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Environmental impact of integrating legumes into European food systems

Porto Costa, Marcela

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Environmental impact of integrating legumes into European food systems

A thesis by:

Marcela Porto Costa

Submitted to the College of Environmental Sciences and Engineering, Bangor University
for the degree of Doctor of Philosophy in Environmental Sciences.

April, 2022

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Funding:

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Thesis Abstract

Food is essential to humankind. By 2050 the world's population will be around 10 billion people. Providing food in an affordable, nutritional, accessible, and sustainable way is an immediate challenge that will persist for the next decades. However current food systems threaten both environmental sustainability and human health. Europeans overconsume energy and protein rich foods, but still lack essential nutrients such as fibre, leading to diseases such as obesity. Introducing legumes into European food systems is proposed as a solution, potentially contributing towards healthy and sustainable diet transitions. Legumes fix nitrogen from the atmosphere, provide fertilisation to the following crop and contribute to lowering the environmental burdens of agricultural systems. Concomitantly, legume grains are able to replace the protein intake currently met by livestock products, whilst promoting balanced nutrition for better health.

Many academics have explored the benefits of legumes based on evaluation of the environmental, or carbon, footprints of legume alternatives to traditional systems, using Life Cycle Assessment (LCA). However, this evidence is fragmented across scientific studies, particularly those that evaluate one aspect of sustainability or one stage of the value chain, lacking an integrated analysis with appropriate scenarios to support effective decision-making. This research therefore reviews the current state-of-the-art LCA for agricultural systems and proposes a novel approach to account for legume-modified rotations for the delivery of human and livestock nutrition within three different European agro-climatic zones. Furthermore, this research evaluates the environmental consequences of substituting food items on a dietary level, linking legume production within (legume-modified) rotations via economic modelling, and considering potential displacement ('leakage') effects using a consequential LCA framework. This research discusses different types of LCA approaches to assess legume food systems in Europe, highlighting the pros and cons of each type and recommending when each type should be applied.

Results show that current LCA approaches face many challenges in accurately accounting for the environmental and nutritional impact of food systems within a sustainable food transition context. These are urgent challenges which need to be addressed. Applying an appropriate LCA approach, framed in an appropriate context, is imperative to inform stakeholders on how to effectively engage with a successful transition to a sustainable agri-food system. On a farm level, the introduction of grain legumes into conventional cereal and oilseed rotations was found to deliver human and animal nutrition at lower environmental cost for most of the 16 impact categories studied across three agro-climatic zones. The novel nutritional functional unit proposed here to aggregate rotation-level outputs improves interpretation of agricultural system LCA, and should be applied more often.

Regarding substitution of food items on a dietary level, consequential LCA was applied to analyse the replacement of meatballs by pea protein, showing environmental advantages in most impact categories evaluated, with a greenhouse gas emissions saving of 2.4 kg CO_2e per 100 g serving, and up to 7.3 kg CO_2e per 100 g serving if spared land is afforested (rather than diverted to other food production). Environmental problems related to nutrient leakage such as acidification and eutrophication are also mitigated. However, unless accompanied by a large reduction in beef consumption, the substitution of cow milk with soy-based milk did not lead to significant GHG mitigation, excluding land sparing effects. This is due to the displacement

of dairy-beef production to less efficient suckler-beef systems. Nonetheless, this ‘leakage’ could be avoided if meat demand is reduced. Furthermore, afforestation on spared grassland could make the substitution of dairy milk with soymilk environmentally advantageous.

In aggregate, this thesis demonstrates that legumes have a central role to play within diet transitions and food system transformation in Europe, contributing towards the realisation of the sustainable EAT-Lancet diet proposed by Willett et al. (2019). Diet change through enhanced legume consumption can support considerable land sparing, livestock emission avoidance and synthetic fertiliser displacement, and can lower environmental burdens regarding climate change and acidification. The largest environmental savings can be achieved when meat is replaced and there is coordination of the production and consumption value chains. Thus, to help to deliver climate neutrality, legume protein should be incentivised to substitute animal protein, alongside a land use strategy that promotes afforestation.

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Abbreviations

ADP: Abiotic Depletion Potential
AN: Ammonium Nitrate
aLCA: Attributional Life Cycle Assessment
AP: Acidification Potential
CAN: Calcium Ammonium Nitrate
CED: Cumulative Energy Demand
CH_4: Methane
COC: carbon opportunity costs
CU: Cereal Unit
cLCA: Consequential Life Cycle Assessment
CO_2: Carbon dioxide
DVprot: Recommended daily value intake of protein
DVfib: Recommended daily value intake of fibre
DE: Digestible Energy
DM: Dry Matter
DP: Digestible Protein
EP: Eco-toxicity Potential
FAO: Food and Agriculture Organization of the United Nations
FU: Functional Unit
GWP: Global Warming Potential
HH: Human Health
IT: Italy
IPCC: Intergovernmental Panel on Climate Change
K: Potassium
KCl: Potassium chloride
K_2O: Potassium oxide
LCA: Life Cycle Assessment
LU: Land Use
LW: Live Weight
MAP: Monoammonium Phosphate
MJ: Mega Joule
N: Nitrogen
N_2: Nitrogen molecule

NDU: Nutrient Density Unit

NDU$_{P-F}$: Nutrient Density Unit Adapted

nFU: nutritional Functional Unit

NH_3: Ammonia

NO: Nitrogen monoxide

NOx: Nitrogen oxide

NO_3^-: Nitrate

N_2O: Nitrous oxide

NO_2: Nitrogen dioxide

NOx: Nitric oxide and/or nitrogen dioxide

NPK: Nitrogen-Phosphorus

P: Phosphorus

P_2PO_5: Phosphate Pentoxide

ODP: Ozone Depletion Potential

P: Phosphorus

PEF: Product Environmental Footprint

POCP: Photochemical Ozone Creation Potential

RO: Romania

Si: Amount of kilocalories in 100g of grain

SC: Scotland

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Publications and contribution to publications

Papers published in journals contained in this thesis:

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This paper is the chapter **three** of this thesis:

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The following submitted manuscript is chapter **four** of this thesis:

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This paper in preparation is the chapter **five** of this thesis:

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Co-author contribution to other papers published during this PhD:

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Saget, S; Costa, M. P.; Styles, D.; Williams, M. Does Circular Reuse of Chickpea Cooking Water to Produce Vegan Mayonnaise Reduce Environmental Impact Compared with Egg Mayonnaise? Sustainability 2021, 13(9), 4726. https://doi.org/10.3390/su13094726.

- Marcela contributed to the LCA modelling of chickpea cooking water, method discussion, and to reviewing and editing.

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- Marcela contributed to LCA methods, sourcing crop data and crop LCA modelling (peas in Germany), and to reviewing and editing. This paper was also used as the basis for chapter four.

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- Marcela helped with the revision and parametrization of the data. Marcela also helped with a training of PestLCI tool in Brazil

1 **Chapter One:** Introduction

Food is essential to humankind. In 2050, there will likely be 3 billion more people to feed than in 2010, reaching around 10 billion people in the world (WRI, 2018). Providing food in an affordable, nutritional, accessible, and sustainable way is an immediate challenge that will also persist for the next decades. However, food systems are also threatening both environmental sustainability and human health (FAO, 2021; Willett et al., 2019).

According to Willett et al. (2019), despite the fact that global calorie production has kept pace with population growth, there are more than 820 million people with insufficient food, and many more consuming a poor diet, not obtaining the nutrients desirable for maintaining good health. This malnutrition is caused by both the lack of access to sufficient quantities of proper nutritional food items, as in many African and Latin American countries, or by poor food habits, such as the excessive consumption of foods with poor nutrition (e.g. those that are energy and protein rich but lacking in other essential nutrients), common in European countries and North America. According to Chaudhary et al. (2018), there is no continent in the world where the population meets the daily recommended fibre intake. The morbidity and mortality risk due to these unhealthy diets are related to factors such as obesity, as well as various non-communicable diseases such as heart disease, stroke, and diabetes. Morbidity and mortality rates are greater for unhealthy diets than unsafe sex, alcohol, drug, and tobacco use combined (Willett et al., 2019).

From an environmental perspective, agricultural emissions and related activities such as deforestation account for almost one fourth of the global emissions (IPCC, 2014). Agricultural activities are large contributors to greenhouse gas (GHG) emissions, as they require substantial quantities of resources such as fertilisers, and water for irrigation (Jägerskog and Jønch Clausen, 2012). Additionally, agricultural activities also cause other environmental concerns such as water pollution (Diaz and Rosenberg, 2008) and biodiversity loss (Foley et al., 2011), amongst others. The animal production sector is associated with intense environmental burdens, caused directly by the animals or indirectly by their feed requirements (Poore and Nemecek, 2018). Two thirds of European agricultural land is given over to the livestock sector, and to feed these livestock Europe sources 70% of high-protein feed via imports. Most of this imported feed is soybean and soymeal imported from Brazil and Argentina, which comes with the associated problems of deforestation and biodiversity loss (Watson et al., 2017; Westhoek et al., 2011).

The increase in consumption of animal-based food is related to population increase but also to the rise in personal incomes (WRI, 2018), urbanization, transnational food corporations, food industry marketing, consumer attitudes and behaviours, among others (Sabaté and Soret, 2014). There has been an increase of 62% in meat consumption globally since 1963, with a three-fold increase for emerging economies. In China, there was a 9-fold increase in meat consumption since the 1980s (Sabaté and Soret, 2014), and lower rates of veganism and vegetarianism are found in richer regions such as North America and Europe, where 6% and 5% of the population are vegetarian respectively (Hargreaves et al., 2021). Nevertheless, there is also an increase in awareness about the importance of heathy and sustainable diets by both academics and consumers (Saget et al., 2021b; Steffen et al., 2015). The decision of consumers to adopt a meat-free or low-meat diet can be based upon many factors including religion, cultural aspects and more. However, recently the main motivations are increasingly related to environmental, ethical and health aspects such as animal welfare, lower pollution, and better intake of nutrients (Hargreaves et al., 2021).

An important strategy to achieve the GHG reduction targets established by the Paris Agreement (UNFCCC, 2015) would be reducing meat consumption and improving agricultural systems to deliver food security whilst reducing the environmental impact (Willett et al., 2019). The development of technologies to increase crop efficiency with the precision application of fertilisers and water into "conventional" intensive systems is not enough to tackle environmental problems. This action has already led Europe to a co-evolution of crop systems with the development of public policies and market dynamics that boost intensive cereal production with a high dependence on mineral fertilisers and agrochemicals (Magrini et al., 2016; Zander et al., 2016). Many attempts have been made to break this technological lock-in state of intensive mono-cropping by "sustainable intensification" practices that not only deliver more output on the same area, but also use less resources, recover degraded agricultural areas, increase carbon content in soils and minimise further native vegetation removals (Costa et al., 2018; Rockström et al., 2020).

