out that the main objective of this study is not to compare the environmental performance of the two cultures with each other but compare their impacts in general terms. Although livestock is known to be more impactful than soybean production, the fact that soybean production is higher, makes the grain more impactful, in absolute terms, for the FEU, GW, TEX and WC categories.

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Comparison of IPCC and PEF methods in assessment of nitrous oxide emissions from Finnish crop production

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Rationale To enable harmonized assessment of the environmental impacts of products the European Commission has developed guidelines for life cycle assessment of products (European Commission 2018a, Manfredi et al. 2012). These Product Environmental Footprint Category Rules (PEFCR) aim in providing better comparability of environmental performance within product categories. Currently, PEFCRs' regarding livestock production recommend modelling feed crops and feed products according to the PEFCR Feed for food producing animals (European Commission 2018b). The assessment with harmonized methodology throughout the assessment of livestock products, reaching to primary production of feed, is considered to yield better comparability of results. PEF guidance and PEFCR of feed products are providing a simplified method for assessing nitrous oxide emissions from field cultivation, to avoid inconsistencies between PEFCRs and further studies. Yet, the PEFCR of feed products is addressing N_2O emission from cultivation as additional environmental information, even if the emission is understood to contribute largely to climate impact of crop production. Still, the PEF method is pointing emission from fertilizer use as important source for N_2O emissions, which is to be accounted, while importance of other sources remains unclear.

Objective Main objective of this study was to investigate the effect of methodological differences to climate change impact from nitrous oxide emissions of typical Finnish feed crop production. Aim was to utilize the Product Environmental Footprint guidance by European Commission for feed crops (European Commission 2018b) in parallel to IPCC methods (IPCC 2006, 2013).

Approach and method An LCA model was constructed to assess the climate change impact from nitrous oxide emissions related to feed crop production. Assessment included direct and indirect N_2O emissions from nitrogen inputs and N_2O from peat decomposition (IPCC 2006, 2013). Two approaches were compared: 1) N_2O emission calculation with IPCC method for feed crop production included N-fertilizer use (mineral and organic), N_2O emissions from the crop residues and N_2O emissions peat soils and 2) with PEF methods, where N_2O emission at minimum is to be included from N-fertilizer use (additional environmental information) and for this a default factor for N_2O from fertilization was utilized accordingly (0.022 kg N_2O/ kg N fertilizer applied). While the simplified emission factor for N_2O from fertilization input is not fully described in the PEF methodology, it is unclear whether this includes N_2O inputs from crop residues or peat soils, or are they to be excluded for simplification. Here, the impact of inclusion of different N_2O sources were tested. N_2O originating from land use change was not considered in this study. Global warming potential was determined with characterization factor 298 for N_2O. Assessment was conducted for feed crops which were defined as typical in Finnish pork and broiler chicken diets (Hietala et al. 2022). These included barley (*Hordeum vulgare*), wheat (*Triticum aestivum*), oat (*Avena sativa*), turnip rape (*Brassica rapa ssp. oleifera*) and rapeseed (*Brassica napus ssp. oleifera*), peas (*Pisum* *sativum*) and faba bean (*Vicia faba*). Brassica species were assessed as combined. The functional unit (FU) for the assessment was of 1 kg of produced crop (as fed) and system border was at farm gate. Crop cultivation characteristics which were utilized in the assessment were as described in Hietala et al. (2022). These were considered to represent typical Finnish feed crop cultivation.

Results and discussion Assessment results are presented in Table 1. for barley, wheat, oat, turnip rape, peas and faba bean. It was shown that when the emission from the inputs was compared, the PEFCR method alone for fertilizer use gave slightly lower results compared to IPCC. When crop residues were accounted, result exceeded IPCC result for most of the crops. Peat soil utilization varied from 2% to 19% among different crops. When the peat soil degradation was included in the assessment, the observations were similar.

Table 1. Climate change impact of nitrous oxide emission from feed crop cultivation, as kg CO_2 eq per kg FU. Comparison of methods.

	Brassica sp.	*V. faba*	*H. vulgare*	*A. sativa*	*T. aestivum*	*P. sativum*
PEF, N fertilization	0.40	0.05	0.14	0.13	0.18	0.08
PEF, N fertilization + peat soils	0.65	0.10	0.25	0.42	0.21	0.14
PEF, N fertilization + peat soils + crop residue	0.72	0.16	0.31	0.47	0.27	0.21
PEF, N fertilization + crop residues	0.47	0.12	0.20	0.18	0.25	0.15
IPCC, N_2O fertilization and crop residues	0.45	0.12	0.19	0.17	0.24	0.14
IPCC, N_2O tot (N fert., crop residues, peat soils)	0.70	0.16	0.30	0.46	0.26	0.21

Conclusions

In the PEF guidance and PEFCR for feed products a harmonized, simplified method is presented for the assessment of nitrous oxide emissions from cultivation. N_2O emissions are known to contribute largely to climate change impact of crop production, yet the PEF guidance is not clearly emphasizing the importance. If the minimum requirement was implemented, depending on the crop, a difference of up to 0.33 kg CO_2 eq per kg was observed in the N_2O emissions from field. Here, it was shown that the simplified method provided in PEF guidance functions as its best when other N_2O emissions from cultivation (crop residues, peat soil degradation) are included in full as according to IPCC. This is suggested to be clearly pointed in PEF guidance as well. The PEF method has been developed to serve as simplified method and requires less data. The nitrous oxide emissions in feed crop primary production and primary production of food crops contribute largely to their total carbon footprint. Thus, the more detailed approach would give more resolution to hotspot analyses. More research would be needed to investigate the applicability of PEF methods in production chain development, while in communicating environmental information the level of accuracy can be adequate.

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Inclusion of soil carbon stock changes in LCA: a comparison between semi-natural grasslands and cultivated grassland in Finnish beef production

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Introduction

Beef consumption and production is a highly contested issue in the sustainability discourse (Röös et al. 2017). Many Life Cycle Assessment (LCA) studies revealed the potential environmental impact of beef (Poore and Nemecek, 2018). However, most of the studies remain incomplete due to the exclusion of soil organic carbon (SOC) stock changes in the assessments (Brandão et al., 2011). SOC stock change may influence the overall environmental impact of beef balancing final greenhouse gas (GHG) emissions values. Beef production systems that utilise grasslands in production may increase SOC stocks (Hammar et al., 2022). However, grasslands under different farming treatments may not contribute equally to SOC stocks. In Finland, the majority of beef production systems utilise cultivated grasslands while a minority relies on semi-natural grasslands, so-called High Nature Value (HNV) farming systems. HNV systems are known for supporting farmland areas in Europe "where agriculture is a major land use and where that agriculture supports, or is associated with, either a high species and habitat diversity or the presence of species of European conservation concern or both" (Andersen et al. 2003). This study aims at assessing the global warming potential (GWP) of beef production while accounting for SOC stock changes in grass-fed beef systems in Finland. The objectives are: i) to estimate and compare the potential SOC stock changes for semi-natural and cultivated grasslands and, ii) from a methodological perspective, to assess the accuracy of the methods to assess SOC stock values in LCA.

Materials and methods

Our dataset includes 6 HNV beef production farms - that is farms that include semi-natural (permanent) vegetation for grazing in addition to cultivated grassland and cereal in rotation - and 1 mainstream farm (without semi-natural grasslands). The assessment of the environmental impact is based on a yearly cycle of beef production system estimated upon 5-year average data collected by the authors in relation to farming practices and farm structure. Yields of cereal crops are based on the last 4 years average of Finnish production at country level (Luke, 2021). We considered yields of 6.3 Mg dry matter (DM)/ha for cultivated grasslands, included in rotation (Lehtonen and Niskanen, 2016) and an average value of 1.8 Mg DM/ha for semi-natural grasslands (Saastamoinen et al. 2017).

Feed intake estimates are based on the original farm data and calculations derived from primarily metabolisable energy (ME) concentration of low-quality forage and livestock characteristics such as breed and growth rates. For further details, see Torres-Miralles et al. (2022). We assessed the potential carbon footprint of HNV beef by applying the LCA method using Solagro Carbon Calculator and OpenLCA 1.11. The system boundary applied was from cradle to farm gate. We applied the ReCiPe Midpoint 2016 (H) impact method to estimate GWP_{100} at the farm level (kg CO_2 eq/ ha) and product level of beef (kg CO_2 eq / kg liveweight (LW)). We included soil organic carbon (SOC) stock changes as an added value in form of CO_2 eq emissions to the final GWP_{100} resultant from the LCA method.

We applied Yasso model (v. Yasso20) to estimate the SOC stock change potential in a 1 m depth soil layer. The annual SOC stock change (ΔSOC, kg C/ha/a) was modelled with two time horizons (i.e. lengths of the modelling period), 20 and 100 years (Eq. (1)). The model had two scenarios: scenario I) the potential SOC stock change in semi-natural grassland and cultivated grassland (=pasture and silage grass/hay; rotational with on average 4-year interval) in comparison to the fixed initial SOC stock and, scenario II) the potential SOC stock change in cultivated grassland in comparison to the initial SOC stock after long-term semi-natural grassland management. The initial SOC stock in the scenario I based on 100 years of silage grass cultivation with high cattle manure application (55 Mg C/ha), and the initial SOC stock was fixed for all farms. In scenario II, the initial SOC stock was specific for each farm (on average 39 Mg C/ha) and corresponded the SOC stock after 100 years of semi-natural grassland cultivation with farm-specific annual C inputs.

$$\frac{\Delta SOC\ stock\ i - \Delta SOC\ stock\ n}{t\ horizon}$$

SOC stock i: initial SOC stock change value
SOC stock n: SOC stock value after the modelling period
t horizon: length of the modelling period in years

Eq. (1)

We calculated the annual C input from crop residues (above-ground residues and roots), rhizodeposition and manure according to Bolinder et al. (2007). We estimated the harvest indices and rhizodeposition rates according to Palosuo et al. (2015). We considered root biomass estimates for cultivated grassland to be 4036 kg DM/ha (Palosuo et al., 2015) and for semi-natural grassland to correspond to the root:shoot ratio of 2.5-fold in comparison to cultivated grassland (Bolinder et al., 2007; Poeplau, 2016). We divided root biomass estimates for both semi-natural and cultivated grassland by 4 years representing the approximated turnover time of the roots. The C input from manure based on the farm-specific estimates of spreadable total N by Solagro Carbon Calculator. We included regional weather data from 1961 to 2021 (Finnish Meteorological Institute).

Preliminary results and discussion

Initial SOC stock values and time horizons influenced final semi-natural grasslands and cultivated grasslands SOC stock values in scenario I and II (Table 1). The GWP_{100} modelled without ΔSOC varied from 2330 to 3640 kg CO_2 eq/ha at the farm level and from 14.6 to 25.4 kg CO_2 eq/kg LW at the product level. The inclusion of ΔSOC increased the GWP_{100} by +12 % to +52 % in scenario I and decreased the GWP_{100} by -2 % to -13 % in scenario II, depending on the time horizon.

Table 1. Average Global Warming Potential (GWP_{100}) values at the farm and product level of beef of 6 HNV and 1 mainstream farms for two initial SOC stock scenarios with two time horizons, 20 and 100 years. Scenario I: ΔSOC in comparison to fixed initial SOC stock, scenario II: ΔSOC of

cultivated grassland in comparison to long-term semi-natural grassland.

	Farm level			Product level		
	GWP_{100} (kg CO_2 eq / ha)	GWP_{100} + ΔSOC (kg CO_2 eq / ha)		GWP_{100} (kg CO_2 eq)	GWP_{100} + ΔSOC (kg CO_2 eq / kg LW)	
		20 years	100 years		20 years	100 years
Scenario I	2567	3641	2879	16.7	19.2	25.4
Scenario II	2567	2330	2519	16.7	14.6	16.3

In scenario I, the SOC stock decreased under semi-natural and cultivated grasslands compared to the initial SOC stock (Table 2). The decrease in SOC stock was greater for semi-natural grassland than for cultivated grassland. In scenario II, conversion of long-term semi-natural grassland to cultivated grassland increased the SOC stock by 288 and 63 kg C/ha/a with a time horizon of 20 and 100 years, respectively. The increase in the SOC stock related mainly to the differences in above-ground crop residue biomasses and root biomasses between semi-natural and cultivated grassland. The total root C input estimated in this study for semi-natural grasslands was lower compared to cultivated grassland. Despite low N input increases the root:shoot ratio of grasses (Gregory et al., 2021), the differences in harvested DM yields between semi-natural and cultivated grasslands influenced the root C input estimates in this study.

Our results indicated that higher productivity of grasslands potentially increases C sequestration to soil, therefore, increases the SOC stock similarly to Gregory et al. (2021). However, not all semi-natural grasslands are equally productive, dry pastures present lower productivity yields compared to meadows (Saastamoinen et al. 2017) and cultivated grasslands. In this study, we utilised an average yield value for semi-natural grasslands, therefore, further detailed comparisons would be needed in order to improve the accuracy of our results. Nevertheless, the modelling approach used in this study showed only the potential SOC stock change with assumed initial SOC. At the farm level, continuously similar C input rate from 20 to 100 years typically leads to SOC stock equilibrium, and hence, the SOC stock remains stable without net C sequestration or net C losses (Freibauer et al., 2004). However, a change in the annual C input rate may affect the SOC stock until the new equilibrium is reached.

Table 2. Average Soil Organic Carbon (SOC) stocks changes (ΔSOC) values of 6 HNV farms and 1 mainstream for semi-natural grassland and cultivated grasslands for two initial SOC stock scenarios with two time horizons, 20 and 100 years. Scenario I: ΔSOC in comparison to fixed initial SOC stock, scenario II: ΔSOC of cultivated grassland in comparison to long-term semi-natural grassland.

	Scenario I				Scenario II			
	Initial SOC (kg C/ha)	C input (kg C/ha/a)	ΔSOC (kg C/ha/a)		Initial SOC (kg C/ha)	C input (kg C/ha/a)	ΔSOC (kg C/ha/a)	
			20 years	100 years			20 years	100 years
Semi-natural grassland	54 659	1197	-547	-159	-	-	-	-
Cultivated grassland	54 659	2051	-238	-70	38 757	2099	288	63

Negative ΔSOC = net C losses form the soil, positive ΔSOC = net C sequestration to the soil.

Research is currently lacking on the carbon accumulation in boreal areas. Further field studies are needed in relation to the productivity of semi-natural grasslands, root biomass estimates and the potential effect of trees in wooden pastures to improve the accuracy of the assessments.

Conclusion

The methodology chosen to assess SOC stock changes (i.e. SOC stock changes initial values or time horizons) influenced greatly the overall $GWP_{100.}$ The inclusion of ΔSOC in LCA would require technical harmonization and further research. Such choices, if not properly addressed, have the potential to mislead mitigation strategies towards more C sequestration contrary to C and biodiversity conservation.