In this context, the integration of grain legumes into European agricultural rotations and diets are key elements for food transition systems, tackling both health and environmental challenges. Legumes are considered a protein alternative to meat, containing contain high amounts of protein, as well as fibre and other nutrients that improve health and reduce the risks of cancer and cardiovascular diseases (Polak et al., 2015). On the agricultural aspect, legumes can offer an option of ecological intensification, as they can fix nitrogen from the atmosphere, providing fertilization for both themselves and the following crops within the rotation, improving soil quality, promoting "break-crop" effects for cereals and possibly enhancing soil biodiversity (Jensen et al., 2011; Jensen and Hauggaard-Nielsen, 2003).

Despite all these benefits, legumes are not yet produced and consumed widely in Europe. Even though legume-based foods are heathier and have lower environmental impact than traditional meat and wheat based foods (Saget et al., 2021b, 2021a, 2020), and are increasingly widely available, the legume consumption rate is still only 1% of the daily energy intake (FAO, 2019). By contrast, Willett et al. (2019) suggests at least 17% of caloric intake would be necessary to meet a sustainable diet standard. Similarly, legumes are present on only 2.1% of Europe's arable land, in contrast to an average of 14% worldwide (Watson et al., 2017).

Many academics have published research in support of public policy changes, displaying legume benefits based on the evaluation of carbon, or wider environmental, footprints via Life Cycle Assessment (LCA) (ISO 14040, 2006), comparing legume alternatives to traditional options (Nemecek et al., 2008; Poore and Nemecek, 2018; Reckling et al., 2016b) or diet change (Davis et al., 2010; Willett et al., 2019). Evidence concerning the economic viability of introducing legumes (Reckling et al., 2016a; Watson et al., 2017) and related policy barriers have also been identified (Magrini et al., 2016; Zander et al., 2016). According to FAO, (2021), comprehensive policies with a broader view (food production and consumption and environment), and with regulatory support, are necessary to change the behaviour of food stakeholders, supporting the change of dietary patterns and food production.

The failure of effective change by food stakeholders in developing legume systems further in Europe, may be connected to the fragmented nature of the current scientific evidence base, particularly across studies that typically evaluate specific aspects of sustainability in isolation, or one aspect of the value chain, lacking an integrated analysis with appropriate deployment scenarios to support effective decision-making. Applying an appropriate LCA approach, framed in an appropriate context, is imperative to adequately inform relevant stakeholders on how to effectively drive a sustainable agri-food system transition.

There are many challenges to be tackled in LCA studies. On the one hand, LCA methodology can support a wider assessment of environmental impact than just GHG emissions (aka, carbon footprint, a commonly used metric), while at the same time supporting a wider view of the value chain, accounting for the impacts from the extraction of raw materials, manufacturing, transportation, transformations, use, disposal and end-of life stages of the product or service evaluated. To run such an analysis, models are somewhat simplified (Brankatschk, 2018). However, on the other hand, and despite having international standards and guidelines such as ISO 14040 (2006), ISO 14044 (2006), LCA still has various limitations that need to be addressed.

Therefore, this research discusses, and proposes solutions to, some of these LCA challenges pertinent to evaluating the potential contribution of legumes to sustainable food system transformation in Europe. Firstly, this research explores the nature of such challenges and identifies the state-of-the-art of LCA applied to cropping systems, with an emphasis on representation of nutrient cycling and other systems effects incurred by legume-modified rotations. It then turns to discuss how LCA can move away from the assessment of a single year's cropping system to a wider rotation analysis, proposing a novel approach to integrate nutrition into farm level assessment, across three European agro-climatic zones. This research also explores aspects of multifunctionality and allocation proposed by the LCA community as being fundamentally important for food system LCA. The environmental impacts of individual diet substitutions are then evaluated, applying a consequential LCA (Weidema and Schmidt, 2010) that avoids allocation, captures rotational changes and accounts for indirect and unintended environmental consequences across interlinked systems.

Finally, we consider the different LCA approaches applied to legume food system transitions in Europe, identifying the main goals and intended target audience, in addition to their advantages and limitations, making recommendations on which approaches should be applied to which situations, and drawing final conclusions about the environmental impacts of introducing legumes into Europe's food systems.

This PhD is part of the Working Package Number Five of the "TRansition paths to sUstainable legume based systems in Europe" (TRUE) research and innovation programme of the Horizon 2020 (H2020) Project (TRUE, 2018). The main purpose of this project and the thesis structure are explained in detail below.

1.1 TRUE Project

This research thesis is supported by the TRUE project (TRUE, 2018), funded by the EU Framework Programme for Research and Innovation H2020, Grant Agreement number 727973. The TRUE Project is a practice-research partnership of 24 institutions that has its goal to identify opportunities and help to increase the integration of legumes in cultivation and consumption across Europe. The Environment Working Package (WP5 - Environment: Environmental LCA and Nutrient Quality Assessment of Legume Cropping and Legume Products) aims to provide a coordinated life cycle based assessment of the environmental impact of legume production and processing coupled with a nutri-economic analysis of legume-enriched food systems. This research will answer the following questions of this work package:

- What is the environmental footprint of animal feed and food produced from legume rotations compared to conventional systems, considering nutrient cycling and break-crop effects in legume-rotations across major EU agro-climatic zones?

- What are the environmental consequences and interlinkages with other value chains of introducing legume-enriched foods produced in Europe, including indirect effects incurred during supply chain transitions?

As part of the True Project, this thesis interacts with other research initiatives under Working Package Five (WP5 - Environment: Environmental LCA and Nutrient Quality Assessment of Legume Cropping and Legume Products) and Working Package Six (WP6- Economics - An Economic Assessment of Sustainable and Profitable Legume Production and Consumption) (Figure 1). Chapter two (literature review) offers a basis for the subsequent chapters of the thesis and a basis to analysis legume crops for assessing the environmental impact of different legume enriched foods and drinks, also evaluated under the working package five. One such legume-enriched study and its modelling data (Saget et al., 2021a) served as an input to chapter four of thesis, together with outputs of the economic farm models from WP6. The environmental modelling of rotations in chapter three and four of this thesis served as a basis for calculating complementary environmental footprint economic scenarios of WP6. A macro incorporation of all footprints calculated under WP5 will be undertaken in a final paper on the environmental consequences of diet changes and drink habits in Europe. Details of these interaction can be observed in Figure 1 below. The publications details are available in the ‘Publications and contribution to publications’ section and the description of each chapter of this thesis follows on the section below.

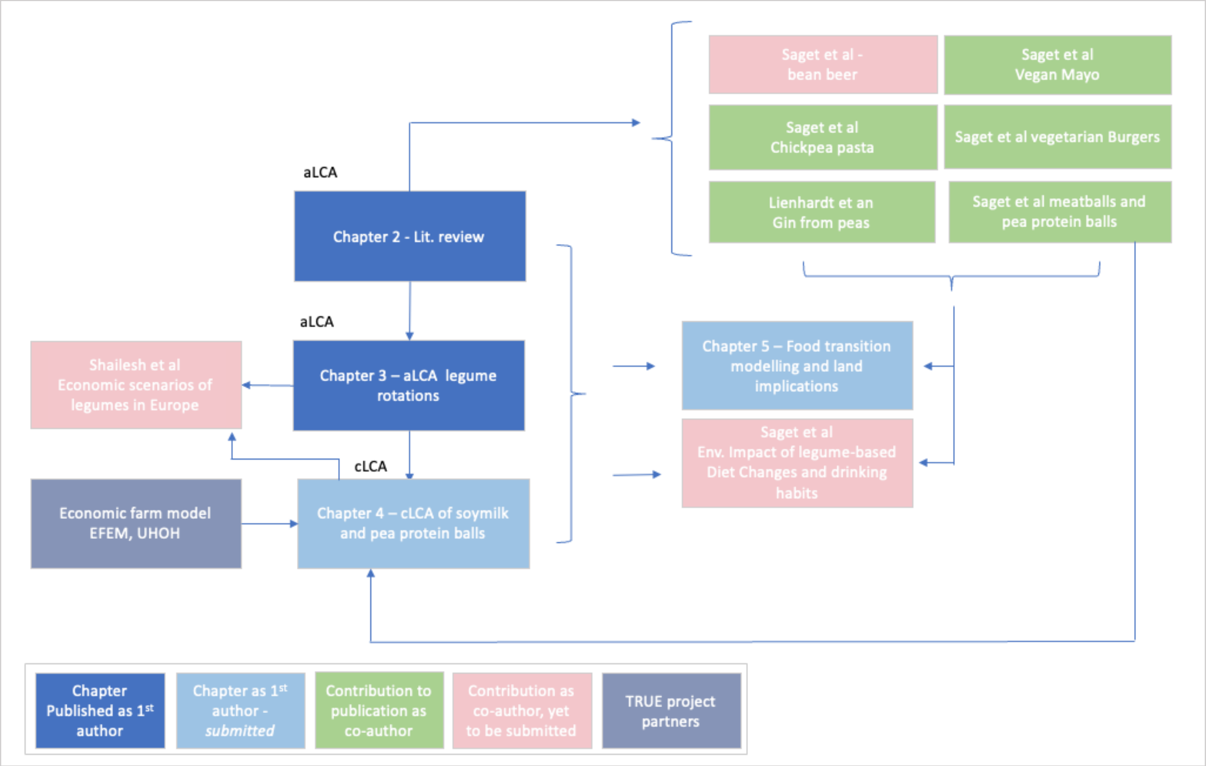

Figure 1: Flowchart of the interaction of this thesis chapter with other research developed under TRUE Project within the Environmental and Economic Working Packages.

1.2 Thesis Goals

1.2.1 Broader Goal

- To evaluate the environmental performance of introducing legumes to European food systems for enhanced sustainable production and consumption

1.2.2 Specific Goals

1. Identify the state of the art of LCA applied to legume rotations, understanding how the method is applied to evaluate the system and to represent, *inter alia*, nutrient cycling and break-crop effects.
2. Calculate the environmental footprint of animal feed and food produced from legume-rotations compared to conventional systems, considering nutrient cycling and break-crop effects in legume-rotations across major EU agro-climatic zones and proposing a novel approach to represent the nutritional value of rotations via a nutritional Functional Unit (FU).

3. Identify the main environmental consequences and other value chain interlinkages of legume-enriched foods produced and consumed in Europe, including indirect effects incurred during supply chain transitions and land use implications and opportunities.
4. Critically evaluate LCA approaches used in the TRUE Project and beyond to provide guidance on the application of LCA to address different goals related to the inclusion of legumes in European food system transitions.

1.2.3 Target Audience

The target audience is intended to include all stakeholders with an interest to develop legume value chains and/or drive food system sustainability. More specifically, the following audiences can use this thesis in these contexts:

- **Academics:** This thesis provides the scientific and LCA community with evidence on the benefits, hotspots and opportunities for the inclusion of legumes in food systems in Europe, identifying methodological limitations, novel approaches and remaining challenges to be addressed in future work by the LCA community.
- **Farmers:** Providing farmers with evidence about the environmental benefits and trade-offs of introducing legumes into the agricultural rotations in Europe, to provide nutrition to animals and people, quantifying important rotational effects that have sometimes been overlooked in traditional LCA studies.
- **Food Industry**: Delivering insights to the food industry on the extent to which legume-enriched foods can be beneficial to the environment, identifying trade-offs and interlinkages with other value chains not directly connected to that industry.
- **Policy makers**: Supplying policy makers with evidence of the benefits of including legumes in European food systems, connecting previous LCA and economic studies conducted on this theme, and demonstrating the potential role of legumes in driving systemic change.
- **Consumers:** This thesis provides evidence of the benefits of including legume in food systems in Europe, in a transparent way, offering a clear view of the environmental benefits and trade-offs associated with behaviour (diet) change.

1.3 Chapter Structure

This thesis consists of six chapters described below. Chapters two, three, four, and five have been prepared in the style of journal articles, as they have already been published or submitted for publication. The details of the publications or submissions can be found below the title in each chapter. Chapters one and six entail the thesis introduction and thesis conclusions, respectively. In summary, the titles and contents of each chapter are as follows:

- **Chapter One: Thesis Introduction and thesis goal**

  This chapter gives the general thesis introduction and its goals with respect to its target audiences.

- **Chapter Two**: ‘Representing crop rotations in life cycle assessment: a review of legume LCA studies’

  This chapter consists of a literature review, conducting a systemic review of how legumes in crop rotations are represented in LCA studies.

- **Chapter three: ‘**Legume-modified rotations deliver nutrition with lower environmental impact’

  This chapter applies LCA to compare the environmental efficiency of ten rotations across three European climatic zones in terms of delivery of human and livestock nutrition. Legume-modified rotations are compared with conventional rotations in terms of performance across 16 environmental impact categories.

- **Chapter Four: ‘**Environmental and land use consequences of replacing milk and beef with plant-based alternatives’

  This chapter investigates the environmental consequences of two independent but interconnected diet choices in a German context: (i) replacing dairy milk with soy milk, and (ii) replacing beef meatballs with pea protein balls. The analysis is related to commodity demand for detailed agricultural rotations and land use changes via farm scale economic modelling coupled with consequential LCA.

- **Chapter Five:** ‘The role of different life cycle assessment approaches in supporting a sustainable food system transition’

  This discussion chapter draws together the findings of the preceding chapters to explore how different approaches to LCA application can be useful in answering questions relating to sustainable legume food systems, drawing on experience from the Horizon 2020 TRUE project. In particular, the chapter explores how LCA can be adapted to link land management with diet change in order to capture the wider environmental effects of prospective transitions towards greater production and consumption of legumes in Europe.

- **Chapter Six:** General Conclusions

  This chapter comprises general conclusions of the thesis, emphasising the key messages for the key stakeholders identified within the target audience.

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2 **Chapter Two:** Representing crop rotations in life cycle assessment: a review of legume LCA studies

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Abstract

Purpose

There is an imperative to accurately assess the environmental sustainability of crop system interventions in the context of food security and climate change. Previous studies have indicated that the incorporation of legumes into cereal rotations could reduce overall environmental burdens from cropping systems. However, most life cycle assessment (LCA) studies focus on individual crops and miss environmental consequences of inter-annual crop sequence and nutrient cycling effects. This review investigates state-of-the-art representation of inter-crop rotation effects within legume LCA studies.

Methods

A literature review was undertaken, starting with a search for all peer-reviewed articles with combinations of ‘LCA’, ‘legumes’ and ‘rotations’ or synonyms thereof. In total, 3180 articles were obtained. Articles were screened for compliance with all of the following requirements: (i) reporting results based on LCA or life cycle inventory methodology; (ii) inclusion of (a) legume(s); (iii) the legume(s) is/are analysed within the context of a wider cropping system (i.e. rotation or intercropping). Seventy articles satisfying these requirements were analysed.

Results and discussion

We identified three broad approaches to legume LCA. Most studies involved simple attributional LCA disregarding important interactions across years and crops in rotations. N-fertilizer reduction through legume residue N carryover is either disregarded or the benefit is attributed to the following crop in such studies, whilst N leaching burdens from residues are usually attributed to the legume crop. Some studies applied robust allocation approaches and/or complex functional units to enable analysis of entire rotation sequences, accounting for nutrient cycling and break crop effects. Finally, a few studies applied consequential LCA to identify downstream substitution effects, though these studies did not simultaneously account for agronomic effects of rotational sequence changes.

Conclusions

We recommend that LCA studies for legume cropping systems should (i) evaluate entire rotations; (ii) represent nitrogen and ideally carbon cycling; (iii) for attributional studies, define at least two functional units, where one should encompass the multifunctional outputs of an entire rotation and the other should enable product footprints to be calculated; (iv) for CLCA studies, account for both agronomic changes in rotations and markets effects; (v) include impact categories that reflect hotspots for agricultural production.

2.1 Introduction

Sustainable and resilient agriculture is critical to tackling climate change whilst delivering food security and reducing dependence on finite resources such as fossil fuels (FAO 2018). Within the European Union, the Common Agricultural Policy (CAP) is a major driving force that influences practice in the agricultural sector (Europe Commission 2018). Grain legumes are supported under CAP within ecological focus areas, agri-environmental schemes and greening requirements, and also promoted within organic farming (Behera et al. 2012). Despite being encouraged by these policies, Zander et al. (2016) argue that legume system development is limited by other stronger market and policy incentives, such as the policies that boost oilseed rape designated to biofuel production (European Parliament 2009). Current European cropping systems rarely include legumes in their rotations. Only 2.1% of arable land is dedicated to cultivating legumes, compared with 14.5% worldwide (FAOStat 2016). This situation contributes to a deficit of 70% of high-protein crop commodities for animal feed in Europe, which is compensated by imports from North and South America (Watson et al. 2017). In addition to raising concerns over food security, large-scale import of protein to the EU (European Parliament 2018), especially soybean, is related to environmental concerns such as deforestation and associated habitat loss and greenhouse gas (GHG) emissions (Nemecek et al. 2008). In this context, one of the priorities for European policy is to reduce the dependence on imported protein (European Commission 2018b).

Legumes are an important source of protein for feed and food. These crops have the ability through symbiotic microbial associations to fix atmospheric nitrogen (N) which is eventually returned to the soil, leading to a reduction in N fertilization needs, not only for their own production but also for the following grain crop in the order of 60 kg of N/ha annually (Preissel et al. 2015). These values can vary according to the soil and cultivar species, for example peas can provide a N credit of 40–49 kg N/ha for the following wheat crop (Plaza-Bonilla et al. 2017). Yields of subsequent cereal crops have been measured at 0.2 to a 1.6 t/ha greater following legumes, and agrochemical use 20–25% lower (Zander et al. 2016). Hence, incorporating legumes into typical cereal rotations across Europe could bring benefits in terms of reducing environmental burdens across multiple crops and derived products, with significant potential to reduce GHG emissions (especially from fertiliser production and use), acidification, terrestrial and aquatic ecotoxicity burdens, among others (Nemecek et al. 2008). However, a possible trade-off of legume cultivation is higher rates of nitrate leaching (Nemecek et al. 2008; Watson et al. 2017). Overall, agricultural experiments and life cycle assessment (LCA) studies suggest that increasing legume production in Europe could be an effective strategy to improve protein security whilst reducing environmental impacts (Nemecek et al. 2008; Karlsson et al. 2015; Stoate et al. 2015; Plaza-Bonilla et al. 2018).

From an economic perspective, legumes are typically regarded as inferior to cereals (Foyer et al. 2016). This perception is challenged by Preissel et al. (2015) who studied 53 legume rotation models in Europe and concluded that 66% of them present competitive gross margins compared with non-legume systems. In addition, Zander et al. (2016) highlight the importance of external effects of legumes which are usually not taken into economic consideration, such as the enhancement of biodiversity and improvement of soil quality and soil organic carbon specifically (Yao et al. 2017; Goglio et al. 2018b).

LCA consists of analysing the environmental aspects of a product or service over the entire value chain of production, use and end-of-life, considering upstream and downstream processes (ISO 14040 2006). According to Klöpffer (2003), 'Life cycle thinking is the prerequisite of any sound sustainability assessment'. The author cautions that modifying a specific production step based on information for only one impact category can bring about negative consequences for other impact categories and other steps of the system. When applied to agriculture, many LCA studies draw boundaries or focus around a single crop or its (co-)product(s) (Bevilacqua et al. 2014; Hedayati et al. 2019). Thus, since the focus of these studies is on one cropping cycle, important interactions across crops and over years within crop rotations may be neglected. Recently, numerous authors have emphasised the importance of analysing whole cropping systems rather than individual crops in those systems (Brankatschk and Finkbeiner 2015; Brankatschk 2018; Peter et al. 2017). Therefore, new LCA methods, calculators and approaches are being proposed to evaluate the environmental impacts of changes to agricultural systems (Brankatschk and Finkbeiner 2015; Stoate et al. 2015; Reckling et al. 2016; Brankatschk 2018; Peter et al. 2017; Carof and Godinot 2018; Goglio et al. 2018b).

Representation of legume rotations are just one example of cropping system challenges in LCA studies. Brankatschk and Finkbeiner (2017) simulate production of wheat bread, cow milk, rapeseed biodiesel and straw for bioethanol by modelling them as discreet annual cultivations or as crop rotations (through attributional LCA), where straw is treated as either a residue or a co-product of the system. Treating straw as a co-product within rotation LCA, the carbon footprints of bread, milk and rapeseed can be 11%, 22% and 16%, lower, respectively, compared with a simple LCA of an annual cultivation cycle, whilst the footprint of bioethanol can be up to 80% higher.

This review aims to understand how LCA has been applied to assess legume rotations (rather than legume crops in isolation). More specifically, it investigates how various inter-crop rotation effects are taken into account and the main barriers representing these effects accurately in LCA. To do this, we ask the following questions:

(i) Which functional units are appropriate for legume rotation systems?

(ii) Where are the optimal system boundaries delineated through space and time (e.g. a single cropping cycle or a crop rotation)?

(iii) How are carbon, nitrogen and wider nutrient cycling effects best represented?

(iv) How and when should allocation be applied?

(v) Which impact categories are most relevant?

2.2 Method

A review was conducted to assess how legume cropping systems are represented in LCA. The literature review was completed in June 2019, based on evaluation of publications from peer-reviewed journals. The search engines used were ScienceDirect and Web of Science. LCA studies for legume rotations and intercropping were assessed by searching the following code: (‘life cycle assessment’ OR ‘carbon footprint’ OR ‘environmental impact’ OR ‘environmental footprint’) AND (‘legume’ OR ‘pulse’ OR ‘leguminous’ OR ‘peas’ OR ‘chickpeas’ OR ‘beans’ OR ‘lentils’ OR ‘lupin’ OR ‘vetch’ OR ‘alfalfa’ OR ‘clover’) AND (‘Rotation’ OR ‘integration’ OR ‘intercropping’ OR ‘cropping system’ OR ‘farming system’). Next, studies were selected where they matched the theme of LCA for legumes within rotation or intercropping systems by screening for compliance with all of the following requirements: (i) reporting results based on LCA or life cycle inventory methodology; (ii) inclusion of (a) legume(s); (iii) the legume(s) is/are analysed within the context of a wider cropping system (i.e. rotation or intercropping). There was no time restriction, since the number of older articles regarding this subject is limited compared with other themes. Two years was the minimum rotation length considered. Soybean was the only legume crop not included, unless it occurred with other legume varieties in the rotation. This decision was taken as soybean is often grown in industrialised mono-cultures or in very short rotations in major producing countries such as the USA and Brazil (WWF 2014). These systems involve fewer crop interactions and are mostly outside of Europe. Leguminous tree species were also outside the scope. European rotations were the main focus of this study, although Canadian and Australian rotations were also considered, as these countries have a high share of their arable land dedicated to legume cultivation (FAOStat 2016).