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Development of a biodiversity impact assessment method for agricultural land use in the boreal zone

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1 Introduction

While agriculture is a major cause of biodiversity loss and other environmental burdens, certain production methods, such as organic farming or grazing by livestock, can also have positive impacts on biodiversity (Bengtsson et al., 2005; FAO, 2020). Yet, environmental assessments of food products, commonly performed using life cycle assessment (LCA), rarely include impacts on biodiversity. Despite recent advancements, several methodological issues hinder the integration of biodiversity into LCA (Crenna et al., 2020); current methods, for example, fail to capture the complexity of biodiversity or impacts on local scales (Knudsen et al., 2017; FAO, 2020).

Failure to account for biodiversity impacts may lead to burden shifting when aiming to reduce negative environmental impacts of agriculture, due to trade-offs between production intensity and benefits on biodiversity (FAO, 2020). Most LCAs calculate environmental loads per unit of food produced (e.g., kg of meat). This means that intensive production systems with high output in relation to inputs generally appear less harmful to the environment than more extensive but often multifunctional production systems (van der Werf et al., 2020). Such assessments favour further intensification of production aimed at minimizing negatives, which may come at the expense of biodiversity and related ecosystem services. To balance several objectives in agricultural production, current assessment methods need to be developed to capture the multiple functions of production, including the positive and negative impacts on biodiversity.

Here we present a plan for developing an assessment approach that aims to address some of the shortcomings of current biodiversity impact assessment methods. This study is a work in progress – we are currently at the data collection phase and results will be available in the near future.

2 Objective

The objective of this study is to develop a biodiversity assessment approach that 1) allows accounting for the impacts of agricultural food production on biodiversity in the context of boreal agriculture, 2) accounts for variations in production methods that have direct and indirect impacts on biodiversity on farmland and other land use types, and 3) is suitable for impact assessments on local to regional scales (i.e., from a farm up to ecoregion).

3 Materials and methods

We aim at developing a two-step assessment method, where the first step allows a quick and general estimation of biodiversity impacts of agricultural land use, and the second step can be used for more detailed assessments, for instance on a farm or landscape scale, when additional data are available.

3.1 Step 1: Characterization factors for agricultural land use types

For the first step, we will calculate characterization factors (CFs) for agricultural land use types, i.e., factors that indicate the potential damage to biodiversity per unit area of each land use class. As input in the calculations, we will use existing data on species occurrence on agricultural lands in Finland, derived from a number of different field studies. The data will cover several taxonomic groups (plants, insects and birds) and several agricultural land use types (arable fields under different crops, cultivated and semi-natural pastures, grasslands, fallows) under different management intensities. To our knowledge, no currently available CFs for biodiversity impact assessment are based on field data from Finland or other boreal regions. We therefore expect that the new CFs will provide more accurate impact assessment results for these regions.

The CFs will be developed by calculating species-area relationships (Knudsen et al., 2017; Chaudhary and Brooks, 2018). We will also estimate β-diversity, i.e., the variation for each land use type among regions. Besides species richness, we will explore options to base the CFs on other metrics, such as species abundance and functional diversity. We will also account for species vulnerability. As a reference state we plan to use traditional rural biotopes, which are semi-natural grasslands formed by traditional low-intensity animal husbandry. These biotopes are the most species-rich agricultural habitats in Finland and harbour a high number of endangered species (Hyvärinen et al., 2019). The CF of the reference land use type will be 0, indicating no impact, and the impacts of all other land use types will be assessed relative to it.

We will produce CFs for the individual species groups separately as well as aggregated values per land use type. Furthermore, the CFs will be calculated separately for agricultural lands under organic and conventional management. For each land use type (e.g., an organic spring cereal field), we will calculate an interval of potential biodiversity impact as well as an average value. The average values (either average CFs for individual species groups or average aggregated CFs) can be used in the less-detailed impact assessments that do not proceed to step 2.

3.2 Step 2: Calculation framework to further differentiate impacts within land use types

For the second step, we aim to develop a calculation framework that allows adjusting the CFs of each land use type by using data on landscape characteristics and agricultural management practices used on the area under assessment. Potential parameters to be used in the calculations include, for example, landscape structure, habitat fragmentation, tilling practices, fertilizer use, crop rotation, wintertime plant cover, grazing pressure, and width of field boundaries and buffer zones. The biodiversity impact of each parameter will be scored by evaluating its potential impact on the species groups used in the development of the CFs. The scoring will be based on scientific literature, expert opinion and recently collected field data that contains information on the impacts of management practices and landscape structure on species diversity on several agricultural land use types in Finland. Based on the scoring of the parameters, the biodiversity impact of a land use type can be adjusted lower or higher on the defined impact interval. For example, the CF of a conventional spring cereal field with reduced tillage and wintertime plant cover would be lower than the maximum CF for the land use type.

Assessment frameworks based on the scoring of management parameters have been previously developed by several authors (e.g., Jeanneret et al., 2014; Lindner et al., 2019; Maier et al., 2019). However, since none of the existing frameworks are based on empirical data from Finland or other boreal countries, they may not be well applicable for assessing the biodiversity impacts of Finnish agricultural production.

3.3 Validation of currently available CFs

The new CFs, based on Finnish field data, can be used to validate other CFs that are currently available for assessing land use impacts on biodiversity, such as the global CFs by Chaudhary and Brooks (2018). Thus, we will conduct an LCA case study where we compare the new CFs with ones in literature to test how suitable other published CFs are for assessing biodiversity impacts in the Finnish agricultural and bioclimatic context. The scoring framework in step 2 and the CFs obtained from it can also be compared with other similar frameworks, such as the SALCA-BD method (Swiss Agricultural LCA – Biodiversity; Jeanneret et al., 2014).

4 Discussion

This study is the first to develop CFs based on species occurrence data from Finnish agricultural lands and an LCA-compatible assessment framework tailored for local to regional scale biodiversity impact assessments in the Finnish and boreal context. The value of this work is to provide more accuracy and detail to assessments in these regions compared to currently available CFs, such as the global CFs calculated for ecoregions and countries by Chaudhary and Brooks (2018), which also include CFs for Finland. These CFs are a revised version of the ones developed by Chaudhary et al. (2015) (that have been recommended by UNEP-SETAC Life Cycle Initiative; Frischknecht and Jolliet, 2016), and their use is recommended by, for example, FAO (2020). However, these CFs are only able to differentiate two broad agricultural land use types, pasture and cropland, under three land use intensities (minimal, light and intense). Our approach adds detail by including a wider range of agricultural land use types, for example by dividing the class "cropland" into several crop types, by differentiating between cultivated and semi-natural pastures, and by adding other semi-natural habitats such as field boundaries. Moreover, our approach makes it possible to include impacts of landscape characteristics and to differentiate the impacts of management practices further than when using three intensity classes.

There are also certain limitations to our approach. The focus on agricultural lands limits the scope of the LCAs, and the CFs will not be suitable for global level assessments. However, the assessment approach can be further expanded in the future to include more land use types (e.g., forests and urban areas), which would allow LCAs of more complex value chains.

5 Conclusion

The results of this study will contribute to the ongoing efforts of the LCA community to integrate biodiversity into LCA. When applied in LCAs, the new CFs and the proposed calculation framework will help identify agricultural production methods that are optimal when accounting for multiple environmental criteria, including biodiversity. The method will provide decision support in terms of handling trade-offs and will be of use to farmers, food industry, researchers and policymakers, particularly in Finland and other boreal regions.

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Biodiversity impact assessment in global food supply chains: A case study for GIS-aided impact assessment of soy

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Purpose: The global food system is identified as the primary driver for ongoing biodiversity loss (Benton et al., 2021). The decline in biological diversity is largely associated with a loss of ecosystem services (ES) which are essential to maintain food provisioning (MEA, 2005). The global food system in this context is both the main cause for and the main threat to global food security risks. Agricultural expansion and intensification as well as associated land use impacts are expected to further increase pressures on natural ecosystems resulting in land degradation, habitat alteration, ES loss and ultimately in biodiversity loss. ES degradation is associated with potential monetary losses by insufficient provisioning services. The yearly contribution of crop pollination service, for instance, has been estimated at €577 billion globally (Potts et al., 2016). An estimated monetary value of all ES delivered by biodiversity (e.g. flood protection, carbon sequestration) was rated at $125-140 trillion per year (OECD, 2019). Although the importance of preserving biological diversity experiences increasing attention (Beck-O'Brien & Bringezu, 2021), biodiversity is currently declining at unrivaled rates - higher than the average rate over the past 10 million years (IPBES, 2019).
Life cycle assessment is recognized as one of the most robust and comprehensive tools for estimating environmental impacts along entire value chains and has been used increasingly for assessing food production and processing systems (Crenna et al., 2019). Although the inclusion of biodiversity impacts in life cycle impact assessments (LCIA) is explored for more than 20 years (Winter et al., 2017), a broadly accepted methodological approach is lacking (UNEP/SETAC, 2017). From the scientific LCA community point of view, weaknesses considering the included drivers and the geographical coverage were identified among others (Crenna et al., 2020). While academic case studies of current biodiversity impact assessment methods exist, a wide application among LCA-practitioners is still missing. This is mostly due to insufficient guidance, data gaps, unsuitable data and aggregation levels, limitations in geographical coverage, methodological complexity, low robustness, or reliability (Lindner et al., 2019). The presented paper provides an approach to solve some issues LCA-practitioners are facing when aiming to calculate biodiversity impacts in global food supply chains. A case study about the biodiversity impact assessment of soy demonstrates that the potential biodiversity impact can be calculated with low and high data availability.

Method: To match real-world requirements, a case study about the potential biodiversity impact of 1 kg of soy from Brazil is calculated. The product system includes only processes on the field and excludes any transportation or processing steps. The biodiversity impact assessment model presented by Lindner et al. (2019) is used to calculate potential biodiversity impacts in various scenarios (see Table 1). The model allows to calculate biodiversity impacts by using either specific input data (primary data), characterizing management parameters (specific approach), or to estimate land use intensity based on hemeroby (generic approach). In cases where at least some specific or qualitative data is present, a mixed approach is also possible, by estimating the hemeroby of single management parameters. Thus, data gaps can be filled by reasonable estimates or as presented in this study by GIS-based datasets. Only globally available GIS-datasets are considered. In scenarios S1.1-S1.4 it is assumed that no primary data is available and land use intensity is estimated based on hemeroby levels three to six (low intensity to high intensity). The area occupation is based on statistical data provided by OECD/FAO (2021). In scenario S2.1 – S 2.4 specific data obtained from three farms in Mato Grosso do Sul is used. Scenario S3.1 – S3.2 includes mainly GIS-based estimates as input data. Parameters which could not be obtained by GIS-datasets were estimated based on proxy, literature values and assumptions. Table 1 provides information on the underlying input parameters and GIS-datasets.

Scenario	**Level of data availability**	**Approach**
S1.1-S1.4	Low – no primary data available	Generic – Modelled for different intensity levels; Area occupation calculated based on FAO statistics (OECD/FAO, 2021)
S2.1-S2.4	High – specific data for three sites in Brazil available; S2.4 based on average of three sites	Specific – Area occupation calculated based on specific data
S3	Low – no primary data available; global GIS data used to fill data gaps	Mixed – Area occupation based on FAO statistics, input parameters based on global GIS data and estimates

Table 1: Overview of impact assessment scenarios

The globalization of local biodiversity impacts in Lindner et al. (2019) is achieved by ecoregion factors, which assign each ecoregion a value based on four parameters (share of grasslands and forests, share of roadless areas, global extinction probability and share of protected wetlands; see Lindner et al. (2019)). As Brazil includes several ecoregions, the correct assignment of ecoregion factors requires the knowledge of the originating ecoregion of the land using process (in this case growing soybeans / agriculture). However, in many cases as well as in generic life cycle impact assessments the correct ecoregion where the land using process is taking place is not known. For this reason, we recalculated the ecoregion factors as presented by Lindner et al. (2019) and made them applicable for generic assessments, where the originating ecoregion is unknown. We incorporated the updated ecoregions as presented by Dinerstein et al. (2017)[1] and scaled the ecoregion factors to both ecoregion and country-level (area-weighted). Furthermore, a second set of country-level ecoregion factors was developed using an approach presented by Mumm & Eberle (2022) which includes spatially explicit and crop specific (included is a set of 42 crop types) production data. The weighting of crop specific country-level ecoregion factors is based on the spatial distribution and production volume of crop specific growing area in each country. This approach enhances the accuracy to the area-weighted country-level ecoregion factors. To compare and test a new globalization factor we developed a novel biodiversity valuation metric. It is partly based on the calculation structure of the ecoregion factor presented by Lindner et al. (2019) and enhanced with more recent datasets as well as parameters which are – to the current knowledge - likely to correlate with biodiversity. The biodiversity condition indicator (BCI) includes recent global estimates of share of forests and grasslands (based on Buchhorn et al., 2020), share of key biodiversity areas (BirdLife International 2022), degree of soil biodiversity (Serna-Chavez et al., 2013), share of roadless areas (Ibisch et al., 2016) and global extinction probability (Kuipers et al., 2019).

[1] The ecoregion factors presented by Lindner et al. (2019) are based on ecoregions provided by Olson et al. (2001). Dinerstein et al. (2017) provide an updated set of ecoregions which slightly differ from the ecoregions presented by Olson et al. (2001).

Management Parameter:	Unit:	Input:	Datasource:
A1.1: Number of weed species in cultivated area	[species/ha]	14	Estimated average based on farm specific input data
A1.2: Existence of rarer species	[% time]	2.6	Average based on farm specific input data
A2.1: Elements of structure in the area	[% area]	10	GIS-based assessment: Estimated by visual inspection of satellite data. Based on the analysis of a 90 km^2 size area in target region.
A2.2: Field size	[ha]	120.17	GIS-based assessment: Estimated by visual inspection of satellite data. Based on the analysis of field sizes of 20 agricultural fields in target region.
A3.1: Intensity of soil movement	[l/ha]	0.33	GIS-based assessment: Based on global tillage map (Porwollik et al. 2019), conservation agriculture, low soil movement intensity
A3.2: Ground uncovered	[% time]	16.6	Estimated based on cropping intensity map (Zhang et al. 2021) and literature values (e.g. Raucci et al. 2014)
A3.3: Crop rotation	[points]	6.5	Estimated based on cropping intensity map (Zhang et al. 2021) and literature values (e.g. Raucci et al. 2014)
A4.1: Intensity of fertilizing	[kg N/ha*a]	31.4	GIS-based assessment: Based on global fertilizer map (Lu & Tian 2017)
A5.1: Plant protection	[applications/a]	16	GIS-based assessment: Based on global pesticide use map (Maggi et al. 2020)

Table 2: Input parameters for GIS-based assessment

Results: Table 3 presents the updated ecoregion factor, the country and crop specific ecoregion factor and the biodiversity condition index for Brazil and the Cerrado ecoregion. The BCI rates Brazil and the Cerrado ecoregion higher than the updated ecoregion factors. The country and crop specific ecoregion factor for soy in Brazil lies in between these two.