The articles obtained were analysed according to their main LCA structure. The first step was to understand the goals of each study and how they were translated into a functional unit. We categorised the functional units according to how many functional variables analysed per study. We further investigated whether these variables were based on independent criteria (e.g. kilogram of product, energetic potential), or combined in a dependent metric where the total amount of product is corrected by a product characteristics such as the fat and protein correct milk value FPCM (European Commission 2018b).

As a second step, the system boundaries were classified according to the main activities included, and excluded, in the LCA studies. The classification varied from simple to more complex approaches. We investigated which phases of the life cycle were included in each study. For example, from cradle to farm gate (until the harvesting of the grain) where activities associated with extraction and manufacturing of the majority of inputs were considered alongside their use on the farm, but nothing more. The other classification varied according to the activities included after the farm gate (downstream processes), such as transport and storage of grains before processing; the industrial phase (up to industry gate); or distribution and retail of the products. Another classification was added when avoided processes or consequential scenarios were considered, involving the expansion of boundaries to include, e.g. the avoidance of the use of a specific fossil fuel in favour of biodiesel.

We further analysed if the authors explicitly considered any soil organic carbon changes (SOC) or N fixing, whether by demonstrating the specific amount of N fixed or by considering any reduction of fertiliser use on the following crop. The penultimate step entailed the study of the allocation methods used in the following instances: (i) between the final products and considered co-products; (ii) allocation of specific upstream processes, such as production of farm machinery; and most importantly, (iii) the allocation of the nutrient flow between legumes and following crops. A final step involved the analysis of the impact categories presented in the studies, including a broad definition to capture critical inventory results, such as land use in square meters per year.

2.3 Results

In total, 3180 studies were obtained as a result of the search. First, studies were screened to discard those that had no relation to the investigated topic. For example, many discarded studies mentioned the word ‘pulse’ in the context of ‘pulse’ of emission, or impulse, or the word ‘beans’ in the context for coffee or cocoa beans. The results also contained studies of microalgae or algae, since they fix atmospheric N and can be found in feed and food value chains. Following the screening with the aforementioned requirements, only 70 published studies satisfied all the criteria established by the review. Studies that were excluded included those that performed a LCA of an individual legume with no rotation context; performed a review of secondary data, such as meta-analysis; simulated diets through commercial datasets instead of performing a simulation of farm systems; recommend LCA as a next step for further understanding of the topic. The paper selection flow chart, according to the questions aforementioned, can be observed in Figure 2.

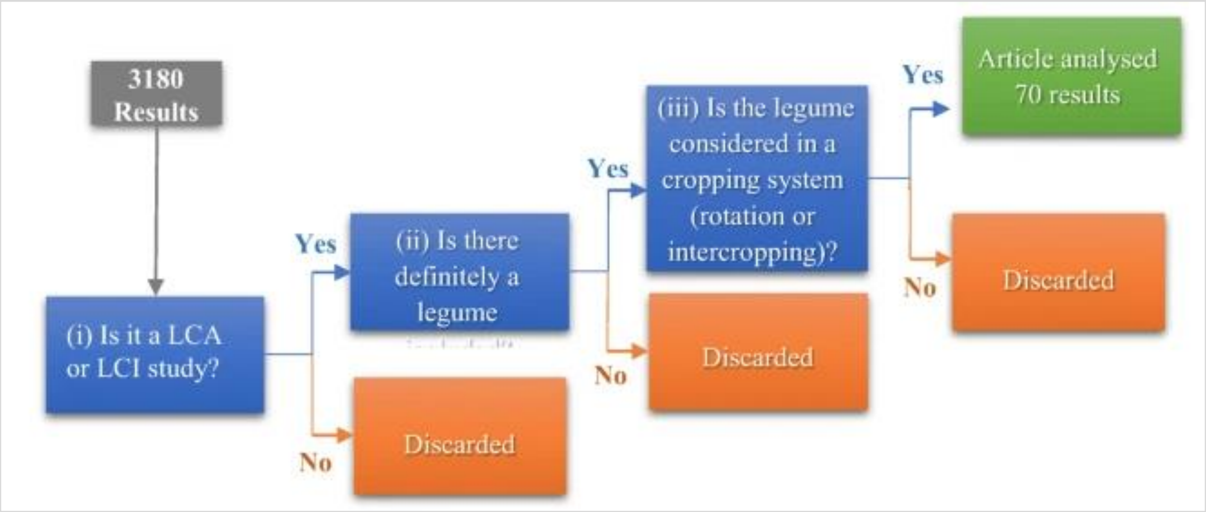

Figure 2: Flow chart describing the sequential screening of articles through application of selection criteria. (i) Reporting results based on LCA or life cycle inventory methodology; (ii) inclusion of (a) legume(s); (iii) the legume(s) is/are analysed within the context of a wider cropping system (i.e. rotation or intercropping).

The complete information about the 70 studies mapped in this review is available in appendix 1.

2.3.1 Definition of goal and functional unit

From our analysis, 44% of the reviewed articles (31) consider only one functional unit, which is related to a physical aspect of production. Table 1 summarises four main categories of functional unit (FU), and their frequency across reviewed articles. The most common FU encountered (24%) was related to area, followed by a simple product characteristic such as mass (dry matter of fresh matter), quantity of protein (kg) or gross energy output of determined products (Dalgaard et al. 2006; Nikièma et al. 2011; Knudsen et al. 2014a; Karlsson et al. 2015; Yao et al. 2017; Cai et al. 2018). Among these studies, the main focus was to assess the environmental impact of producing a specific crop within the crop rotation, such as wheat (Barton et al. 2014; Yao et al. 2017) or switchgrass for bioenergy (Ashworth et al. 2015). When study goals went beyond assessment of a single product, to assess rotation level efficiency, the FU most commonly used was based on area and time, such as production quantity from 1 ha over 1 year or over the duration of a rotation cycle. This FU was found in 17 articles (24%)

such as in Nemecek et al. (2008) and Goglio et al. (2018b). This area-time FU is known as a Land Management Functional Unit (Nemecek and Erzinger 2005), where the goal is to maintain agricultural production on the land whilst reducing its environmental impacts—the common unit is everything produced in 1 ha in 1 year.

Table 1: Types of functional units encountered in the articles assessed in this review.

Function unit	**Frequency of occurrence**	**No. of articles**
One simple product-based variable (e.g. kg, MJ, protein)	20%	14
One simple area-based variable (e.g. ha)	24%	17
Two simple independent variables (e.g. kg + ha)	20%	14
Three simple independent variables: (e.g. kg + ha + €)	19%	13
Two dependent variables—product amount and quality aspect of it (such as milk FPCM[1], which considers fat and protein content), rice equivalent (amount and cost of a grain related to rice)	13%	9
Other (multi-variable)	4%	3

[1] FPCM: Fat and protein correct milk value (European Commission 2018a)

The remaining 39 articles (56%) analysed at least two types of FU, with numerous authors proposing that one FU is insufficient to assess multi-product crop rotations (Carranza-Gallego et al. 2018; Hoffman et al. 2018; Reinsch et al. 2018). Almost 20% of articles (13) analysed three or more types of FU. Nemecek et al. (2008) and Zucali et al. (2018), for instance, applied a productive FU, expressed in kg DM or gross energy content, an area-based FU, and a financial FU expressed in monetary value (receipts minus direct costs of production). Prechsl et al. (2017) applied the cereal unit (CU), primarily designed for allocation within rotations, as a FU, in addition to mass- and area-based FUs. The CU converts all grain into a common reference unit calculated by the feed energy digestibility for animals (Brankatschk and Finkbeiner 2014).

Nine papers (13%) presented a FU that combines two simple independent variables, the physical quantity of product with a physical aspect of quality. This is the case for energy studies, which evaluate not only the amount of crop produced but also the gross energy content or the final useful energy generation potential of the material. Dairy studies were included in this review because they explicitly account for legume feed production (Pirlo et al. 2014), usually reporting the mass of milk corrected for protein and fat content as the FU, as recommended by FAO (2016). Some studies convert multiple crop outputs from a rotation into a specific grain equivalent. Alam et al. (2019) converted the mustard crop under rotation into rice equivalent yield (REY). The REY is calculated by the mustard crop yield multiplied by its market price and then divided by the market price of rice, in effect representing an economic revenue FU.

Grönroos et al. (2006), Tuomisto et al. (2012) and Röös et al. (2016) were the only studies captured by this review that propose a multi-variable FU, where multi-functionality is addressed by integrating a specific portfolio of required outputs into a single FU. They proposed a composition of different products; thus, the function of the systems under analysis is achieving an exactly defined proportion of different products, such as, for Röös et al. (2016), a drink with the function of milk + protein for humans + rapeseed oil and protein feed corresponded to an amount of grain legumes + grazing of 49 ha of semi-natural grasslands. Similarly, Tuomisto et al. (2012) proposed 460 t of potatoes + 88 t of winter wheat + 60 t of field beans + 66 t of spring wheat as functional unit.

Almost all studies (94%) performed a comparison of products or systems. Accounting LCAs were found in calculators elaborated to generate footprints for particular crops within rotations (Peter et al. 2017; Carof and Godinot 2018; Goglio et al. 2018b). In these studies, the main goal was to quantify and understand the impact of one product or process through its value chain rather than perform a comparison.

2.3.2 Approach and definition of the system boundaries

A majority of studies applied an attributional LCA approach (Rebitzer et al. 2004). Consequential LCA (Ekvall and Weidema 2004) was applied only by Knudsen et al. (2014a) and Karlsson et al. (2015), whilst attributional LCA with consequential scenarios were found in 7 studies (10%). These LCA studies simulated substitution and avoided production in supply chains situated outside of the direct cropping system boundaries. In relation to the boundaries adopted, more than two-thirds of the reviewed studies (71%) consist of analyses from cradle to farm gate and therefore included upstream processes such as the manufacture, transport and use of inputs to the farm in addition to farm operations and processes (Table 2). Only 7% of the studies added activities such as transportation and storage beyond the farm gate, and 9% include processes up to product manufacture to represent consumable products (Table 2). Some of the studies (4%) focused only on farm activities and processes, or only accounted for some of the main upstream processes associated with farm inputs (Kristensen et al. 2011; De Vries et al. 2014; Hauggaard-Nielsen et al. 2016). This is very common in studies that calculated only carbon footprints and/or just focus on field measurements (Dalgaard et al. 2006; Hunt et al. 2017; Reinsch et al. 2018). Five studies (7%) extended the boundaries from farm gate to a wider scenario scale involving multiple farm systems, to calculate possible environmental effects on a larger scale. Karlsson et al. (2015) incorporated a consequential LCA of fava bean use, changing it from the protein feed for dairy cows to processing in a green biorefinery producing ethanol, protein concentrate feed and fuel briquettes, or with the whole crop used as roughage feed. Knudsen et al. (2014a) analysed the consequences of introducing peas and fava beans in European rotations by accounting for reduced production of soybeans outside of Europe. Despite focusing only on GHG emissions, this study addresses key concerns about the wider sustainability of modifications made to globally inter-connected food systems, similarly to Styles et al. (2017).