Ecoregion/Country:	Updated ecoregion factor	Country and crop specific ecoregion factor (Soy)	Biodiversity condition index (BCI)
Cerrado	0.41504742	-	0.44466448
Brazil	0.35198955	0.36758222	0.4085642

Table 3: Ecoregion factor, crop specific ecoregion factor for soy and biodiversity condition index on country and ecoregion level

An excerpt of the results of the biodiversity impact assessment case study is presented in Table 4. Detailed results are provided in the supplementary. The methodology presented by Lindner et al. (2019) was applied using the updated ecoregion factors, the crop and country-specific ecoregion factors and the BCI for Brazil. Input parameters were based on the generic hemeroby assessment, the specific input parameters provided by three farms in Brazil (primary input data) and the GIS-based input parameters (see Table 2).

	Description	Global weighting	Biodiversity Impact [BVI*m2*a]
S1.2	Generic assessment based on hemeroby; low-to-medium intensity agriculture; hemeroby level: 4	Updated EF (country-area-weighted):	0.13736089
		Updated EF (country-crop-weighted):	0.1434458
		BCI (country-area-weighted):	0.15943866
S1.3	Generic assessment based on hemeroby; medium-to-high intensity agriculture; hemeroby level: 5	Updated EF (country-area-weighted)	0.27166623
		Updated EF (country-crop-weighted)	0.28370069
		BCI (country-area-weighted)	0.31533066
S2.4	Specific assessment. Averaged input data from three Brazilian farms	Updated EF (country-area-weighted)	0.20227822
		Updated EF (country-crop-weighted)	0.21123888
		BCI (country-area-weighted)	0.23479004

S3	Mixed approach, GIS-aided data acquisition	Updated EF (country-area-weighted)	0.23228796
		Updated EF (country-crop-weighted)	0.24257801
		BCI (country-area-weighted)	0.26962319

Table 4: Excerpt of results for the biodiversity impact assessment of one kilogram soy from Brazil

The results of the biodiversity impact assessment based on averaged primary input ranges between hemeroby level four and five which is equal to a medium intensity agriculture. When considering the typical Brazilian agriculture with a widespread no-tillage approach on the one hand and the intensive use of pesticides on the other hand, the results seem reasonable. With a biodiversity impact ranging between 0.20 and 0.23 BVI*m2*a per kilogram soy (depending on the underlying ecoregion factor/BCI) there is a tendency to intensive agriculture. This can mostly be traced back to the large average field sizes and the intensive use of pesticides. The results of the GIS-based assessment are more conservative with a slightly higher biodiversity impact ranging between 0.23 and 0.26 BVI*m2*a per kilogram soy, depending on the underlying ecoregion factor/BCI. The GIS-based estimates result in higher input values for fertilization and pesticide use. All other input values are similar to the averaged primary data.

Conclusion: The aim of this study was to simulate real-world LCIA application scenarios with different levels of data availability and to evaluate the applicability of global GIS-based datasets. A recently published biodiversity impact assessment method (Lindner et al., 2019) is applied in several scenarios. As a reference to the GIS-based impact assessment, Lindner et al. (2019) allow a generic impact assessment based on estimates of agricultural intensity and resulting hemeroby-levels besides the impact assessment based on primary input data.

This study shows that both the generic approach as well as the GIS-based approach provide reasonable biodiversity impact assessment results comparable to that when using primary input data received from on-site farms. The generic and GIS-based impact assessments are especially useful in situation where data availability is scarce.

The ecoregion factor presented by Lindner et al. (2019) was updated with a consideration of the updated ecoregions as reported by Dinerstein et al. (2017). To match the requirements of LCA-practitioners, the updated ecoregion factors were calculated on ecoregion and on country level using area-weighting as well as a crop specific production quantity weighting as presented by Mumm & Eberle (2022). For testing purposes, a novel biodiversity condition indicator (BCI) was developed and calculated on ecoregion and country level. The indicator aims - similar to the ecoregion factor in Lindner et al. (2019) - to put local biodiversity impacts in a global context. It considers recently developed datasets including soil biodiversity metrics and key biodiversity areas which are likely to correlate with biodiversity. However, a more extensive validation and test of the BCI has to be considered when aiming to use it in future LCIA studies.

The present paper shows that GIS-aided LCIA is possible and provides reasonable results. Furthermore, it provides guidance on how to assess biodiversity impacts in a case study with scarce data availability by enhancing and partly replacing primary data with globally available approximations. In doing so, the present work promotes biodiversity impact assessment among LCA-practitioners and supports a wide application in the global food-industry.

Further research on the development of global GIS-datasets and the integration of such data in LCIA can provide the LCA community with the ability to assess biodiversity impacts of products and processes when primary data is absent, or data quality is low.

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Application of the Life Cycle Analysis methodology including the lack of food safety in the Base Business Unit "Piscra"

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In this work, a study is carried out applying the methodology that combines the Life Cycle Analysis with Hazard Analysis and Critical Control Points proposed by Meneses (2017) to the UEB "Piscra" that markets Tench HG for export. In this way, the determination of the risks that the production and consumption of food represents to human health and the ecosystem is achieved, based on the international standards ISO 14040, ISO 14044 and NC 136, Once a diagnosis is carried out Environmental of the entity, the Life cycle inventory was created.
The functional unit, which is the base to which the calculations refer, is the annual production calculated as an average of the years 2018, 2019 and 2020, the value corresponds to 52.2 t of tench HG per year for export, represented 60% of the UEB's productions.
The work methodology is based on combining the HACCP and ACV methodologies; therefore the critical control points and the inventory table are determined considering all the inputs and outputs to the system.
Table 1 shows the identified control points and Table 2 shows the life cycle inventory.

Table 1 Determination of critical control points

Ingredient / Stage	Danger	**P1**	**P2**	**P3**	**P4**	**CCP**
Extraction and Capture	F: Presence of algae, grass, other branches and dirt.	SI	NO	No		NO
	M: Parasites or other pathogenic germs.	SI	NO	No		NO
Reception and weighing	F: Presence of algae, grass, other branches and dirt	SI	SI			SI
	M: Parasites or other pathogenic germs.	SI	NO	No		NO
Headless - gutted - washed	M: contamination with m. or pathogen or biotoxin	SI	SI			SI

Table 2 Inventory for the product system of the tench production process

INPUT	**Quantity**	**Unit**
Whole Tench	113.3526	t
Diesel	15057.44	L
Electricity	114824.67	Kwh
Lubricants	178	t
Water	4800	m3
polystyrene boxes	1500	kg
Cloro	350	L
OUPUT		

Tench HG export	52.142202	t
Solid waste (animal feed)	26.071101	t
fish by-products	35.13931	t
BOD	3600	mg
COD	13200	mg
Fats and oils	960	mg
Settleable solids	2400	mg
Total phosphorus	2400	mg

To calculate the impact associated with the categories related to the lack of food safety, the environmental mechanism for these categories is considered. The impacts of each contaminating substance whose presence in the food constitutes a danger and a risk to human health were obtained from the information of the critical control points. In this way, the potential lack of safety is defined for the midpoint impact categories: lack of food safety due to physical, chemical and microbiological hazards. The calculation of the potentials is individual according to the characterization factors reported by Meneses (2017)

The environmental profile is obtained through the Recipe midpoint methodology, including food safety, related to physical, chemical and microbiological hazards and it is observed in figure 1. As a result of the evaluation, it was observed that the greatest contribution to the impact categories is given by electricity consumption, in all categories except for the water consumption category and that the lack of food safety is dominated by microbiological risk.

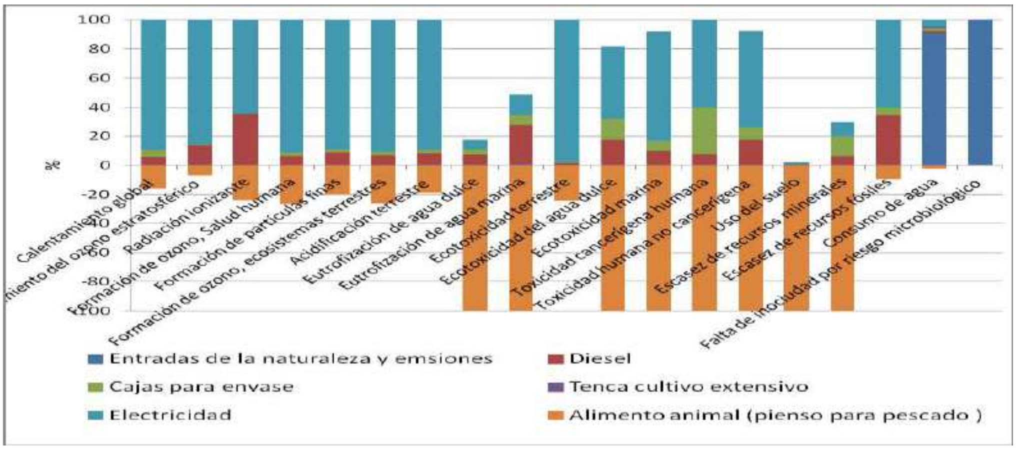

Figure 1. Enviromental profile

The life cycle analysis (LCA) methodology, including the categories of impact due to lack of food safety, makes it possible to carry out a more in-depth analysis of the impact of food, aspects that are excluded from the analysis when the traditional methodology is used.
Based on the results of this work, the Haacp plan is proposed to control microbiological danger and the management plan to contribute to the saving of energy carriers and water.

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How does LCA capture the environmental impacts of agroforestry systems? An illustrative case study

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Abstract

Rationale

Life Cycle Assessment (LCA) is a practical tool to quantify the environmental impacts of a product or system (Arvanitoyannis, 2008). Although LCA has been widely applied in agriculture (see e.g., Knudsen et al., 2019; Mogensen et al., 2014), the environmental quantification of Agroforestry Systems (AFS) in temperate latitudes requires further attention (García de Jalón et al., 2018). Despite the available evidence regarding AFS environmental benefits, effects can be heterogeneous (Torralba et al., 2016). This is because the integration of trees in agriculture interacts in complex ways. As such, the benefits and drawbacks of AFS could be argued as context-specific. At the farm level alone, many variables, components and (by)products can influence environmental estimations (van der Werf et al., 2020). Likewise, narrow methodological approaches (e.g., product-based functional units, system boundaries, and various allocation methods) can fail to capture the interplay of farm landscapes, agroecological principles and ecosystem services. In light of these methodological challenges, it is essential to reflect the dynamics of AFS in LCA more accurately. Broadening and improving the scope of analysis in LCA of AFS is, therefore, a priority.

Objective

This paper aims to conduct a literature review on LCA in AFS linked to agri-food products. This review is used as the basis for (i) evaluating to which degree the LCA methodology captures the benefits and drawbacks of AFS and (ii) demonstrating how methodological choices lead to different LCA results through an illustrative case study of a Danish farm. The primary and secondary research questions are:

- What evidence exists in processed-based LCA concerning the environmental impacts of AFS in agri-food systems?
- How can methodological choices affect the interpretation of AFS in processed-based LCA?

Methodology

The literature review was guided by protocols provided by Zumsteg et al. (2012) and Bilotta et al. (2014). Studies were extracted from online scientific libraries and academic databases, such as *Scopus*, *Science Direct, CABI Direct, AGRIS, MDPI* and *Web of Science*. The illustrative case study is based

on a real-world farm characterized by organic and agrosilvopastoral activities involving pigs, grass-clover and poplar trees in the western part of Denmark. The chosen farm was purposively sampled (Yin, 2009) due to its agroforestry profile, agri-food products, data availability and geographical accessibility. Primary and secondary farm and value chain data will be collected through field surveys, stakeholder interviews, and the scientific literature. Relevant environmental impacts (e.g., biodiversity loss potential) and important biophysical processes (e.g., carbon sequestration) will be analyzed using the LCA methodology from cradle-to-grave.

Expected results

The results of this paper will contribute to the field of LCA in two ways. First, it will guide scholars to the most recent LCA literature on AFS by summarizing and outlining critical methodological choices in agri-food systems. Second, it will provide an overview of trends, patterns, challenges, limitations and opportunities of AFS in the LCA literature as well as in all phases of the LCA through an illustrative case study of an agrosilvopastoral farm.

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Environmental performance of rainbow trout (*Oncorhynchus mykiss*) production in Galicia-Spain: A Life Cycle Assessment approach

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Extended abstract

The present study aimed to assess the environmental impacts in the production of rainbow trout in a medium-sized plant that produces ca. 1700 metric tons per year in Galicia (NW Spain) using Life Cycle Assessment (LCA) methodology. The novelty of the study is based on two perspectives. On the one hand, to the best of the authors' knowledge, this study is the first to analyze freshwater aquaculture systems in Galicia. On the other hand, it provides an analysis which aims at including the most recent methodological advances in aquaculture LCA, by computing, for instance, the environmental impacts linked to the use of antibiotics (including microbial resistance).

The study was carried out according to ISO 14040 and 14044 (ISO, 2006a, 2006b). The functional unit (FU) was 1 t of round fresh rainbow trout produced at the farm gate. The system boundary included activities from the hatching stage to the farm gate. Data used to model rainbow trout production were obtained directly from the company (reference year: 2017). The processes included aquafeed production, transport of chemicals and aquafeed, hatchery, fattening, fishing and slaughtering. Furthermore, these stages included the linked upstream processes, such as raw material production of aquafeed, antibiotics, chemotherapeutics, electricity and fuel, as well as the downstream processes linked to emissions to soil, water or air, as well as waste management.

The production input data for materials and energy were retrieved from the Ecoinvent v3.6 database. When inputs were not available in the aforementioned database, these were obtained from Agribalyse v3.0.1 and Agri-footprint v5.0 databases. However, given the lack of data on antibiotic production in LCA databases, the antibiotics used at the plant were modelled following the methodological scheme suggested by Stone et al. (2011).

Regarding the computation of Life Cycle Impact Assessment results, global warming potential (GWP) was estimated with the IPCC 2013 method (IPCC, 2013), whereas terrestrial acidification (TAP) and freshwater eutrophication (FEP) were computed using ReCiPe 2016 Midpoint (H) v1.1 (Huijbregts et al., 2017). The AWARE method was used to estimate water scarcity (WS). Freshwater ecotoxicity (Tox) was calculated using USEtox version 2.02 (Rosenbaum et al., 2008). Finally, the current study addressed the antibiotic use-related environmental impact assessment, through the recent proposed antibiotic resistance (ABR) enrichment characterization factors (CFs)

(PAF m^3 day kg^{-1}) (Nyberg et al., 2021).

In order to identify the key inputs in the environmental performance, as well as potential improvement opportunities, a sensitivity analysis was carried out. Firstly, the effect of feed conversion rate (FCR) changes (±10%) in environmental impacts was assessed. Secondly, sensitivity related to energy consumption was evaluated under two approaches. On the one hand, evaluating scenarios of better and worse energy efficiency than the baseline scenario (±20% of standard grid electricity consumption). On the other, the shift from grid electricity to alternative wind power was analyzed.

Table 1. Environmental impacts of 1 metric ton of fresh rainbow trout, and 1 metric ton of aquafeed produced in Galicia-Spain

Product	GWP (kg CO_2 eq)	TAP (kg SO_2 eq)	FEP (kg P eq)	WS (m^3)	Tox (PAF m^3)
Rainbow trout	1778.7	17.4	6.9	7081.3	14,330,101
Aquafeed	1271.6	14.2	0.2	6297.9	6,317,416

Table 1 shows the environmental profile of the production of 1 metric ton of fresh rainbow trout. From these results, the aquafeed stood out as the main contributor to most impact categories (i.e., GWP, TAP, WS and Tox), due upstream agricultural and fishing processes, whereas farm operation was responsible for the larger part of the impact in FEP, mainly due direct emissions of nutrients from fish feeding. Electricity is the second major contributor to GWP, TAP, and WS. Meanwhile, ABR enrichment impact added up to 12088 PAF m^3 day per metric ton of fresh rainbow trout, which was dominated by amoxicillin (84%). When the assessment is focused on aquafeed production, three feed ingredients dominated all environmental impact categories: krill oil, wheat and sunflower oil. Thus, krill oil was the main contributor to GWP, TAP, and Tox, whereas wheat and sunflower oil were the carrying ingredients in FEP and WS, respectively.

When comparing the results with the scientific literature, results for GWP, acidification potential and eutrophication Potential (based on CML Baseline method) of Galician rainbow trout were within the average ranges reported by previous studies (Avadí and Fréon, 2015; Chen et al., 2015; Dekamin et al., 2015; Maiolo et al., 2021; Samuel-Fitwi et al., 2013; Silvenius et al., 2017). Regardless of uncertainties linked to the use differing databases and assessment methods, which must be taken into consideration in further research, the main reasons for differences across the freshwater aquaculture LCA studies are linked to the diverse production systems used and their different FCR to produce the same FU, as also highlighted by the recent scientific review by Philis et al. (2019). Furthermore, the sensitivity analysis showed that FCR is a key parameter to improve the environmental performance of fresh rainbow trout production. Therefore, a variation of 10% in FCR triggered proportional variations in the assessed impact categories. Similarly, variations in electricity consumption (20%) produced slight variations in all impact categories. Meanwhile the substitution of grid electricity to wind power reduced impacts up to 20% in most impact categories.

In conclusion, results revealed that aquafeed production is the main driver of most environmental impacts of fresh rainbow trout, with the exception of freshwater eutrophication, which was dominated by farm operation. Moreover, there are opportunities to improve the environmental performance of this production system by improving FCR and shifting from grid electricity to wind power. Despite the relatively lower contribution of antibiotic production to all impact categories, new alternatives to antibiotic use could be investigated, in order to reduce the ABR enrichment impact linked with antibiotics release to freshwater bodies.

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Nuts evaluated on environmental, nutritional and social sustainability: a multi-criteria decision analysis

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Rationale and objective

Nuts are an important source of macro- and micronutrients. The EAT-Lancet Commission has recommended an intake of 25 g each of peanuts and tree nuts per capita and day for a Diet for Planetary Health (Willett et al., 2019). This would require a substantial increase in global production (Vanham et al., 2020). However, it can entail trade-offs. For example, the water footprints of groundnuts and other nuts as an aggregated food group are greater than other plant-based foods such as fruits and vegetables or legumes (Poore & Nemecek, 2018), although the water footprints of individual nut varieties vary greatly (Vanham et al., 2020). Despite nuts' importance for sustainable diets and the variability of nutritional attributes and impacts, nuts are usually studied as a single food group and just for a single dimension of sustainability. Especially social impacts are rarely assessed. Multi-criteria decision analysis can complement life cycle assessment and is particularly useful in contexts where performance must be evaluated across sustainability dimensions (Zanghelini et al., 2018). Using it to identify more sustainable nut types to meet the dietary recommendations can contribute to a sustainable diet transition.

Approach and methodology

Based on a multi-criteria decision analysis, we ranked ten nuts and seeds at a global level against environmental, nutritional, and social criteria (Cap et al., 2022). The nuts and seeds included almonds, Brazil nuts, cashews, chestnuts, groundnuts (peanuts), hazelnuts, pistachios, sesame seeds, sunflower seeds, and walnuts. The functional unit was 50 g raw (unroasted) shelled-equivalent product at the farm gate. Three environmental criteria included carbon, land stress, and water scarcity footprints; two nutritional criteria included a Nutrient-Rich Foods (NRF) index (Fulgoni III et al., 2009) and a dietary-dependent Nutritional Quality Index (NQI) (Sonesson et al., 2019), considering 35 and 16 nutrients; and six social criteria included child labor, forced labor, working poverty, labor rights, gender gap, and work safety, with data collected mostly from the International Labour Organization Department of Statistics (2020). Country-level indicators (all except for the NRF) were aggregated to global production-weighted averages (population-weighted, in the case of the NQI). After normalization, weights among criteria were defined statistically based on the standard deviation within indicators and correlation coefficient between indicators following the CRiteria Importance Through Inter-criteria Correlation (CRITIC) technique (Diakoulaki et al., 1995). Values were aggregated into a single score with the weighted geometric product as a partially non-compensatory method. Several sensitivity analyses tested various sources of uncertainty through the use of country-level input data, changes to criteria weights (including equal weights, alternative statistical weights, and multiple hypothetical stakeholder preferences), and the use of a fully compensatory aggregation method (linear weighted sum).

Main results and discussion

Walnuts and sunflower seeds performed consistently well across sustainability criteria. They ranked in the top two positions in the baseline assessment and most sensitivity analyses. In contrast, cashews performed relatively poorly and ranked last. Peanuts, as the currently most commonly consumed nuts, ranked in intermediate positions, being fourth in the baseline assessment and partly lower in the sensitivity analyses. Peanuts' performance was worse across social than environmental criteria. Dietary shifts towards more sustainable nuts, with supply matching the demand, could improve the overall environmental, nutritional, and social impacts of nut production and consumption by an average of 23% relative to current global weighted impacts. Only forced labor would slightly increase. Economic indicators, such as affordability and farmers' income, merit further exploration in an extension of the framework.

Conclusion

There is potential to improve the sustainability of nuts and seeds. Although consuming more walnuts and sunflower seeds and fewer cashews may lead to such improved sustainability outcomes, more research is needed to better understand the complex socio-economic factors influencing nut and seed sustainability. The developed multi-criteria decision analysis framework (Cap et al., 2022) and especially the social risk assessment method thereof can also inform future sustainability assessments for other food groups.

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Towards sustainable shea: applying social and environmental life cycle assessment to a shea value chain

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Introduction

Shea butter has traditionally been an important crop to the women of the sub-Sahara West Africa. Shea is popularly known as The Women's Crop because they are collected predominantly by women. In recent years shea has become an important raw ingredient in the cosmetic and confectionaries industry. Since the shea fruit is collected form the wild with very low to no input to the system they have been championed as an oil crop with low environmental impact to replace other more impactful oil crops. Not only is shea thought to have a low environmental impact but due to the strong correlation to women of the crop has been highlighted for its potential to offer a pathway to women empowerment in the shea region.
This study aims to address these environmental claims by providing a cradle-to-gate LCA of commercially produced shea stearin by Fuji Oil Ghana. Additionally, the social impacts of the value chain will also be assessed by providing a social LCA of the shea value chain in Ghana.

Methodology

This LCA was performed according to the standard methodology described in ISO 14040 series by the International Organization of Standardization. The LCA model was created in SimaPro version 9.3. The functional unit was 1 kg shea stearin. The scope of the LCA is cradle-to-gate, the boundaries are described in fig 1. ReCiPe was used as the impact assessment method.

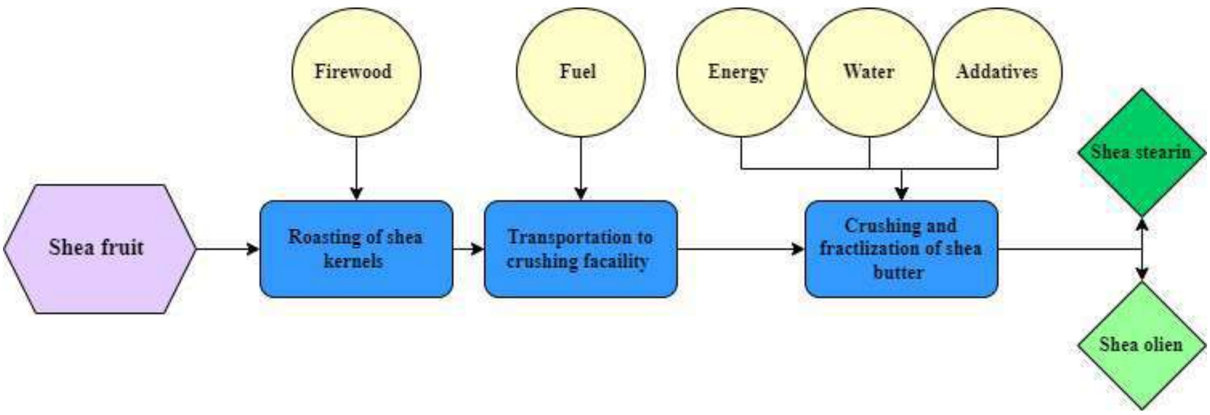

Figure 1. Shea value chain

Economic allocation is applied based on recommendation of the product environmental footprint guidelines (PEF) for the two coproducts of the system. The LCA includes the impact categories

global warming potential, particulate matter, land use change, eutrophication, acidification and water consumption.
The social LCA follows the methodology of the Product Social Impact Assessment (PSIA) handbook. Stakeholders and impact categories reported were based on a hotspot analysis conducted in accordance with the PSIA methodology. Data was collected from the field view interviews and surveys with a wide group of stakeholders.

Results and discussion

Throughout the value chain the most impactful stage of the stearin production for many of the impact categories was the crushing and fractalization. While for land use change category the roasting of the shea at the villages caused the largest impact due to firewood use.
The social impact assessment revealed that current projects in place with in the shea supply chain are having desired effected don women empowerment and trading relationships with in the small scall entrepreneurs stakeholder group. Due to systemic issues in the region regarding health and safety and basic needs these categories showed there is room for improvement. Within the workers stakeholder group issue around health and safety and remuneration were highlighted and need further investigation.

Conclusion

In conclusion the main drivers of environmental impact of shea are related to firewood use and processing of the kernel at the facility. Biogenic carbon presents an interesting conundrum in this system with the majority of CO_2 emissions coming from burning firewood. Therefore, the majority of the impact in the GWP categories welcome from the energy required for shea butter processing. The impact of firewood use can be seen in the land use change category.
The SLCA revealed the positive impact of the current social projects Fuji Oil has created or is participating in. It also highlighted areas that need to further address in the value chain and potential areas of improvement. With the two combined studies a full picture of the current sustainably status of this value chain was able to be established.

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Aligning companies in carbon reduction targets setting and planning; Chile wine industry case study

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The Science Based Targets initiative (SBTi) is a powerful influence for companies across all industries and countries for setting and committing to carbon reduction targets aligned to the climate science. The initiative provides guidance, methodologies, and practical support such as calculators, amongst others that are relevant for companies in this commitment process. To date, there are more than 2,000 companies committed and more than 1,000 with targets set.

With the focus largely being on reducing dependence on fossil fuels for energy, often underplayed is that globally, agriculture, forestry, and other land uses (AFOLU) is responsible for about 25% of global emissions, with approximately half from agriculture (Roe, et al., 2019). Within this segment, Chile is the 4th wine exporter country in the world and the 1st in the "new world" (ODEPA, 2017). This industry has been working firmly over the past 11 years in addressing sustainability, mainly led by the Wine trade Association "Wines of Chile" through their Sustainability Code of the Chilean Wine Industry. With the motivation to continue working in sustainability and the understanding of the global climate emergency, Wines of Chile recognized the need to address this in a science-based manner and as an industry.

Viña Concha y Toro was the first winery in Latin America and the first company in Chile to commit to Science Based Targets initiative. With the support of Edge Environment (EDGE), they developed quantifiable plans to reach these carbon reduction targets. Viña Concha y Toro and EDGE, with the intention of scaling the work and creating higher impact, proposed to "Wines of Chile" to develop a national project with the whole industry to motivate and guide each one of the companies in the target reduction setting and action planning development, which was well received and begun in 2020.

The objective of this project was to create a simple tool for the Chilean wine industry to set carbon reduction targets based on science and to evaluate in a flexible and adaptable manner, the reduction potential of specific initiatives and their costs to develop action plans for each company.
It was defined to have an open project that allow all wineries in Chile to join at any time. Currently, there are 16 companies participating which represent more than 60% of Chilean wine exports. These companies are: Viña Concha y Toro, Viña Montes, Viña Aresti, Viña Los Vascos, Viña Antinori, VSPT Wine Group, Viña Casa Silva, Viña Emiliana, Viña Requingua, Viña Cono Sur, Viña Santa Rita, Viña Polkura, Viña Luis Felipe Edwards, Viña La Rosa, Viña Almaviva and Indomita Wine Company Chile (IWCC).

The first stage of the project was alignment and harmonization of carbon footprinting. Companies were categorized according to their carbon footprinting past calculations; 50% not measured, 13% only scope 1 and 2, 6% measured more than 2 years ago, 19% scope 1, 2 and 3 not verified and 13% scope 1, 2 and 3, by a third party, aligned with GHG Protocol, audited, or validated. This way different paths were defined for each one. For those wineries that the footprint was incomplete, not updated or not verified, carbon footprint was measured following GHG Protocol Corporate Accounting and Reporting Standard guidelines. The calculation considered scope 1 (stationary and mobile fuel combustion, fugitive emissions, soil emissions (from management and use of fertilizers), direct emissions from waste treatment on site), scope 2 (purchase of electricity) and scope 3 (purchased good and services, capital goods, upstream and downstream transportation, waste generated in operations, business travel, end of life treatment of sold products).
An MS Excel data collection tool was developed specific for this industry; training was provided individually to use them and understand the relevant impact scopes and categories, and then the footprints were calculated in a harmonized and comparable way.