Table 2: Boundaries established by the articles assessed in this review.

Boundaries	**Frequency of occurrence**	**No. of articles**
Cradle to farm gate	71%	50
Cradle to transport or storage	7%	5
Cradle to process, industry gate or retail	9%	6
Cradle to farm or industrial gate + avoided emissions of CLCA scenarios	7%	5
Cradle to grave	1%	1
Farm or farm plus upstream processes for some main inputs	4%	3

2.3.3 N carryover, carbon sequestration and allocation methods

Legumes have the ability to fix atmospheric N and consequently to provide N to the following crop, reducing the need of external synthetic fertilization (Preissel et al. 2015; Reckling et al. 2016; Watson et al. 2017). The majority of LCA studies of legume rotations (70%) either explicitly accounted for the amount of N fixed by legumes using literature estimates or implicitly by a reduction in fertilization of the next crop in rotation sequence

(Table 3). The N benefit was not considered in 3% of the studies, due to lack of reliable data (Prechsl et al. 2017; Hedayati et al. 2019) or because it was judged as irrelevant for the total impact calculation (Knudsen et al. 2014a). For the studies that did not mention any N fixation or where insufficient information was provided to understand the method (27%), two options are possible: (i) no N carryover was accounted for; (ii) N carryover was implicitly accounted for based on, e.g. primary activity data for fertilizer application to the following crop.

Table 3: Numbers of articles reviewed that account for N carryover effects and carbon sequestration

	N fixing assessed?		**Soil organic carbon change assessed?**	
	Frequency of occurrence	**No. of articles**	**Frequency of occurrence**	**No. of articles**
Yes	70%	49	39%	27
No	3%	2	20%	14
Not clear/not mentioned	27%	19	41%	29

Soil organic carbon (SOC) sequestration is often not taken into account in agriculture LCAs, mainly because the crop will be processed and most of the biogenic carbon sequestered in the plant tissue during growth will return to the atmosphere (Rees et al. 2005). However, SOC is known to change slowly over long periods in cropping systems (Ostle et al. 2009; Smith 2014). A number of studies indicate long-term SOC decline in European arable soils, especially because of short and cereal-dominated rotations and management practices such as full, frequent ploughing and straw removal (Smith 2004). The potential for SOC accumulation depends on the quality and quantity (biomass) of residues (Watson et al. 2017). Even though legumes are known to produce more N-rich residues compared with cereals (Meyer-Aurich et al. 2006; Carranca et al. 2009; Begum et al. 2014; Laudicina et al. 2014; Tosti et al. 2014), they typically produce less residue biomass (Meyer-Aurich et al. 2006; Begum et al. 2014). Some studies point to a SOC decrease when a legume crop is introduced into cereal-dominated systems, due to the smaller amount of above and below ground biomass generated by legumes when compared with cereals, such Meyer-Aurich et al. (2006) who analysed soybean and maize cultivation, and Laudicina et al. (2014) who analysed wheat/fava bean rotations. However, other studies paint a more complex picture across the many species and cultivars of legumes, which typically produce nutrient-rich residues that decompose more rapidly than cereal residues due to their lower lignin content (Laudicina et al. 2014). The rapid decomposition of legumes contributes a break crop effect, promoting an increase in the following crop yields, which in turn can increase biomass residue inputs (above and below ground), and therefore contribute to a higher equilibrium level of SOC (Drury and Tan 1995). These effects may not be attributed to legumes, but to the high-yielding following crops (e.g. cereals).

In this review, 39% of studies considered SOC sequestration when calculating global warming potential, whilst 20% explicitly declared that they did not include it. The remaining 41% did not mention SOC effects, and presumably did not account for them (Table 3). Yang et al. (2014) state that accounting for carbon sequestration can influence the final carbon footprint by 15 to 20%.

To understand how the potential benefits (N fixation and carbon sequestration) and burdens (leaching potential and GHG emissions) of legume production were distributed within cropping systems, this review also analysed methods of allocation across multiple products from rotations (Last Column of Table *4*, Appendix 1). Allocation is defined by ISO as ‘partitioning the input or output flows of a process or a product system between the product system under study and one or more other product systems’ (ISO 14040 2006). Overall, 46% of studies do not explicitly mention where and how cultivation burdens may have been allocated across crops within rotation cycles. Some studies mention other aspects of allocation, such as how machinery building aspects were taken into account or how final products such as meat and milk were allocated from dairy production, without specifying the cultivation stage.

According to the ISO standard, allocation should be avoided where possible by subdivision of the system into sub-processes with specific data or by expanding product systems to include the wider functionality of co-products in the main goal of the study (ISO 14044 2006). Where allocation cannot be avoided, a physical relation between the co-products should be adopted. Economic allocation is recommended when there is no other possibility (ISO 14044 2006). Since the ISO standards were established as a general framework for LCA, there has been a clear effort from scientists to address allocation challenges for cropping systems (Goglio et al. 2012; Barton et al. 2014; Martínez-Blanco et al. 2014). Brankatschk and Finkbeiner (2015) proposed use of the aforementioned CU as a basis for biophysical allocation, based on crop digestible energy content for animals. The CU is applicable when most of the rotation (cereal) outputs are destined for animal feed, but is less relevant when products are destined directly for human consumption, bioenergy generation or use as fibre.

A significant share (15.5%) of reviewed papers declare having no co-products, usually those that define an area-based FU or those that define the timeframe as being post harvesting of a previous crop until the harvest of the following crop. Under the latter approach, the burdens and benefits associated with non-harvested legume cover crops, for example, are fully attributed to crop harvested after the legume cultivation (Prechsl et al. 2017; Hoffman et al. 2018), or attributed to multiple following crops harvested after the legume cultivation (Peter et al. 2017). However, if the legume cover crop is harvested and leaves the farm boundaries, the N benefit promoted by the legume crop is fully attributed to the following crop, whilst the leaching is fully attributed to the legume crop (Figure 3). Thus, the manner in which emission factors and N carryover credits are often calculated can lead to an attribution of credits and burdens between legumes and subsequent crops that is detrimental to the apparent environmental efficiency of legumes (Brankatschk 2018).

Figure 4 shows how allocation methods for carryover nutrients can link the benefits of N fixation by legume crops with burdens, such as leaching across all crops in the rotation. In this review, nineteen (27%) of the studies opted for mass, energy or economic allocation. Only two studies (3%) applied system expansion, and two others (3%) applied biophysical allocation. In four studies (5.5% of sample), allocation was applied using more than one method in the sensitivity analysis or through a N-relation metric. Naudin et al. 2014 evaluate allocation in intercropping systems through (i) mass, based on the yield of each grain, (ii) economic output, (iii) N allocation, considering the N yields in grains and (iv) system expansion.

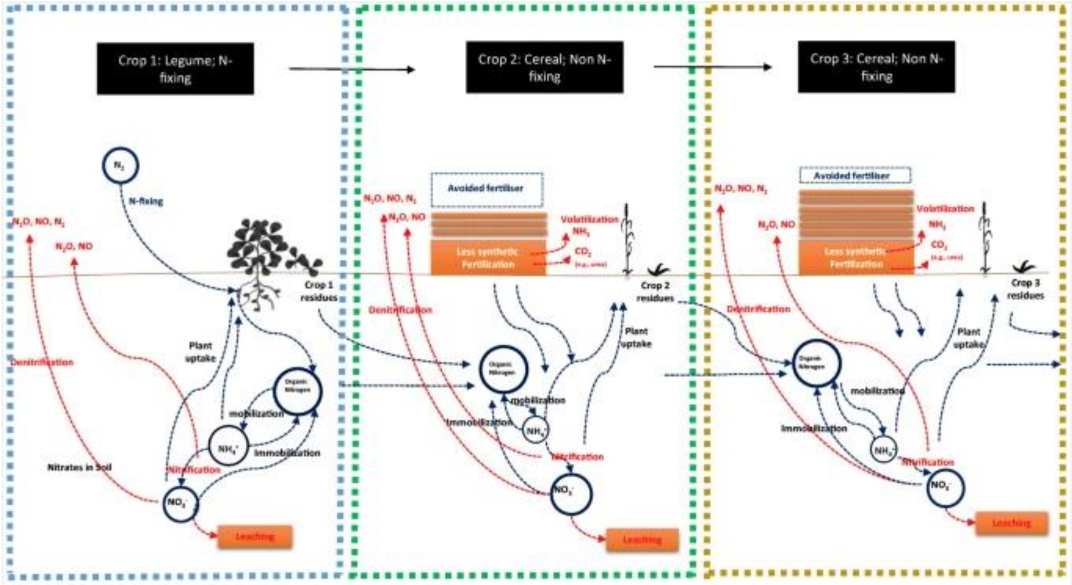

Figure 3: The nitrogen fixed by a legume crop and the crop residues of legume crop 1 can offer a benefit of reduced fertilization for the following crops in the rotation. If considering typical boundaries adopted by LCA studies, from the soil preparation up to the harvest process of each crop, the reduced fertilizer applications associated with carryover of residue N from crop 1 translate into reduced burdens for crop 2 and crop 3, whilst the total burden of nitrogen leaching and nitrous oxide emission associated with residue N is attributed to the legume crop 1.

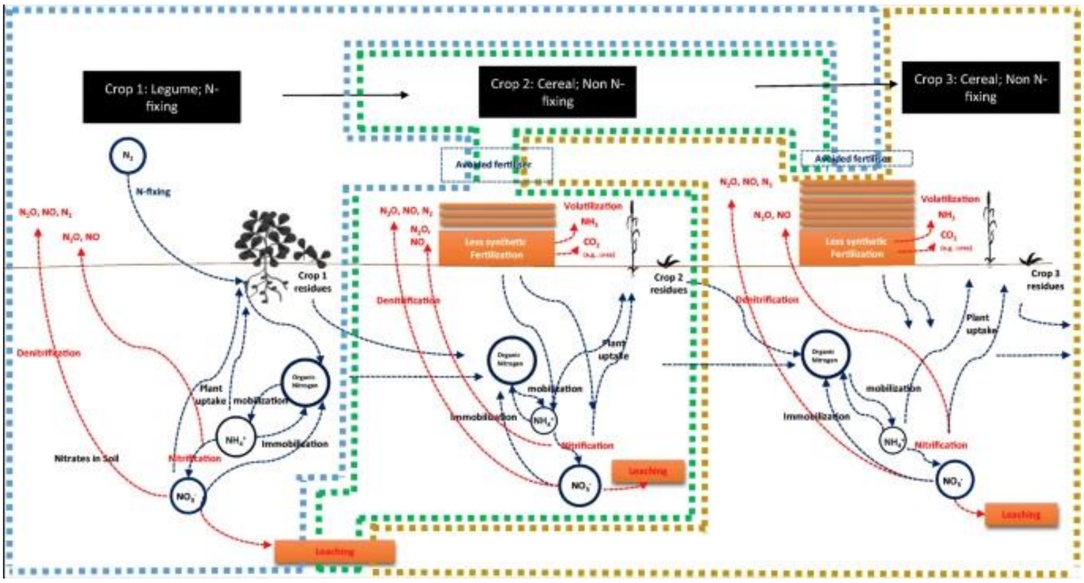

Figure 4: Allocation methods for carryover nutrients can link the benefits of N fixation by crop 1 to reduced fertilizer requirements for the following crops in the rotation (crops 2 and 3), whilst burdens, such as leaching and nitrous oxide, will be distributed across all crops in the rotation, according to the selected allocation criteria by the LCA practitioner (e.g. mass, energy, biophysical).