The second stage of the project had as an objective to develop individual plans from a shared basis. A workshop with companies was held to identify initiatives to reduce their footprints where the result was a list of 16 different actions, with the following having more traction; solar panels, purchase of renewable energy through PPAs, lighter glass bottles, change of refrigerants, change of packaging, electromobility and change of fertilizers. A calculator adapted to each company was developed, which allows wineries to compare their Business-as-Usual scenario with Science Based Targets trajectories and to create their own modifiable path incorporating the previously identified actions; since these be activated or disactivated, changing the year in which the action could be implemented, and modifying reduction potential. The tool developed also includes marginal abatement cost curves (MACC) which aim to generate an implementation pathway to companies, also modifiable in cost according to the reality of each winery. This would show companies the most cost-effective way to reach targets over time.

The final stage of the Project considers the commitment and target setting with the Science Based Targets Initiative. Now, 25% of the companies are in process of committing, 31% are committed and 19% of them have targets. In addition to this, some companies are already motivating their suppliers to commit as well, extending the impact of the initiative.

This case study represents a real example where companies of a same industry can work together, creating synergies and sharing knowledge that accelerates the transition to decarbonization in a specific industry. It also creates scale economies in individual costs of consultancy for calculations and plan development and generates comparative and competitive advantage for a national industry through positioning and recognition (from SBTi).
The next challenge is how to replicate and scale this case study in other industries and countries, so companies can work together and achieve relevant impact reductions that make a difference.

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Water scarcity footprint of a forest area in north-central Portugal

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The water footprint (WF) is a tool based on life cycle assessment (LCA) with the purpose to inform decision-makers, governmental or non-governmental organizations of their potential environmental impacts related to water use. The WF gives insights on how these impacts can be reduced (e.g. for the purpose of strategic planning, priority setting, product or process design, decisions about investment of resources) and is also a communication tool from business-to-business and business-to-consumer.

Agricultural and forestry activities are potentially water-intensive users and polluters (Haddeland et al. 2012, Page et al. 2011). The water scarcity footprint assesses the spatially differentiated impacts of water flows such as (evapo-)transpiration (ET) -green water ET (from rain) and blue water ET (from aquifer, freshwater lakes and aquifers)-, surface runoff, and aquifer recharge) is particularly relevant for forest products.

This study is devoted to improving the green water scarcity footprint (WSF) tool when applied to forests, in order to contribute to make this tool more robust for supporting decision making processes related with water management issues. The case study of eucalypt forest in Portugal was selected for calculating the WSF because of the relevance of this species in Portugal and the controversy existing in the Portuguese society about the role of eucalypt in water consumption. The eucalypt occupation area has been increasing since the late 1970s and currently represents the largest forest area in Portugal (26%) (ICNF 2015). Eucalypt is an exotic fast-growing tree that is often pointed out by society due to its high-water consumption and impact on water availability for maintaining ecosystem functions. However, the scientific evidence for this simplistic point of view is scarce and contradictory, as this is in fact a complex issue that depends on many factors related with climate, geology, soil as well as forest stand characteristics.

The study area is the Ermida river basin, located in north-central Portugal, which is predominantly covered by rainfed eucalypt plantations. The climate of the study area can be classified as humid mesothermal, with moderate but prolonged warm dry summers. According to the climate normals (1971-2000) the annual average temperature was of 10ºC and mean rainfall ranging from 34 mm (July) to 252 mm (December) from the nearest climate station (41°49'N, 7°47'W at 1005 m above sea level) (IPMA 2021).

Soil and Water Assessment Tool (SWAT) was applied to the Ermida river basin for simulating hydrological parameters. SWAT is a conceptual, time-continuous and semi-distributed hydrologic model developed to predict changes in landscape management practices on water, and chemical yields, while it also explicitly accounts for climate change (Neitsch et al. 2011). SWAT outputs are spatially and temporally differentiated and include water flows such as ET.

The typical WF structure proposed by the ISO 14046 standard was applied to calculate the WSF of Ermida river basin. A gate-to-gate approach was applied, i.e. only the green water used by the stand was consider, and the functional unit was defined as $m^3.ha^{-1}.yr^{-1}$.

The inventory analysis consists in the compilation of water flows spatially and temporally differentiated using geographic information system (GIS). In this sense, ET comes from SWAT simulations over 10 years of eucalypt forest management (one rotation). The consumption of green water in land use, per se, does not necessarily lead to a reduction in surface water contributing to water scarcity. Indeed, the potential impacts on water availability depend clearly on local land-use and land cover changes, and on the natural vegetation that is replaced. Therefore, effective ET was calculated based on the ET modelled by SWAT minus the ET of natural vegetation that would replace eucalypt forest in absence of anthropogenic interventions. However, the characterization of natural vegetation and the calculation of green ET from natural vegetation is still a handicap and a limitation at the inventory level, that hampers a wider application of the WSF of agriculture/forest systems. In this study, the effective green ET was obtained by the ET of actual vegetation minus the green ET of a past time period (climate normal).

In the impact assessment, the WSF was assessed by multiplying the characterisation factors developed by Quinteiro et al. (2019) (ranging from 0.01 to 1) at 9x9 km spatial resolution by the inventory data (effective green ET). The WSF results were presented in spatially differentiated maps of easy interpretation for all the stakeholders, highlighting the sub-catchments where measures to overcome the inefficient water use and its shortage should be developed and adopted.

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Comparing the global warming impact of frozen and alternative supply chains

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With a growing attention to sustainable food systems, retailers and consumers start asking questions about the sustainability of frozen supply chains. Frozen products require more electricity for storage than its chilled or jarred/canned alternatives. At the same time, frozen products have a lower food waste due to the low-perishable nature of frozen food. In this study we analyze these trade-offs and determine if there are significant differences between frozen and non-frozen food products in terms of environmental impact.

This is done by comparing 22 frozen food products with their alternatives (equivalent products using other preservation methods). These alternatives can be chilled or ambient (e.g. jars and cans). The food products are from different food categories: fish, plant-based protein and vegetables. The study is done together with a large frozen food manufacturer that provided us with primary data on the frozen supply chains. To select the alternative product to compare the frozen to, a streamlined and transparent approach was followed. To ensure that differences in environmental impact between the frozen food product and its alternative stem solely from the preservation method and not from other factors, the ingredient composition, processing efficiencies, ingredient distribution route, and location of consumption remains constant. More specifically, the most notable differences between the frozen products and their alternatives will be inherent differences in the product processing, temperature of transport vehicles, the storage processes and food loss and waste. This is done to take a conservative approach to the differences between frozen and alternative products, meaning that it removes potential benefits of frozen products resulting from for example centralized large scale processing and the ability for ingredients to be available year-round. Any differences will be solely due to the frozen/non-frozen supply chain

The products are compared based on the functional unit of three portions (since an average OECD household consists of 2.6 people (OECD, 2009)). The portion size given by the frozen food company is assumed to also apply for the non-frozen food product. This study mainly focuses on global warming potential (kg CO_2 eq) but other impact categories are analyzed to ensure there are no significant other trade-offs. The impact assessment used to analyze these impact categories is the EF method 3.0, from the most recent version of the Product Environmental Footprint (PEF) method (Zampori and Pant, 2019). This impact assessment method is assembled by the European Commission as a result of a consensus process based on the state-of-the art science per impact category. Due to their subjective and uncertain nature, no normalization, grouping or cross-category weighting has been applied. The study is executed confirm ISO 14040/44: 2006 (ISO, 2006a, 2006b) and externally reviewed by a review panel.

The results and corresponding interpretation steps provide insight in factors that influence the results of the comparison between the frozen and non-frozen food product. In general, we conclude that there are four main factors that determine whether the carbon footprint of a frozen product is higher or lower than that of an alternative, when the carbon footprint of the production phase are assumed to be identical. These factors are not necessarily main contributors to the total impact, but they are the main source of difference between the frozen and non-frozen products. The four factors identified are:

- The electricity mix used by retail and consumer. An energy mix with a lower carbon footprint per kWh is beneficial for frozen products. The products included in this study use the average country electricity mix in the country of consumption. Over time, these mixes are expected to move in the direction of lower carbon footprint, thereby moving in favor of the frozen product.
- The number of days the consumer stores the frozen product in their freezer. A shorter freezer storage time is beneficial for frozen products. It is unclear if the 30 days of frozen storage assumed in this study is an accurate representation of reality. However, as the carbon footprint of electricity mixes becomes lower, the sensitivity to the frozen storage days becomes less significant.
- The amount of food loss and waste at retail and consumer. If the food loss and waste of the alternative product is higher than that of the frozen product, whether this is due to high perishability, low turnover or something else, the carbon footprint of the frozen product is more likely to be favorable.
- The inherent carbon footprint of the product itself. If the production of the product (i.e. the ingredients cultivation and processing) has a higher carbon footprint, the greenhouse gas emissions associated with food loss and waste of that product will also be higher than that of products with a lower carbon footprint for its production. This is mainly due to extra production needed to compensate for the food loss and waste. Therefore, a change in the food loss and waste percentage of products with a relatively high production carbon footprint will have a larger absolute effect than the same change for a product with a relatively low production carbon footprint. So for the products with a relatively high production carbon footprint, smaller differences in the food loss and waste between a frozen and non-frozen product can make a significant difference.

Keeping these factors in mind, the results of this study show that when it comes to carbon footprint, there is no general advantage or disadvantage to using frozen food products compared to products using alternative preservation methods. However, it does support the hypothesis that when food loss and waste rates in the retail and consumer stages are lower for a frozen product compared to a non-frozen alternative, this may compensate for the additional energy use caused by a frozen supply chain when looking at carbon footprint.

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Front-of-pack LCA-labelling for food products: finding the balance between scalability and precision

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Background

Front-of-pack LCA-labelling for food products is essential to aid the transition to a more sustainable food system through 1) providing reliable information on which consumers can make informed sustainable purchasing decisions and 2) incentivizing food producers to reduce the impacts of their products. It is the responsibility of specialists in the food sector, alongside LCA practitioners and sustainability experts to ensure that these labels are sufficiently reliable and robust to be an effective tool for systemic change. Quantifying product environmental footprints with LCA is highly complex, and dependent on an array of factors and intricacies, making conducting an ISO- (ISO, 2006b, 2006a, 2013) or PEF-compliant (Zampori & Pant, 2019) LCA a large time and cost investment. If the product is within scope of a PEFCR, the results enable consumers to compare a product against a benchmark with the assurance of robustness. However, until PEFCRs are developed to cover more of the food sector, and the process is accessible for widespread application (i.e. through a tool), alternative labelling systems are being adopted. A simplified LCA-label is a great solution to enable consumers to make informed purchasing decisions. However, as the overarching goal is to direct consumers towards truly more sustainable products, and reduce the environmental impact of the food system, we must be sure that the labels which direct these decisions are concrete and robust.

A number of labels are emerging as a solution which puts pressure on food producers to participate and add an LCA-based label to their products. Two of these emergent labels are Eco-Score by ADEME (ADEME, 2021) and Eco-Impact by Foundation Earth (Foundation Earth, 2021). This research aims to critically assess the potential of Eco-Score or Eco-Impact being the appropriate LCA-labeling solutions for the food sector. Based on this assessment, key characteristics for an effective LCA-labelling system for food products are proposed which could be applied to future labels coming to market.

Method

This research critically assessed the Eco-Score and Eco-Impact methodologies, requiring a different approach for both. The Eco-Score of a product can be calculated by oneself independently. Therefore, to critically assess Eco-Score, publicly available data was collated and analyzed, using some case study food products to understand the methodology.
The Eco-Impact of a product needs to be calculated by submitting primary data to Mondra (Mondra, 2021) who conducts the product LCAs, which are then used as the basis for the Eco-Impact score assigned by Foundation Earth. To understand and assess the methodology, we collaborated with a large frozen food producer to go through the process required to calculate an Eco-Impact label for five different food products. Throughout this pilot case study experience, conversations with

Mondra and Foundation Earth filled in the knowledge gaps which were not addressed by publicly available data.
In parallel, a framework which outlines the key aspects essential for a credible LCA food labelling system was created which could be used as a starting point to assess future labelling initiatives to occur.

Results
To calculate the Eco-Score of a product, the methodology considers two aspects: the LCA score and bonus/penalty points based on additional criteria. The cradle-to-grave LCA score is based upon a value from a secondary dataset and does not include any primary data. To calculate the Eco-Impact of a product, primary data is used alongside reputable secondary sources to form a high-quality cradle-to-gate LCA. For an initial overview of the differences, refer to Table 1.

Table 1. Overview of a few main characteristics of the two labelling methodologies compared to a PEFCR

	Eco-Score	**Eco-Impact**	**PEFCR**
System boundaries	Cradle-to-grave	Cradle to retail door	Cradle-to-grave
Background database	AGRIBALYSE (Asselin-Balençon et al., 2020)	HESTIA database for cultivation (Hestia, 2021) Other LCI databases for other parts of the value chain	Environmental Footprint (EF) dat abase (Zampori & Pant, 2019)
Impact categories included	EF 14x impact categories are combined to a "single score"	Climate change, water scarcity, Eutrophication and Biodiversity loss from land use	EF impact categories (Zampori & Pant, 2019)
Impact assessment method	EF 3.0 (Zampori & Pant, 2019)	Selected set of characterization models and weighting by Foundation Earth Advisory Board	EF IA (most recent version available) (Zampori & Pant, 2019)
Use of primary data	Close to none	High	High and targeted at the most important processes
Appropriate for product-to-product comparisons?	No. Only for comparison between product categories	Yes	Yes

Discussion
Critical assessment of Eco-Score:
Whilst Eco-Score offers a very fast, cheap and scalable option, its oversimplification of footprinting makes product-to-product comparison greatly imprecise, and its widespread adoption would not effectively meet the goals of LCA-labelling.

Critical assessment of Eco-Impact:
Until Eco-Impact covers the full product life cycle and a more holistic range of impact categories, it is not sufficiently suitable for the overarching goal. Excluding the consumer stage most notably ignores one of the largest issues the sector faces: food waste at the consumer. If we want to truly reduce our impact, this should be included in the LCA-labelling system to incentivize targeted sustainability efforts. The diversity of food products requires a holistic approach to capture the array of environmental impacts on the environment to incentivize all sustainability efforts and avoid blindly walking into environmental trade-offs.

Practical experience from a company:
Doing this research alongside a large food producer revealed additional issues in the practical

application of these labels. For instance, when calculating the Eco-Score label, there is limited opportunity to customize for their specific value chain or product characteristics, or for sustainability efforts to be reflected in the score. Dissimilarly, for Eco-Impact, a very high annual cost is required to renew the label which makes it inaccessible to SMEs and creates a "lock-in" for the company.

Suggested criteria for an effective food LCA-labelling system:
To ensure consumers are provided with reliable environmental information, an LCA labelling system should meet certain criteria. These are suggested as (in hierarchical order): (1) Based on a science-based cradle-to-grave methodology 3rd party verified with regular open consultations, including regionalization throughout the value chain to capture influential location-specific differences (2) Use primary data for processes directly controlled and those identified as environmental impact hotspots (3) Covering at least all impact categories proven to be most relevant for the product type. Additionally, the LCA labelling should be in a format that facilitates sustainable purchasing decisions (e.g. QR codes for further insights, and grading that is scientifically valid yet meaningful for consumers).

Conclusions

Labels formed based on PEFCRs meet the criteria, however until they cover all food product categories and use scalable solutions, alternative LCA-labelling systems are being adopted. Eco-Score and Eco-Impact labels do not yet accurately represent the cradle-to-grave footprint of the actual product itself or facilitate genuine product-to-product comparisons. Not only does this provide an inadequate base for consumers to base purchasing decisions on, but it also prevents most optimally achieving the goals of an LCA-labelling system: reducing the environmental impact of the food sector. Until PEFCRs are ready for adoption, or a mature LCA-labelling system is fit for market, stakeholders should collaborate to ensure environmental footprinting of food products is done right instead of rushing into an immature system.

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Estimating environmental and cost impacts of utilizing printed intelligence in approaches maintaining microbiological food safety

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Hazardous elements in foods can be physical, including foreign objects such as glass, chemical, e.g., toxic compounds, or microbiological, including foodborne pathogens. In maintaining high biological food hygiene by preventing health hazards, such as microbes in foodstuffs, food safety protocols are in important role.

In the European Union, the microbiological requirements for food are defined in the Commission Regulation Microbiological criteria for foodstuffs. While authorities guide, control and check the food hygiene plans of the operators for their compliance to food hygiene legislation, food business operators are responsible for ensuring the safety of the foodstuffs they are producing [(EC) No 2073/2005)].

Different protocols are followed by food business operators, by which the food safety is ensured. While the existing good practices are found to provide the adequate food safety, novel measures are being developed. One part of this development is digitalisation and digital technology development, which will be in the scope of the PrintoFood project. In this project, the printed intelligence and structural electronics based technological solutions will be developed to improve the safety and efficiency but also sustainability in the food chain. The project is bringing together expertise from research and development, design, manufacturing, and operational testing to develop products relevant for food safety and self-sufficiency improvement.

The objective of the study is to develop a printed intelligence based structural element to ensure the demanded food hygiene level. The disinfection is to be based on visible, violet-blue 380-430 nm light. Especially the 405 nm light has been proven to harness strong antimicrobial activity (Maclean et al. 2014). The selected case in this study is a fresh fish display counter, which is typically disinfected daily after use. While the violet-blue light has been proven to have antimicrobial characteristics, the intensity of light is in key role. Here, the aim is to develop system, which provides amplified light intensity resulting in more time-efficient process for daily disinfection. Amplification is introduced by utilization of photoactive materials. The efficiency of the selected developed systems is tested by measuring the microbial growth inhibition under each treatment. To provide information and knowledge for food safety use of the developed system, the selected microbes in testing include typical, harmful food borne pathogens *Escherichia coli* and *Listeria monocytogenes*.

Life cycle assessment is to be utilized to measure the environmental and cost efficiency of the developed systems in parallel to existing good hygiene practices of food safety. In few studies food related sanitation methods have been studied for their environmental impacts (e.g. Eide et al. 2003, Vigil et al. 2020). Here the cost analysis together with environmental impact assessment will provide new insights. According to França et al. (2021) in only few food chain related studies LCA and LCC have been conducted in parallel.

Even if a major part of the environmental and cost impacts of the food chain are known to be generated in the primary production, or in the early stages of the life cycle, the food safety protocols are in important role in keeping the required hygiene level of the products. This is a major factor in e.g., reducing food waste and decreasing the environmental and cost impacts caused by food losses and food waste. The project will be analysing the impacts of the selected cases from the food chain, by utilizing a hygiene requirement -based functional unit. The inventory data is to be collected for the lab scale system, adjusted for the actual operational scale. LCA and LCC databases such as Ecoinvent are to be utilized for the assessment to provide secondary data for components and detergents (Wernet et al. 2016). Parallel assessments are conducted for the existing and the methods developed by the PrintoFood project.

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To what extent do food imports and their origin affect the environmental impact of the Swiss agricultural sector?

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Introduction

Trade is one of the main factors affecting a country's environmental footprint (de Boer et al. 2019, Tukker et al. 2016, Steen-Olsen et al. 2012). In the EU food sector, the environmental impact could be reduced by 24% to 47% if the origin of imports were optimized towards the countries with environmental friendly production (de Boer et al., 2019). We found similar results for Switzerland in various studies on the environmental impact of the Swiss food system (Bystricky et al. 2017, Zimmermann et al. 2017, Bystricky et al. 2020). Food imports account for a significant share of the environmental impacts of the Swiss basket of food products. As one way to improve this, we proposed a shift of food imports to countries where food production has lower environmental impacts. In this contribution, we answer the following questions:

- How does the environmental impact per kilogram of food change depending on the country of production and
- To what extent is the environmental impact of the Swiss basket of food products affected when food is imported from countries where it is produced environmentally friendly?

Methods

To test the impact of different import origins on the overall LCA results of the food sector, we used two scenarios from Bystricky et al. (2020) that describe the development of the Swiss agricultural sector including imports under different agricultural policies until 2025.

To limit the number of import products to be analyzed, we selected four impact categories and identified the food and feed items that account for the least favorable 25% of each of these environmental impacts (Table 1). For these food products, we retrieved life cycle inventories (LCI) from LCI databases (ecoinvent, World Food LCA Database, SALCA, AGRIBALYSE) and compared them based on their respective environmental impact per kilogram.

Table 1: Imported food and feed products investigated

Milk
Beef
Pork
Maize
Maize gluten
Soybean oil and meal
Pomaceous fruit

For comparison, we also conducted a literature review to identify parameters that explain the differences in the environmental impact of foods from different origins.

The scenarios for the Swiss agricultural sector were adjusted accordingly: we replaced food items from Table 1 from countries with high environmental impacts with the same food items from countries with more environmentally friendly production and analyzed the overall effect. We optimized the scenarios based on four impact categories, namely biodiversity (species loss potential), water scarcity, freshwater ecotoxicity and global warming potential, and did a full LCA with a comprehensive set of LCIA indicators for all four optimizations.

Results and discussion

The optimization of the scenarios according to the origin of food imports resulted in a reduction of impacts for all impact categories considered. The highest reduction potential was found for freshwater ecotoxicity and species loss potential (both -27%) followed by water scarcity (-19%) and global warming potential (-4%). Optimizing food and feed imports based on the four impact categories mentioned above had no unfavorable and in some cases even favorable effects on other impact categories (deforestation was reduced by up to 46%). The transport of food and feed has only a minor effect on the overall environmental impact of the scenarios (max 4%).

Biodiversity loss is linked to species endangerment, which depends on the world region where a food or feed item is produced. In addition, the intensity of production system influences species loss. The impact on water scarcity is also highly dependent on origin, as irrigation varies greatly between regions. The freshwater ecotoxicity impact of food production depends on the pesticide legislation of the country of origin and the type and intensity of the production system. Comparatively high levels of freshwater ecotoxicity were found for food and feed items from countries where the use of certain toxic pesticides is permitted. Global warming was less influenced by different import origins. Land use change, emissions from animal husbandry, production intensity and the use of concentrate feed were the main contributors here.

An additional point of discussion is the system boundary considered. If the focus lies on the importing country only, the environmental impact of its food system can be improved by shifting import countries. However, a shift of imports to countries with a lower environmental footprint could mean that in the global trade market, other countries could end up with the less favorable products, and there might be no overall positive effect globally.

Conclusions

The optimization of import origins in the scenarios was shown to have a considerable effect on reducing the environmental impact of the Swiss food sector. The production system and intensity, the geographical location and the country-specific legislation were identified as the most important parameters driving differences in the environmental impacts of imported food and feed from different countries of origin.

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Eco-design pathways in spirit distillation – case of semi-continuous distillation

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In the world, lots of alcoholic liquids obtained after fruits' fermentation are distilled to obtain higher alcohol concentration drinks (brandy, pisco, calvados, kirsch, etc.). Different technologies of distillation exist such as simple distillation, fractional distillation, continuous and semi-continuous distillation.

In metropolitan France, the main spirits obtained from fruits after distillation are produced from grape (or wine and grape-cake), apple (or cider), pear, cherry, raspberry, Mirabelle or plum. An important part of them is produced under Protected Designation of Origin (PDO) with specifications. Most of the PDOs' specifications (MMA, 2015; 2021) impose the use of copper for pot still as well as period of distillation. Most of the distilleries producing PDO spirits use gas combustion to distillate and semi-continuous distillation process.

During the semi-continuous distillation, the obtained vapours need to be cooled to obtain the alcohol. Cooling agent is water (tap water, rainwater, …) and may be used in open or closed circuit. According to the French regulation concerning the classified facilities for the environmental protection, the capacity of production of each site allows or not to use an open cooling circuit:

- Upper than 50 hL of pure alcohol, the closed cooling circuit is imposed. These sites use then refrigeration units to cool the water. Most of the professional distillers are in this case.
- Lower than 50 hL, the distilleries may use open cooling circuit and can reject used water if their temperature is lower than 30°C. Most of the grower-distillers are in this case.

The objectives of this work are to assess the environmental impacts of two alternatives concerning semi-continuous distillation process and to explore the interest of different eco-design pathways to reduce distillation impacts.

Life Cycle Assessment (LCA) is done in SimaPro software with EcoInvent V3.6 and Agribalyse V3 databases and ReCiPe 2016 (H) method. LCA based on average data obtained by survey or expert data is done on both systems. The functional unit is "produce 1hL of pure alcohol". The limits of the studied systems go from the arrival of the alcoholic juice to the obtention, after the double distillation, of alcohol with an alcoholic degree between 65 % et 72,4 % without aging. The used data are the consumption of water, gas, electricity, and the production of the pot still.

For open cooling circuit (Fig. 1, O), the hotspots are the gas combustion and the manufacture of pot still. Electricity consumption has only a significate impact on ionizing radiations. For closed cooling circuit (Fig. 1, C), the hotspots are the gas and electricity consumption and the manufacture of pot still. Wastewater treatment has significate impacts on freshwater (53%) and marine eutrophication (94%). For each system, the manufacturing of the pot still is an important contributor while the infrastructures are often absent from the modelling of products in LCA.

As the use of a closed cooling circuit consumes much more electricity due to refrigerating system,

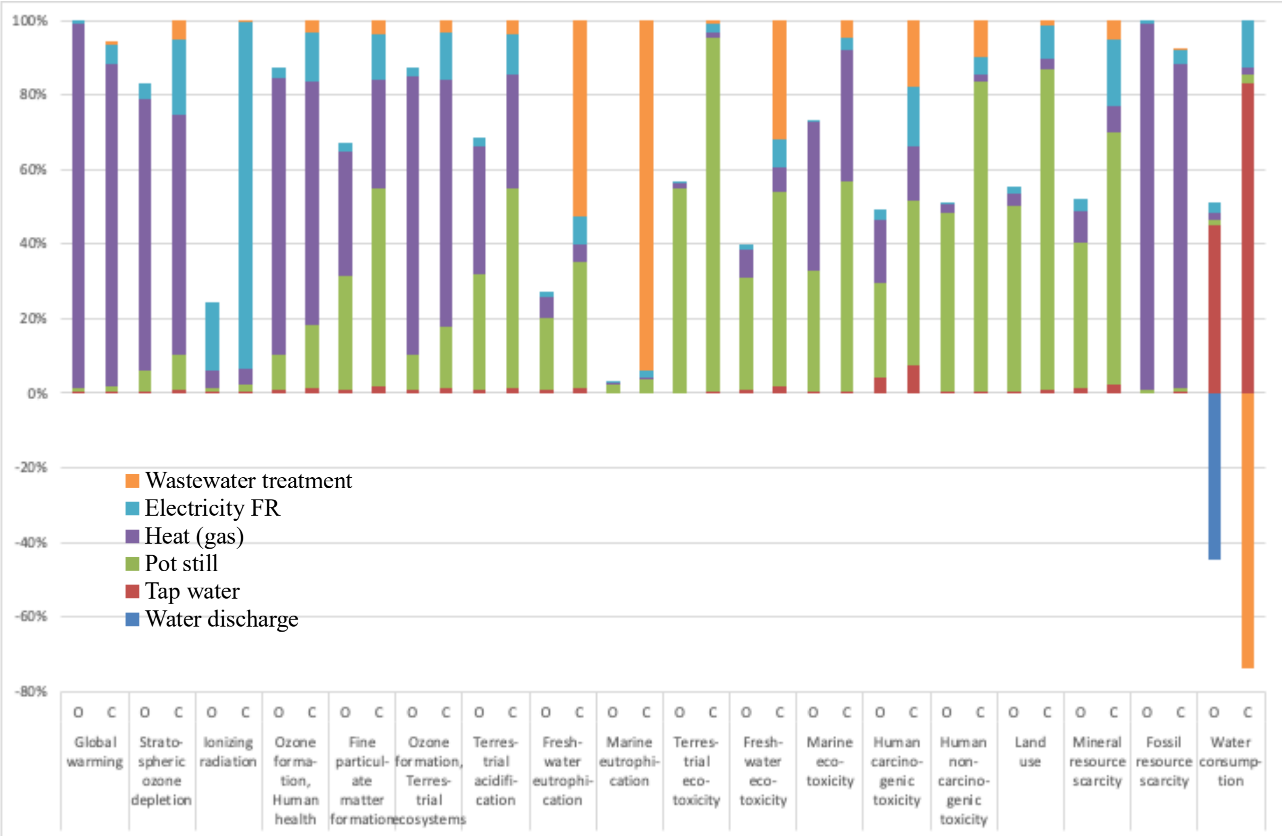

Figure 1: Comparison of impacts of 1 hL of pure alcohol produced with discontinuous distillation with an open (O) or a closed (C) cooling circuit.

the impacts of the closed cooling circuit are often more important than the open cooling circuit.
As part of the data were difficult to obtain, a comparison of the impacts of these two alternatives is done with the literature data (Jolibert, 2016; Vasquez-Rowe et al., 2017) to validate the obtained results. The distillation of brandy in France proposed by Jolibert (2016) in Agribalyse V3 and analysed with ReCiPe 2016 (H) has much lower impacts (-19% to -94%) than those obtained with the present data. Among the explanations for these differences, there are the consideration of the manufacture of the still in this study and the lower energy consumption in the study by Jolibert (2016).
Different eco-design tracks are possible while remaining within the requirements of the specifications of the appellations, which impose the use of semi-continuous distillation. For example, the combustion optimisation, reuse of the heat, valorisation of the heat are some possibilities. The combustion optimisation is possible by changing the boiler burner or the combustible. The reuse of the heat of the cooling circuit is an interesting track. Some distillers have already begun to improve their energetic performance. Almost all distillation sites already reuse a part of their heat:

- to preheat the alcoholic liquid before distillation to reduce their gas consumption.
- to heat the water used to wash the boiler between two distillations and avoid the temperature drop of the equipment.