Nemecek et al. (2015) undertook an LCA of 60 crop combinations comparing legume-cereal rotations with cereal rotations. In their study, under the productive FU, the time frame is one agricultural year. Therefore, in order to capture the effects of a rotation, each crop was analysed according to its sequence in the rotation. A cereal crop was considered after a cereal, legume, rapeseed or sunflower crop; thus, the reduction of fertiliser due to N carryover from the previous crop was computed for each particular case. Additionally, crops cultivated after a catch crop were studied separately. According to the authors, the analysis of a certain crop after each individual possible preceding crop in a rotation can be very resource-intensive. Macwilliam et al. (2014) used a protein FU, enabling all products to be represented in terms of kilogram of protein. In this approach, the rotation is treated as a black box process (inputs and outputs are not specified per crop) and allocation is avoided. The study assesses the impact of introducing pea and lentil into cereal rotations and calculates the nitrous oxide emissions for pulses based on the N content in below and aboveground biomass.

None of the reviewed articles attributed full credit for avoided fertilisation requirements to the legume crop in the rotation, as recommended by the Australian guidelines (Grant et al. 2019). Those guidelines recommend this approach as the most practical way to separate out the impact of legumes cultivated in rotation with cereals, and specifically propose that 100% of avoided fertiliser credits in following crops, and 100% of the leaching (burdens) from the legume crop, and attributed to the legume.

2.3.4 Selection of impact categories

Two-thirds of the reviewed studies (66%) present the results across only one or two impact categories. Half the studies only reported global warming potential; the remaining 34% considered more than two impact categories. After global warming potential, the most encountered words were, in order of declining frequency: Energy, Eutrophication, Acidification, Ecotoxicity, Ozone, and Land Use (Table 4, Appendix 1).

Despite some legumes being irrigated, water use was rarely reported, being assessed in two studies only. Tuomisto et al. (2012) calculate the blue water in km^3 of water consumed per year at a global scale through a planetary boundary method (Rockström et al. 2009). Rodrigues et al. (2016) mention the water and mineral resource depletion impact categories of the ILCD method (EC-JRC-IES 2011), but the authors do not present final results for this method. The UNEP consensus for water footprint recommended by the European Environmental Bureau (2018)—the WULCA method (Boulay et al. 2018)—assesses not only the amount of water used but also the scarcity potential at a watershed level. Use of WULCA was not encountered in any of the legume rotation studies.

Possible effects of legume intercropping systems include more efficient use of diesel because of a dual crop plant machine which sows two seeds instead of one after the other, combined with reduced N fertilisation, increased soil organic carbon and increased yield (Ashworth et al. 2015). When LCA is applied, the result of these efficiencies can be detected across multiple impact categories. Ashworth et al. (2015) analyse the environmental footprint of intercropping switchgrass with legumes (such as red clover) and calculate potential reduced impacts across ecotoxicity, acidification, eutrophication, global warming and photochemical ozone creation impact categories per ton of switchgrass. Most of the papers that refer to the land use impact category do not report the potential effects on soil quality (Milà i Canals et al. 2007) or biodiversity loss (Koellner and Scholz 2007, 2008; Chaudhary et al. 2015). The most common result found under land use is a simple metric of annual land occupation per kg grain produced (m^2 yr^{-1}), representing an inventory quantity rather than an impact per se.

2.3.5 Summary of the types of LCA papers found in this review

From the 70 articles analysed, it was possible to observe four primary types of study, according to the descriptions below.

I. Attributional LCA of a single crop in a rotation. These studies usually involve a simple LCA that sometimes includes experimental field emission data for the annual crop under study. This kind of study attributes N losses from residues to the studied crop (or to a following crop in a separate LCA of that crop), and usually only accounts for fertiliser-N avoidance implicitly for the studied (legume) crop. Details on rotation sequences are lacking in such LCA studies, and usually a simple FU is used, such as kg of specific product.

II. Attributional LCA of an entire rotation sequence with a simple aggregated FU. A common FU in this type of study is area over time or total dry matter production. When individual crops within the rotation are targeted for individual foot-printing under this type, allocation is required. In this last situation, the type I is integrated in the analysis.

III. Attributional LCA of an entire rotation sequence with a complex aggregated FU. This differs from type II studies in the complexity of the FU applied. Either a single FU encompasses multiple products and services delivered by a rotation or multiple FUs are applied to understand the implications of FU choice on rotation- and crop-level environmental efficiency. In this analysis, product substitution and inclusion of consequential scenarios can be found; however, the main modelling is done by an attributional LCA.

IV. Consequential LCA of introducing legumes into rotations, in which case all effects (marginal changes relative to the relevant pre-existing systems) can be attributed to the legume intervention.

From the 70 articles reviewed, more than half (56%) were classified as type II. Only 24% were classified as type III, and only one article was classified as type IV. It is important to note that the search terms deliberately excluded many type I studies, as they have not mentioned ‘rotation’ or similar terms. Sensitivity analysis was rarely implemented across the studies, although some authors performed it for allocation methods (Table 4, Appendix 1).

2.4 Discussion

A crop rotation is multifunctional in that it produces a range of products for different purposes, such as animal feed, food for direct human consumption, energy or fibre. Introducing more legumes into European rotations has been proposed to improve the sustainability of European food and feed production (Watson et al. 2017). However, changes to rotation sequences, nutrient cycling and yields of crops within rotations mean that simple attributional LCA of the individual legume crops introduced into rotations does not adequately represent consequences for the environmental efficiency of rotations and related food systems, nor of individual crops within modified rotations. The solutions to better representation of rotation-level effects of legume integration within LCA lie in either (i) attributing an environmental footprint to each product in the rotation, taking into account their interaction with the preceding and following crops; or (ii) defining a rotation level FU that can meaningfully represent multiple products (and services) delivered by rotations.

Of the four types of legume rotation LCA studies we categorised, type I is the most prevalent in the wider literature, but many such studies were filtered out of this particular review which focuses on rotations. Type I attributional LCA studies of discreet cultivation systems underpin widely used large-scale datasets (Blonk Consultants 2018; Moreno-Ruiz et al. 2018), and usually present footprints per kg of a crop (product) excluding rotation interactions. Type I LCA studies often ignore crop sequence interactions and draw the boundaries around a single cropping year—neglecting N fertiliser substitution benefits associated with legume residue N carryover, or representing this fertilisation credit in a reduced footprint for following (non-legume) crop(s). Meanwhile, leaching burdens are often attributed to the legumes. Thus, eutrophication and global warming burdens may be over-allocated to legumes, and under-allocated to following (cereal) crops (Cai et al. 2018). Type II studies involve assessment of whole rotation systems, often with a simple aggregating FU, often based on area over time. These were the most prevalent type of study reviewed here, but their interpretation has little significance from a production efficiency perspective—results may be used to draw conclusions about land management rather than the environmental efficiency of food production (Schau and Fet 2008). Thus, the most widely applied types of crop rotation LCA have important deficiencies that constrain their usefulness in informing more sustainable food production.

The amount of N carryover is strongly influenced by the incorporation of legumes into rotations (Kayser et al. 2010), whilst soil carbon content is influenced by specific management practices (Vestberg et al. 2002). These factors can significantly influence the environmental footprint of crops and derived products, but the type of allocation method employed determines the extent to which legumes are credited with fertiliser avoidance credits or leaching and N2O emission burdens (Naudin et al. 2014). Representing these factors is important to draw out potential effects of legumes in order to accurately inform stakeholders (Kayser et al. 2010), but typically requires field-scale modelling. Procedures to avoid allocation were encountered in this review. Peter et al. (2017) demonstrate the sensitivity of crop footprints to allocation methods through a legume cover crop case study. If alfalfa is not harvested but used as a green manure, the following crop can have a 7–8% higher carbon footprint, and an 11–13% higher cumulative energy demand, but if the environmental impact is attributed to the harvested alfalfa crop, the legume crop (alfalfa in this example) has a 99% larger carbon footprint, whilst the following crop has a 1% smaller footprint. In the first situation, alfalfa was first considered as a green manure, in other words, an input (nutrient provider) for the following crop (product), so its impact will count towards the succeeding crop footprint. In the second situation, alfalfa is considered as an individual crop, which contributes towards delivering the functional unit chosen by the practitioner (dry matter, energy, etc.), and therefore a product that has impacts associated with it. This approach is valid, but misses the potential multifunctionality of alfalfa in providing N fertilisation to the next crop (and the fact that a significant share of the leaching burden of alfalfa is biophysically related to this additional function). Other studies employed sub-process division to avoid allocation, considering rotations as a composition of annual crop cultivations (Nemecek et al. 2011; Prechsl et al. 2017; Goglio et al. 2018b).

The CU (Brankatschk and Finkbeiner 2014), based on the digestible energy content of animal feed commodities, is a useful metric to aggregate multiple products from crop rotations. It does not affect the system boundaries and brings robustness to the LCA (Brankatschk and

Finkbeiner 2015). However, the method is constrained to rotations primarily producing animal feeds, and to only one dimension of animal nutrition, and could reinforce the lock-in of European rotations to cereal dominance promoted by public polices, market demand and specialization based on agrochemical paradigms (Magrini et al. 2016). Therefore, using the CU might not be appropriate for studies focussing on the production of crops for direct human consumption, or indeed, for other uses, including protein-rich animal feeds of which there is a deficit within Europe (Watson et al. 2017). Other kinds of physical or biophysical allocations for rotation systems have been proposed. Martínez-Blanco et al. (2014) recommend N release as a parameter to allocate compost effects across crops, though this requires reliable estimation of mineralisation rates. Alternatively, the authors recommend allocation based on N (or phosphorus/potassium) uptake by the plant (Martínez-Blanco et al. 2014). Knudsen et al. (2014b) also discuss different allocation methods for green manures and other catch crops. They suggest allocating based on N residual effect (as used by Tuomisto et al. (2012)) or by area. At present, no consensus for allocation methods in rotation systems has been achieved, which can lead to highly variable results and interpretation (Goglio et al. 2012; Martínez-Blanco et al. 2014; Brankatschk and Finkbeiner 2015). Sensitivity analysis is rarely applied in LCA studies. Given the variances outlined above, we propose that attributional LCA studies on legume cropping systems should apply sensitivity analyses at least to allocation methods.