Some of the distillers have developed ingenious solutions to reuse the heat of the cooling circuit water such as home or green house heating. The potential of different valorisations of the heat contained into the cooling circuit must be assessed. To reduce the impacts of the manufacturing of the still, maintenance operations seem more than necessary to prolong its lifespan.
The results of this LCA on distillation and the requests of the French low carbon strategy led to identify the hotspots of this process, the interest of some eco-design tracks and the need of a dedicated tool to do streamlined LCA for distilleries.

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Environmental efficiency of bean preparation in restaurants and households

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Keywords: *beans, life cycle assessment, environmental impact*

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Abstract

New habits and lifestyles are gradually changing the way of life for many people around the world (MICHAEL, 2013). The consumption of food outside the home has been growing significantly and the demand for food with less environmental impact has also increased, motivated by the greater environmental awareness of consumers, mainly due to climate change (MENDES, 2010). Considering these new eating habits and the search for processes that cause less impact on the environment, the initial objective of this project was to evaluate the environmental efficiency of the stages of preparing beans in restaurants. However, with the closure of many restaurants during the pandemic, this study was extended to households The methodology used was that of Life Cycle Assessment, in a gate-to-gate approach, that is, focused on the actual stage of meal preparation. Data were collected through interviews and visits to nine restaurants and eight households located in the city of São Paulo. A large difference was observed in the average energy consumption between restaurants (2.7 MJ/kg of raw beans) and households (10.6 MJ/kg of raw beans). The differences obtained in the survey clearly point to a better environmental performance of the meal prepared outside the home, mainly due to the scale effect, with a lower energy consumption. The study contributes to the diffusion and importance of Life Cycle Assessment - LCA as a framework to analyze the food preparation.

Objective

This article is part of a project that aims to evaluate the environmental efficiency of the preparing meals stages in the restaurants and at home. In particular, results obtained in the preparation of beans in these establishments are shown.

Methodology

The study is based on ISO 14040 (2006) Environmental management - Life cycle assessment - Principles and framework, and the data survey follows a gate-to-gate approach. A detailed questionnaire was developed in order to identify the methods employed and inputs /outputs resulted from each meal proceeding. The questionnaire included information such as the type of pan used, type of stove, preparation method, cooking time, etc. During the visits, the following inputs were measured: raw ingredients, the gas consumption by stoves, quantities of ready-to-eat beans, as well as leftovers resulting from Balances were used for determining the masses of each input. The time of cooking was also registered.

Main Results and discussion

A large difference was observed in the average energy consumption between restaurants (2.7 MJ/kg of raw beans) and households (10.6 MJ/kg of raw beans), the latter being about 4 times higher than the former. The emission of greenhouse gases follows the same proportion: 46.7CO_2eq in restaurants and 187.5CO_2eq in restaurants.Part of this high difference is due to differences in the weight ratios of beans and water used, as the energy expenditure is due to the need to heat the whole set. Thus, the more water used per kg of raw beans, the greater the demand for cooking energy, a fact perhaps unnoticed by most handlers.

Table 1: Main parameters of the bean cooking process in restaurants and households. Functional Unit: (parameter/ kg of raw beans)

	Restaurants			Households		
Parameter	Average (*)	Min - Max	CV%	Average (#)	Min - Max	CV%
Input						
Raw Bean (kg)	1.00	1.00 – 1.00	0.0	1.00	1.00 – 1.00	0.0
Water (kg)	4.07	3.33 – 5.09	14.4	4.88	3.69 – 6.49	19.8
Energy consumption (MJ)	2.67	1.59 – 3.79	22.2	10.62	5.32 – 16.16	42.0
Output						
Cooked Beans (kg)	2.39	1.92 – 3.02	17.1	2.66	2.06 – 3.03	12.0
CO_2 eq (Kg)	46.7	25.3 – 67.5	25.0	187.5	94.9 – 288.0	43.3

(, #) = average of 9 and 8 samples*

Conclusion

The results obtained allowed the collection of several important data related to the preparation of beans. Meal preparation in restaurants is more efficient than at home in many ways. The average energy consumption in households per kilogram of beans is about 4.0 times higher than the average consumption measured in restaurants, probably due to a scale-up effect. It was observed that the bean/water ratios significantly influence energy consumption and that it is possible to optimize them, given the great variability between them.

The study presented here was restricted only to the food preparation stage, although it is known that transport costs for the purchase of food, whether in restaurants or at home, are also likely to have a significant impact. These data may be added in future studies, and were not included here, so that the food processing step could be highlighted.

Acknowledgments

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FLUI project: extrusion systems for the production of biofunctional flexible films applied to food packaging from lignocellulosic residues

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Keywords: Bioplastics, LCA, lignocellulosic biomass, food waste, bioactive compounds, engineering technology development

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Rational: The use of biodegradable packaging developed from polymers of renewable origin, such as PLA, is a key option for the reduction of environmental pollution caused by the disposal of non-biodegradable packaging (Halal, 2014). Likewise, in order to improve the quality and also the shelf life of packaged products, reducing food waste, more and more biodegradable plastic flexible films are used in packaging. Among the biodegradable polymers, the ones that have attracted the most attention are those obtained from renewable sources, due to the lower environmental impact caused. Although the production costs are higher than those of conventional polymers, biodegradable biopolymers have been the subject of extensive research and evaluation (Martelli et al., 2014). PLA is considered safe for human health and is stable, which allows it to be safely used for food packaging. In addition, its production is considered economically viable (Oliveira and Borges, 2020) and is a good candidate for replacement of PET. Several studies have been conducted in order to improve the performance of PLA in sustainable packaging applications.

Objective: The FLUI project's main goal is the development of a new bio-PLA extrusion equipment, disruptive for its capacity of extrusion and simultaneous incorporation of bioactive compounds. Represents a modular way, for the production of functionalized flexible films (FLUI systems) applied in food packaging and with innovation vision and application range for high and low moisture contents and a more sustainable end of life of flexible films with lower environmental impacts. These new biofunctional and biodegradable flexible films will extend the shelf life of packaged products by reducing food waste, contributing to the goals and action plans for the Circular Economy, and at the same time, by being produced from bio-PLA will contribute to reducing the consumption of fossil-based plastics and non-biodegradable and use renewable raw materials, and in particular by-products and waste from agro-forestry activities that do not compete with the food sector.

Approach and methodology: The project is centred on three major axes: i) disruptive engineering technology development - development of a new equipment (FLUI) for simultaneous extrusion of bio-PLA and integration of bioactive extracts for the production of flexible biofunctional films for food packaging; ii) Valorisation of lignocellulosic resource and a new packaging safe and sustainable design composed of biofunctional and biodegradable flexible films for efficient food preservation with extended food shelf life; iii) Life Cycle Assessment - Reducing Environmental Impacts in the holistic life cycle perspective of flexible films.

Results and discussion: As results of the FLUI project the following is expected: i) Development of the first prototype system for PLA extrusion and simultaneous incorporation of bioactive extracts to produce biofunctional films for food packaging. This prototype system will consist of a disruptive innovative solution for the production of biofunctional PLA flexible film; ii) Development of new packaging that is entirely biodegradable and biofunctional thanks to the use of PLA (of organic origin) and the integration of bioactive extracts (from agri-food waste). The packaging will be in accordance with current standards, ensuring the safety and sustainable of packaged food products. In a strategic vision of valorisation of regional food products from the Interior Region of Portugal and utilization of lignocellulosic biomass generated by forest and marginal land, it is proposed to use this biomass for the production of lactic acid (PLA intermediate); iii) In a perspective of life cycle thinking, the new equipment to be developed presents itself as extremely innovative since it allows the production of flexible films and biofunctional films (FLUI Films) for food packaging with the following characteristics: a) Development of flexible films through lignocellulosic biomass residues; b) incorporation of bioactive compounds, through agro-food waste that enable the increase of shelf life of food and the reduction of food waste; iii) Reduction of environmental impacts associated with flexible films (80% compared to fossil-based solutions and 50% compared to PLA based on food waste). For this purpose, a holistic LCA study will be developed.

Conclusions: The present project will enable the transition to the market of innovative and disruptive equipment with the solutions present in the market (TRL6) for the production of biofunctional flexible films intended for the production of food packaging. The equipment to be developed will allow the extrusion of biodegradable polymer of biological origin in parallel for the production of films and the integration of bioactive extracts. The developments of these prototypes will be accompanied by the investigation of the production of PLA from agro-industrial residues, as well as the identification, characterization and integration of bioactive extracts resistant to the extrusion temperature of the PLA matrix, at different stages of the extrusion process. The development of these prototypes will be supported by an efficient ecodesign model in order to maximize their economic and environmental impact compared to those currently available on the market.

Acknowledgments

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Participant recruitment and retention in a Life Cycle Assessment study: Recruiting Canadian organic farmers during COVID-19

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Introduction

Participant recruitment is a significant challenge when pursuing research (Blanton et al., 2006; Pencokofer et al., 2011; Leavens et al., 2019). However, recruiting and retaining an appropriate number of participants is vital for study generalizability and validity (Visovsky & Morrison-Beed, 2012). A brief review of the literature concerning participant recruitment and retention shows several health-centric studies (e.g., how to recruit and retain participants for clinical trials). While some techniques from the health field may be transferable, there is a gap in the strategies and challenges of recruiting and retaining participants from the agricultural community. The limited research on participant recruitment is particularly evident for life cycle assessment (LCA) studies where primary data collection surveys can be long and detailed. Here we report on an in-depth analysis of participant recruitment and retention efforts in support of an agricultural-sector LCA study undertaken during the COVID-19 pandemic. Specifically, we sought to:

i) Understand the opportunities and challenges that exist in recruiting farmers for survey participation during a global pandemic.
ii) Examine the methods used to recruit farmers for participation in addition to method successes and limitations.
iii) Consider factors contributing to low participant recruitment and retention and provide strategies to increase participation in future studies.

Methods

Currently, no formal database of organic farmers (the target of our study) exists in Canada. A list of potential participants was created through Google searches, contacting national and provincial agricultural organizations, and asking other farmers for potential leads. Initial recruitment of identified farmers was undertaken using publicly available contact information, such as e-mail, phone number, or website contact forms. Upon initial contact, the research purpose was described and farmers were invited to participate in a survey that would take between one to three hours, depending on ease of data recall, and size of farm operation. Survey sections included: farm location, operation and rotation details; inputs to nutrient and plant protect measures, field operations, post-harvest operations; and an optional farmer demographics questionnaire. Due to pandemic restrictions on travel and in-person meetings, surveys could be completed online via the digital survey instrument, REDCap, or in hardcopy, distributed by mail. Participants could also complete the survey with a researcher through a video chat or phone call. As pandemic restrictions eased, participants were offered in-person meetings to help fill out the survey.

Initially, farmers were not offered remuneration. Several months into participant recruitment, a lack of farmer engagement prompted a change to offering $50 cash remuneration to participants who submitted a complete survey for each crop grown. Remuneration was also provided to participants who completed surveys before the compensation was announced.

Contact with potential participant farmers was attempted a maximum of three times. Following a first unsuccessful contact attempt, a second, and then a third contact attempt was made after observing two-week waiting periods between attempts. Potential participants contacted via phone were left a voicemail if that option was available. Farmers who answered 'maybe' to participating in the survey were only contacted again if they requested a follow-up at a later date. Farmers who agreed to participate were provided a version of the survey in their chosen mode.

Results and Conclusion

The success of many research projects hinges on the successful recruitment and retention of participants. LCA studies necessitate strong participant engagement for robust data and accurate results. Overall, 683 potential participants were identified and contacted to participate in our study. Despite repeated attempts to make initial contact with farmers, multiple modes of survey form offered, and compensation provided upon survey completion, only 50 complete survey responses (7.3%) were received. Potential factors contributing to our low final recruitment include pandemic-related restrictions which limited opportunities to interact in-person. It could also have resulted from survey fatigue as many farmers reported completing similar surveys around the same time. Finally, the length and detail required of an LCA-centric survey also potentially deterred some potential participants. However, a majority of farmers who submitted complete surveys were those who had the opportunity to speak to a researcher on the phone, had organized and readily-available data, and expressed a genuine interest in the outcomes of the project. Regardless, there are several important things to consider when recruiting farmers for an LCA study:

1. Introduce remuneration at the beginning of recruitment. Although remuneration was not a significant factor for many willing participants, not introducing it initially may have excluded potential participants.
2. Disclose the amount of time and effort for survey completion. Potential participants will be less likely to open and leave the survey blank if they know the duration prior to starting.
3. Allow for multiple survey methods. Most participants opted for the digital version, but several requested a hardcopy or a walk-through with a researcher. The variety of options allows for increased accessibility and survey completions.
4. If available, reach participants by phone throughout the recruitment process

When recruiting participants in a post-pandemic world, particularly farmers, it is necessary to consider their needs and adjust accordingly. Some participants may still prefer an in-person visit or a survey in the mail in an increasingly digital world. Furthermore, it is essential to contact more participants than necessary to account for the many who will ultimately opt out. Studies will have a higher response potential by being flexible and having prepared survey recruiters.

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Articulation of sustainable livestock value chain in the district of Campo Verde - Ucayali

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Abstract

In Peru, agro-livestock sector represents about 6% of the GDP, which contributes to our country's economic development; even during the pandemic stage, in an economic recession, the agro-livestock sector continued growing. However, it is a bipolar growth, since the big company has improved its technology, productive system, and articulation of the supply chain, which enabled great profits and a differentiated competitive advantage; the situation presented by small companies or rural communities shows deficiencies in their productive systems and low technological level, obtaining profits that, frequently, are lower than their costs.