Defining a FU for multifunctional cropping systems is challenging, since several products with different fates arise from these systems. No consensus definition of FU for legume rotations or intercropping systems was found from the types investigated in this review. However, awareness of the complexity of representing crops within crop rotations in LCA is increasing. Numerous authors have already applied multiple FU in order to understand systems from the perspective of an entire rotation (Nemecek et al. 2011; MacWilliam et al. 2014; Yang et al. 2014; Prechsl et al. 2017), especially in type III studies (Röös et al. 2016). Recent studies have proposed FUs that address the delivery of different functions (type III). For example, a multi-product approach has been proposed by Röös et al. (2016) and Costa et al. (2018). Costa et al. (2018) propose a FU based on a population demand for five food and energy products over a period of 7 years. This approach enables agricultural systems and rotations producing a range of different products to be compared in terms of their delivery of a proportion of overall human consumption. Allocation is fully avoided whilst the study captures important interactions across the years and elements (crops, trees and livestock) of rotations. The difference between the multi-variable and land use approaches is that the multi-variable FU allows a comparison of a mix of products versus their independent production. In other words, this is a way of measuring the efficiency of integrating the products into a cropping system compared with producing them by their traditional mode, such as mono-cropping. As with the area-based FU, the disadvantage of such multifunctional FUs is that they do not provide a single product environmental footprint as required for labelling and evaluation of diet choice among other goals.

Final consumption and human nutrition FUs are often used to compare diet choices (Willett et al. 2019). However, due to the amount and complexity of data, most diet studies use international datasets rather than undertaking farm LCAs. To compare the nutritional footprints of alternative diets, potentially hundreds of footprints of food products are needed (Willett et al. 2019). To counter this situation, FUs that only cover one nutritional aspect are becoming common, such as protein content (MacWilliam et al. 2014; Karlsson et al. 2015). These FUs are not representative of other key nutrients. Furthermore, protein quality varies considerably depending on the source, with different amino acid compositions affecting human (and animal) nutrition (Sonesson et al. 2017; Leinonen et al. 2019). In developed countries, protein quality is less pertinent considering that the population largely over consumes protein, and net protein utilisation from various sources is similar for the adult population (WHO 2007). Notarnicola et al. (2017) recommend a careful analysis of nutritional values comprising not only fat, protein and energy but also other relevant nutrients. Van Dooren (2017) proposes a nutrition density unit as a FU, considering more than one nutritional aspect. However, Notarnicola et al. (2017) highlighted the limitation of such a FU when considering products that are consumed for a social aim, such as wine, beer, and coffee. Establishing human nutrition as a FU can bring additional limitations, especially when applying a cradle-to-gate boundary. First, it can be difficult to define nutritional composition for each product at the farm gate, in terms of specific elements (proteins, fatty acids, carbohydrates, vitamins, etc.) owing to the influence of soil type, climate and management (e.g. level of fertilisation) on concentrations of these elements. Additionally, nutritional FUs are usually intended for application to prepared foods ready to eat, following processing and cooking. In farm-level LCAs (most common approach for types I, II and III), nutritional aspects are difficult to define because the grains cultivated on the farm have different and sometimes unknown fates. The grains can supply different value chains across the food and feed industries requiring different levels of processing and therefore exhibiting different final nutritional values (FAO 2016). For example, cultivated chickpeas can be processed into flour, pasta, hummus, canned grains or just dried grains to be soaked and consumed. Therefore, assuming a nutritional value for chickpeas at farm level could be misrepresentative. Second, the FU could limit the boundaries of diverse agriculture systems, where co-products intended for energy or textile uses would need to be allocated off. Therefore, the best solution identified in this review is by Goglio et al. (2018a). Recognising the aforementioned limitations, they suggest a dual approach for crop rotations, simultaneously providing results for the rotation as a whole and for each product in the cropping system.

Assessing multiple impact categories can be also complicated in regional studies with wider boundaries, such as those integrating regional or international consequential analyses. In a consequential analysis, used by Knudsen et al. (2014a), the overall impact of producing more grain legumes in Europe was revealed to have a small climate benefit compared with importing soybeans. However, their study did not address nutrient carryover or other consequences at farm level, and only assessed GWP. One of the key potential advantages of introducing more legume cropping in Europe is the delivery of ecosystem services promoted by grain legumes (Karlsson et al. 2015). The choice of impact categories varies among the studies, and global warming potential is by far the most adopted impact category across all studies, which neglects potentially important co-benefits and trade-offs. For example, Costa et al. (2018) showed that complex crop-animal-tree rotation systems had a lower global warming potential but very high abiotic depletion (due to more use of animal feed compounds) compared with conventional (separate) systems. Regarding the calculators and tools designed to address LCA cropping system interactions, the Crop.LCA tool (Goglio et al. 2018b) is the only one that provides acidification potential, eutrophication and energy demand alongside global warming potential.

Following international guidelines such as ILCD (EC- JRC -IES 2011), or the more recent Product Environmental Footprint (European Commission 2018b), could be challenging for entire crop rotations owing to high data requirements. Impact categories and methods that assess soil quality, structure and biodiversity are not commonly reported in LCA (Gabel et al. 2016; Teixeira et al. 2016). Soil is often analysed at inventory level, e.g. accounting for the amount of land in the life cycle rather than a factor representing quality of land in terms of, e.g. SOC (Milà i Canals et al. 2007) or biodiversity (Koellner and Scholz 2007).

Product substitution and inclusion of consequential scenarios are found in studies performing product system expansion (type III). A common practice of product substitution is when organic fertilisation, including via legume residue incorporation, leads to credits from avoided synthetic fertilizer use (Nemecek et al. 2011; Brockmann et al. 2018). However, the inclusion of multiple avoided products and consequential analyses could be questionable due to the lack of standardisation and multiple speculative possibilities that can be evaluated (Mackenzie et al. 2017). Despite these limitations, the consequential approach has value in its ability to capture important indirect and intersystem effects (Ekvall and Weidema 2004). This is pertinent when the goal of LCA studies is to evaluate the consequences of introducing more legumes in to European rotations.

Consequential LCAs (type IV) are rarely applied to analyse legumes. However, the approach is pertinent when the goal is to understand cropping system changes at a regional scale. Compared with attributional LCA, consequential LCA could avoid the need for allocation through application of expanded system boundaries, whilst also capturing important potential (indirect) displacement effects in other supply chains. The lower yields of legume crops compared with cereals could mean that (cereal) production is displaced elsewhere, causing indirect land use change and international ‘leakage’ of environmental impacts (Styles et al. 2017). Meanwhile, legumes have an important role to play in diet change (providing quality plant protein to replace animal protein) and, as discussed, can enhance yields of subsequent crops. Therefore, legume deployment could also indirectly lead to carbon sequestration via, e.g. afforestation on spared land (Lamb et al. 2016). The balance of the aforementioned effects requires holistic evaluation of legume rotations and downstream (avoided) value chains. Consequential LCA has an important role to play here.

2.5 Conclusion

LCA is a key methodology to analyse the sustainability of food systems. This review finds that important interactions across years and crops are often neglected in LCA studies evaluating legume crops within rotations. Recent studies have demonstrated the importance of such interactions for product footprints (Brankatschk and Finkbeiner 2015; Nemecek et al. 2015; Goglio et al. 2018b). Thus, we recommend that LCA studies for legume cropping systems should (i) evaluate entire rotations and not just a single year of cultivation, at least including the crop following the legume; (ii) represent N, ideally also carbon, cycling alongside other agronomic effects within rotations (further fundamental research and agronomic models may be required); (iii) for attributional studies, define at least two functional units, where one should encompass the multifunctional outputs of entire rotation sequences (e.g. by assessing human or animal nutritional potential) and the other should enable product footprints to be calculated. Sensitivity analyses are important to test the effect of different allocation methods on footprints. (iv) for consequential LCA studies, account for both agronomic changes in rotations and displacement effects within crop commodity markets following the introduction of legume crops; (v) include impact categories that reflect hotspots for agricultural production, beyond just global warming potential (carbon footprints). There is a need to develop clear guidelines for assessing crop rotations in their entirety, and the effect of introducing new crops into rotations, which could be undertaken by a task force comprising multiple agri-sustainability and LCA stakeholders. Any guidelines should complement and build on existing general LCA guidelines and address appropriate functional units, system boundaries, priority impact categories and allocation methods.

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2.8 Appendix 1

Table 4: Papers regarding studies of legumes rotations through the Life Cycle Assessment

No	Date	Article	Focus of the study	Rotation/ Intercropping system with legumes?	N fixing assessed ?	Soil Organic Carbon	Functional Unit	Approach	Accounting (A) or comparison (C) ?	Alternatives compared/ assessed	Boundaries	Tools/ Method	Impact categories/ results	Allocation
1	2019	(Bais-moleman, Schulp and Verburg, 2019)	Sustainability of food system	Replacing monoculture cropping by crop rotation with legumes: maize and wheat with legume	Yes	No	consumption person/day	Attributional + Consequential scenario	C	1) human diet; 2) food waste in livestock diets; 3) monoculture vs. cropping to crop rotation, 4) incorporating crop residues into the soil.	Cradle to farm gate	BioGrace (2014), IPCC (2006), FeedPrint (2015)	Global Warming Potential (GWP)/ Land Use (m2/fu)	economic, land sharing, sensitive analysis with mass allocation
2	2019	(Alam, Bell and Biswas, 2019)	Rice rotations and its managements	Lentil, mung bean rice; mustard, irrigated rice rotations	NC	Yes	1 tonne of rice or rice equivalent yield (REY)	Attributional	C	Different systems management: puddled (CT) and non-puddled (NP) rice with the increased residue return (HR) and low residue return (LR)	Cradle to farm gate	IPCC 2013	Global Warming Potential	Not mentioned
3	2019	(Jacobs, Koch and Märländer, 2019)	Preceding crops in sugar beet cultivation	Sugar beet in rotation with winter wheat, mustard, silage maize and pea	Yes	No	Area [ha.yr]	Attributional	C	(i) winter wheat mustard sugar beet (ii) mustard silage maize sugar beet (iii) phacelia grain pea mustard sugar beet	Cradle to farm gate	IPCC 2013	Global warming potential	energy: dry matter yield * default energy content of each crop
4	2019	(Hedayati et al., 2019)	e Cotton supply chain Hot-Spots	Cotton-chickpea (legumes)	No	No	1 metric tonne cotton fibre (lint) at port.	Attributional	C	Cotton-break crop system.	Cradle to Port	IPCC 2006	Global warming potential	Economic among co-products of cotton
5	2018	(Carof and Godinot, 2018)	online tool to calculate three nitrogen indicators for farming systems	Temporary grassland (grass only, grass and legumes), maize, winter wheat, and alfalfa;	Yes	Yes	Area (per ha)	Attributional	A	Different farm systems (Example as 38 farming systems)	Cradle to farm gate	Bockstaller et al. (2009) and Rose et al. (2016)	SyNE: N-efficiency; SyNB: N-balance RNE: Relative N- efficiency; Global Warming Potential	