Purpose. Improve production levels through animal characterization, allowing the articulation of added value in bovine derivative products to generate competitiveness in the dimensions of social sustainability (community growth), environmental sustainability (resource planning) and economic sustainability (poverty reduction).

Methods. To strengthen the livestock value chain, it is necessary to identify and characterize the way of life and the environment where livestock farmers work and live. For this purpose, the main tool used is the livelihoods framework (analysis of the five capitals).

Results and discussion. Therefore, it is necessary to strengthen agro-livestock development in rural areas, which will improve rural people' quality of life and align with the Sustainable Development Goals (SDGs) such as poverty reduction, zero hunger, decent work and economic growth. The purpose of this research is to map livestock processes, identify the actors that make up the sustainable livestock value chain, characterize their living environment in order to articulate rural communities' work with markets, supported by government entities and private companies. It also proposes a production system that reduces environmental impact by analyzing carbon footprint.

Conclusions. The proposal will increase the income level of Campo Verde's farmers by 15% and reduce livestock operations' carbon footprint by 13%.

Keywords: *Livelihoods in Livestock Farming; Characterization of Campo Verde's bull; SDGs contribution*

Introduction

According to the UN (2022), by the year 2030, we will be around 8,500 million people worldwide. Which means a considerable challenge for food security; in this scenario, agriculture and animal breeding are the pillars for sensitive and critical development. The development of humanity in its evolution has depended on livestock products since, at least the emergence of agriculture, as it is a major source of nutrients. Livestock activitie is of vital importance to the economies of developing countries, where food insecurity is an endemic concern listed in the goals of the 2030 agenda (FAO, 2018).

In addition, there are concerns about the reduction of the labor force in both, livestock and agriculture, because it has been predicted that urban areas will continue growing at an accelerated rate, representing 70% of the world's population in 2050 (compared to 49% today), the result would be an increasing food demand (consumption in urban areas) and a decreasing supply (limited production in rural areas). Therefore, in reference to the Sustainable Development Goals, the non-planned future will have a significant impact on Sustainable Development Goals 1 and 2, SDG 1 - poverty reduction and SDG 2 - zero hunger. This means that we need to focus on projects to improve these sectors' current conditions. In addition, there is evidence that a growth percentage of GDP originated by the agribusiness and livestock sector will have double impact compared to other sectors (FAO, 2009).
In industrialized countries, livestock farming comes from large cattle ranchers who own thousands of head of cattle; a

very different scenario is livestock farming in Latin American countries, where production is centered on family and rural livestock, representing a source of basic foods that contribute to the food security of their population, thus the economy of the countries in the region; which represents economic opportunities and a reduction in poverty levels. However, this growth must guarantee the preservation of the environment. According to FAO data, livestock farming contributes 46% of the Agricultural Gross Domestic Product and has grown at an annual rate of 3.7%, which is higher than the growth of other sectors (Agronews Castilla y León, 2022).

In Peru, livestock farming, like agriculture, presents a schizophrenic behavior. On the one hand, a large company that applies engineering in its development and obtains a competitive advantage; and on the other hand, family and rural livestock farming that presents a precarious development, and seeks to subsist economically. According to MIDAGRI reports, livestock development varies considerably among the different regions of the country, and is composed of: a) Commercial livestock: Performed on the coast, characterized by modern cattle breeding; b) Small and medium livestock: Performed on the coast, highlands and jungle of the country, characterized by the predominance of small dairy farmers, c) Livestock with subsistence production: Also performed on the three regions, characterized by having few heads of cattle (Blog Perú, 2022).

The Ucayali region has made significant economic gains over the past 12 years through the production of fresh milk. A small proportion of fresh milk is marketed in government social programs such as the "vaso de leche" (glass of milk) in the city of Pucallpa (Villacorta, Rios, & Vela, 2014). However, in the case of raising bulls for meat, there is still an industry that does not add value in finished products; it does not classify types of meat, and does not process by-products.

Material and methods

Livestock farming is one of the most important economic activities developed by the peruvian rural population; it represents approximately 40% of the Gross Value of Agricultural Production (Ministerio de Agricultura, 2017). This activity is performed in the 3 regions, in each of those, with a specific characterization based on the climate, natural resources and system they use to breed their animals.

In the case of the livestock raising performed in Campo Verde - Ucayali, it is called extensive since it is mostly focused on forage grazing feeding. This type of farming has low productivity indicators and a poor environmental performance because of the low-quality single crop used (Messer and Townsley, 2003). In Ucayali, as in the rest of the country, the producers are divided in two types depending on the animal raised: a) Fattening cattle: The herd only includes bulls. The farmer feeds and cares for his animals until they reach the desired weight in the market (between 500 and 600 kg); then, they are sold in local markets, to "commission agents" that transfer them to Lima and local slaughterhouses and b) Breeding cattle: The herd consists mainly of cows and one or two bulls (the stallions), the main purpose is to reproduce for selling the weaned animals. Some farmers also use the milk for direct selling or artisanal processing derivatives as cheese, yogurt and others.

Human Capital

In Campo Verde, 68.7% of the economically active population is dedicated to agriculture, livestock, hunting and forestry (Municipalidad de Campo Verde, 2016). In 2018, between 8.2% and 15.1% of the population lived in poverty or extreme poverty (Instituto Nacional de Estadística e Informática, 2018). Despite the lack of attention to the agricultural sector, it has grown in recent years; however, one of its major shortcomings is the lack of training in species and pasture management, commercialization, derivatives production and other topics.

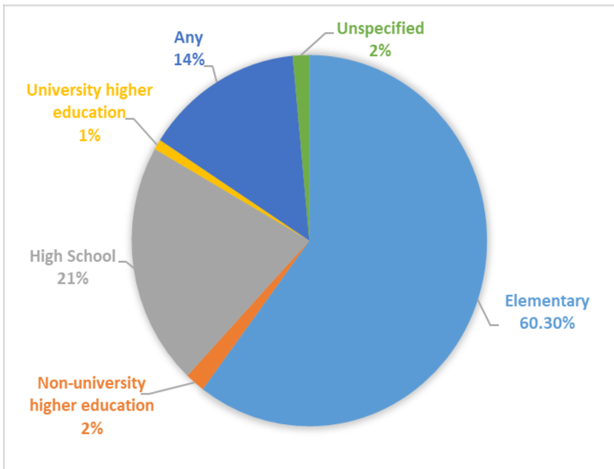

Figure 1 - Educational level of individual producers (INEI, 2012)

In families dedicated to farming and raising animals, it is the father who is in charge of making decisions and working with the animals; his older children support him when they reach enough age. In terms of health indicators, in 2022, 31.8% of children aged 6 to 59 months who received care in health centers were anemic (Ministerio de Salud, 2022). The 2017 census shows that 68.3% of the population in Ucayali is going to an education center; the illiteracy rate in the region amounts to 4,6% (Instituto Nacional de Estadística e Informática, 2017).

Natural Capital

One of the most important components of livestock production is feeding; in the case of Campo Verde, it is based on the natural pastures and balanced feed, mineral sales or commercial concentrates as complements depending on the accessibility and price. Most farmers divide their land into paddocks and rotate the animals so that they can consume the grass in certain areas while the others recover, this is a technique that has been passed generation through generation and sometimes it leads to overutilization of the areas because they are not estimating the animals' forage need (some of them have more animals than their land capacity) or the time they need to recover used areas (they move the animals through the corrals before time).

Figure 2– Natural pastures Campo Verde, Ucayali

Social Capital

In 2016, Campo Verde town hall reported only one breeders association; most of the producers are informal; which reduces their opportunity to access financial help. More than 97% are individual producers; 1.1% have constituted a "formal society" and 1.1% are native communities. The first two, despite the fact that they represent 98.5% of the producers, they drive 18.7% of the land; native communities own more than 76% of the land extension (INEI, 2012).

Financial Capital

Around 86% of the producers in the region ignore the function of the Rural Saving and Credit entities as institutions dedicated to finance agricultural loans (INEI, 2012). According to a report from MINAGRI (2020), only 9% of the farmers in Ucayali had access to credits; they used the money to improve their breeding and cultivation process, balanced feed, medicines and animals. The main entities that offer facilities to livestock farmers for access to loans are the town hall (Municipal savings), EDPYMES, Rural Saving and AGROBANCO, a nacional entity focused on loans to agriculture and livestock. In 2017, only 8.7% of the livestock producers applied for a credit and 10.5% of them were financed by the national entity, AGROBANCO.

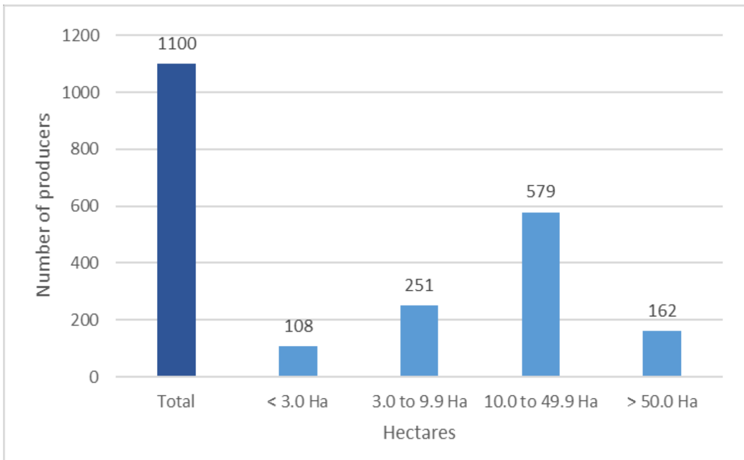

Figure 3 - Agricultural producers who obtained a loan according to agricultural units in 2012 (INEI, 2012)

Physical Capital

Most of the breeding areas are located around the village of Campo Verde and the Federico Basadre highway; to access, it is necessary to use the roads that are very damaged by the heavy rains in that zone. Road conditions complicate the transportation of animals because, at certain times of the year, it is impossible to access by truck or vehicle, so producers must move their animals on foot, they use horses to facilitate the task, to where they can be loaded onto trucks. Producers have some working tools such as cultivators or spray backpacks to take care of the pastures and the animals. They also use small logs to build the corrals they use to feed the animals, vaccination, and selection.

Figure 4 – Livestock in Campo Verde, Ucayali

In the case of the breeding cattle activity, in Campo Verde - Ucayali, the producers take care of the animals until they reach enough weight to be sold on the markets, between 500 and 600 kg depending on the animal's breed. Small producers would normally sell their animals to comissionists or near "Weighing scales" that group a larger number of animals and then take them to the local markets or slaughterhouse. While alive, the animal price is calculated using the current fee (S/./kg that which varies depending on the season and offer), the animals' weight would be divided in parts and each of those would have a specific price into the market. As mentioned before, the target weight for an adult bull is around 600kg; the 50% is most valuable part, approximately 300 kg of beef and bones; 33kg (10-105%) correspond to the leather; 12kg (1.9%) is the offal, which includes the heart, liver, kidney and lung; 10kg (3.2%) would be meet fat; 10kg (3.3%) would be the belly, tripes, spleens and feets; the bull head would be between 10 to 15kg (1.6%); the rest (30%) would be waste that includes blood, water and feces.

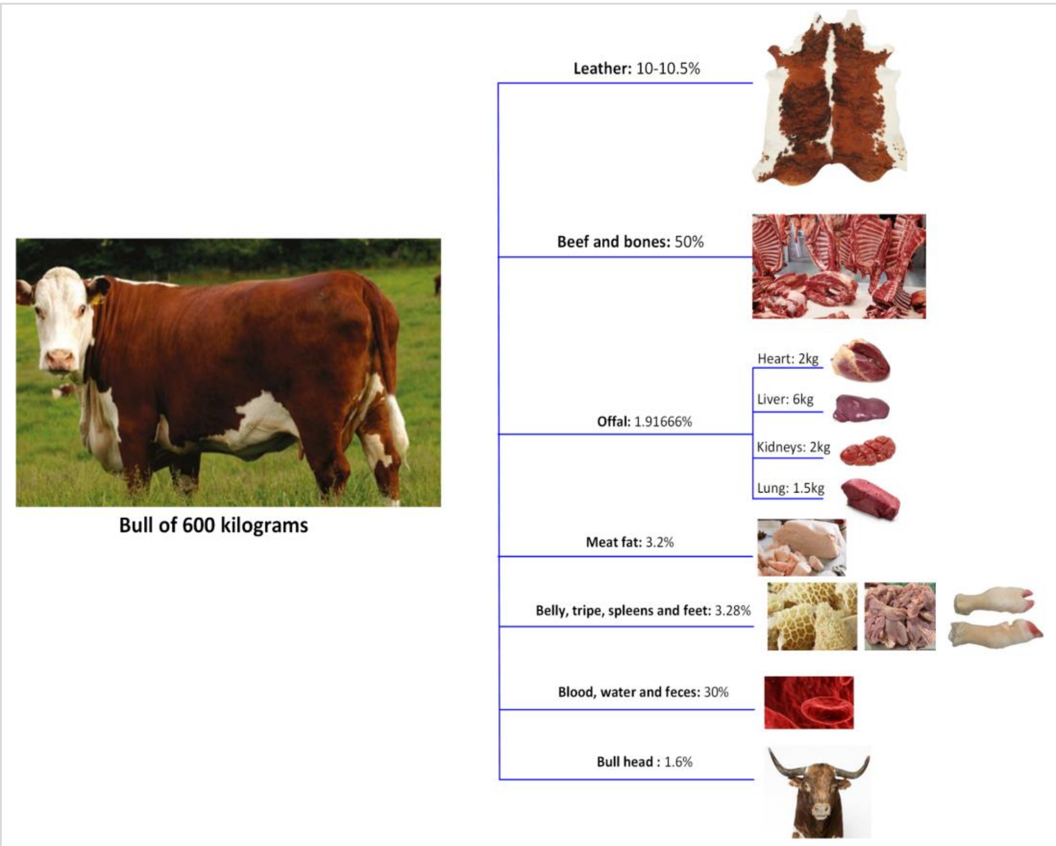

Figure 5 - Proportion of product derived from bulls in adulthood

Results and conclusions

The characterization of the raw material has allowed us to take better advantage of the products derived from the slaughter of the bull; for example, it has improved the utilization of the meat in its different cuts for consumption. Having a better meat process through Lean Manufacturing tools will allow a improved utilization of the meat, from the usual 50% to 56%; this will significantly impact the monetary income of the cattle raising families, along with the strategies to generate complementary products such as the elaboration of artisanal tanneries, will increase the family income by about 21.5%, allowing the strengthening of the sustainable development objective of the company. Also, better processing and waste minimization is reflected in a lower impact of the carbon footprint, which after conducting the inventory and using the ecoinvent database, a reduction of about 13% of the carbon footprint in CO2 equivalent could be observed.

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