6	2018	Goglio, et al., 2018a)	Comparing GHG methods for rotation systems	Rotations (annual and perennial) with beans, wheat, barley, canola, maize, and alfalfa	Yes	Yes	1 GJ of gross energy output 1 ha	Attributional	C	Annual rotation (A): maize -faba bean-spring wheat - canola - spring barley - spring wheat and then maize Perennial rotation (P): maize-faba bean-four years of perennial cropping with alfalfa - maize	Cradle to farm gate	IPCC (2013); ICBM (Andren and Katterer (1997)), DNDC model (Uzoma et al., 2015).	Global Warming Potential	Not mentioned
7	2018	(Plaza-bonilla et al., 2018)	low-input innovative cropping system w/ legumes as cover crops	Rotations with no legume, 1 legume crop and 2 legumes crop	Yes	Yes	Area (ha)	Attributional	C	GLO: Sorghum - Sunflower-vetch-Wheat- (Vetch-oat); GL1:Sunflower-Mustard-Winter Pea-Mustard-Wheat-(Vetch-Oat) GL12: Soybean - Spring pea -Mustard-Wheat -Mustard	Cradle to farm gate	IPCC 2006	Global Warming Potential	Not mentioned
8	2018	(Carranza-Gallego et al., 2018)	wheat varieties under organic and conventional managements	Wheat -legume (Faba beans)	NC	Yes	1 ha of land and 1 kg of product	Attributional	C	Wheat -legume (ORG) wheat monocropping (CON)	Cradle to farm gate	IPCC 2013	Global Warming Potential	Economic
9	2018	(Hoffman et al., 2018)	organic and conventional production systems management	Corn-rye)-Soybean-Wheat-Soybean; (Corn-rye)-Soybean-Wheat-Soybean; vetch-(corn-rye)-soybean; vetch-(corn-rye)-soybean-wheat; Corn-rye/Soybean-Wheat/Alfalfa - Alfalfa - Alfalfa	Yes	No	Area (ha) and per crop yield	Attributional	C	(NT): (Corn-rye)-Soybean-Wheat-Soybean (CT): (Corn-rye)-Soybean-Wheat-Soybean (Org2) : vetch-(corn-rye)-soybean (Org3): vetch-(corn-rye)-soybean-wheat; (Org6): Corn-rye/Soybean-Wheat/Alfalfa - Alfalfa - Alfalfa	Cradle to farm gate	Farm Energy Analysis Tool (FEAT)	Global Warming Potential and energy use	Economic/mass-energy. Impact attributed to rye and legume cover crops were allocated to soybean and corn, respectively
10	2018	(Zucali et al., 2018)	Home-grown fodder crops and Milk through different cropping systems	Permanent crops (grass and alfalfa); cultivation of crops preserved as silage and cropping system aimed on the	Yes	No	Multiples FU (ha, kg of DM; 1 MJ of Net Energy for lactation (NEl); and 1 kg of	Attributional	C	HAY scenario: the entire farm land is dedicated to permanent crops (grass and **alfalfa)** for hay production; - SILAGE scenario: most of the farm land	Cradle to farm gate and cradle-to-the-animal's mouth	CML-IA baseline 3.01 method	Global Warming Potential; Acidification; Eutrophication; Non-renewable energy use (MJ).	Meat and milk: biological relation

				production of protein from home-grown feed.			digestible protein) MILK: 1 kg of fat and protein corrected milk (FPCM)			is used for cultivation of crops preserved as silage; **(lucerne** hay) - PROTEIN scenario: the cropping **system** is aimed to maximize the production of protein from home-grown feed.				
11	2018	(Reinsch et al., 2018)	Feed supply: Field management options	permanent grassland; grassland renovation; grassland conversion to maize and grass with clover	NC	NM	ha and (GJ ME ha−1) of harvested forage	Attributional	C	• Intact permanent grassland (PG) • Grassland renovation in spring (SR) • Grassland renovation in autumn (AR) • Grassland conversion to maize (CM) •Grassland (Grass-clover)	Only crop emissions	IPCC 2006 ; 2007	Global Warming Potential (GWP)	Not mentioned
12	2018	(Cai et al., 2018)	Rice rotations	Rotation of rice with fava beans, wheat, rapeseed oil and vetch	Yes	Yes	1 ha/yr	Attributional	C	Rotation of fava beans and vetch with rice: Rice-wheat (R-W); Rice-Rape (R-Ra); Rice-**Fava bean** (R-F); Rice-milk **vetch** (R-M)	Cradle to farm gate	IPCC 2006	Global Warming Potential (GWP)	Not mentioned
13	2018	(Hellwing et al., 2018)	Feed rotations for Bull calves	Feed import and forage ration based on grass-clover silage	NC	NM	amount of edible product	Attributional	C	(1) pelleted concentrate, chopped barley straw treated with sugar beet molasses; (2) maize cob silage ration with 40% of DM, soya bean meal, rapeseed meal and dried sugar beet pulp; (3) grass-clover silage (25% of DM), (4) grass-clover silage (60% of DM), rolled barley and rapeseed meal.	Cradle to slaughterhouse	Mogensen et al., (2014,2015, 2016)	Global Warming Potential (GWP)	Not mentioned
14	2018	(Goglio, et al., 2018c)	Tool that you can build many different rotations including energy crops	(maize-spring wheat)-canola - spring barley), while in the legume system,	Yes	Yes	Area (ha) kg of harvested product GJ of harvested	Attributional	A/C	Rotation without legume and with legume.	Cradle to farm gate	CED (Huijbregts et al. (2010),) ; GWP (IPCC	Cumulative Energy Demand (CED) Global Warming Potential (GWP) Acidification	different timeframes; - different considerations of by-products

				faba bean replaces maize			energy output Unit of economic value					2013), CML (2015)	Potential (AP) Eutrophication Potential (EP)	
15	2018	(Lesur-Dumoulin et al., 2018)	Crop systems energy design	Energy crops rotations such as mischantus, pea, wheat, alfalfa, rapeseed, among others	Yes	Yes	Area [ha. Yr]	Attributional	C	(1) M.giganteus-winter pea-rapeseed- wheat -alfalfa- wheat (2) Alfalfa- wheat-rapeseed-corn- pea-rapeseed- wheat; M.giganteus -alfalfa-triticale (catch crop)-corn; (3) M.giganteus -alfalfa - triticale-rapeseed- wheat (4) and (5) simulations of different time for crops on rotation	Cradle to farm gate	IPCC 2006	Global warming potential, Energy efficiency	NM
16	2018	(Yadav et al., 2018)	Tillage and mulching practices under rice-mustard system	Rotation with two tillage systems as the main-plot andfour mulch types as the sub-plot treatments under a split-plot design.	Yes	NM	Rice equivalent yield (REY)	Attributional	C	(1) rice straw mulch; (2) green manure mulch with Gliricidia sp; (3) brown manuring mulch of Cowpea (4) no mulch	Cradle to farm gate	Chaudhary et al., 2017 IPCC, 2007	Energy balance (energy use efficiency (EUE), energy productivity (EP)) Global warming potential	no co-products therefore no allocation
17	2017	(Prechsl et al., 2017)	cropping systems and cover crops	cover crop , winter wheat; cover crop, maize, faba bean, winter wheat and two years of grass–clover ley; (cover crop: white mustard or vetch)	No	No	Year Area (ha.yr) per Cereal Unit	Attributional	C	I. stockless conventional farming- vs. organic farming; II. Tillage: intensive tillage vs. no tillage or reduced tillage; III. Cover crop: non-legume vs. legume vs. mixture vs. control (fallow) (i) Summer fallow–wheat; (ii) Huai bean–wheat (iii) soybean –wheat; (iv) mung bean -wheat.	Cradle to farm gate	SALCA (Nemecek et al., 2010; Nemecek et al., 2011)	Global warming potential; Aquatic and terrestrial eutrophication; ecotoxicity; Biodiversity	no co-products therefore no allocation
18	2017	(Yao et al., 2017)	Green manure for wheat production	Soybean-Wheat; Huai bean-Wheat; Mung Bean-Wheat	Yes	Yes	Area (ha)	Attributional	C	(i) summer fallow–winter wheat (ii) Huai bean –winter wheat	Cradle to farm gate	IPCC 2013	Global Warming Potential (GWP)	NM

										(iii) soybean –winter wheat (iv) mung bean – winter wheat.				
19	2017	(Carlson et al., 2017)	Tool for carbon footprint (Ofoot) / case to assess an organic farm	potato - leguminous winter cover crop	Yes	Yes	kg of product or area (ha)	Attributional	A/C	(1) winter legume cover crop with fertilizer; (2): removal of winter cover with use of fertilizer; (3) removal of fertilizer with use of legume winter cover crop; (4): removal of fertilizer and replacement of a legume cover crop with a non-legume	Cradle to farm gate	IPCC 2007	Global Warming Potential (GWP)	NM
20	2017	(Parajuli et al., 2017)	Biorefinary	maize, grass-clover, ryegrass and straw from winter wheat. Grass-clover and ryegrass are perennial crops grown in crop rotation, while others are annual crops	Yes	Yes	DM of product (t); Area (ha); Energy (Mj);	Attributional	C	Maize, **grass-clover**, ryegrass and straw from winter wheat as products for biorefinary	Cradle to farm gate	The “EPD 2013” and “EPD 2008” method (Environdec, 2015); Freshwater Ecotoxicity (ILCD) plus Farm level (PestLCI 2.0.6 (Dijkman et al., 2012) and USEtox (Rosenbaum et al., 2008) PBD (De Schryver et al. (2010))	Global Warming Potential; Eutrophication; Non-Renewable Energy use (NRE); Fresh Water Ecotoxicity (PFWTox); Biodiversity Damages (PBD)	NM
21	2017	(Peter et al, 2017)	Tool for rotations (energy crops);	Crop rotation including double cropping systems and a green manuring crop and a second rotation including	Yes	No	area-based = ha; product-based = kg dry matter base = kg; product-based= MJ	Attributional	C	two crop rotations in two different regions in Germany - focus on EC(energy Crops)	Cradle to farm gate	CED (ISO 14040 and 14044 (2006)) ; GWP (IPCC 2013)	Cumulative Energy Demand (CED); Global Warming Potential (GWP)	nutrient carryover: The impacts are divided according to the specified number of crops;

				perennial alfalfa-grass sown as a secondary crop underneath the main crop barley.			of methane production potential							
22	2017	(Hunt, Hill and Liebman, 2017)	freshwater toxicity of crop rotations diversity systems	Corn-soybean sequences with oat/red clover/alfalfa	NC	NM	Area [ha]	Attributional	C	2-year corn-soybean sequence 3-year corn-soybean-oat/red clover sequence 4-year corn-soybean-oat/alfalfa-alfalfa sequence	farm level only	USETOX 2.0	Eco-toxicity	No co-products, therefore no allocation
23	2017	(Devakumar, Pardis and Manjunath, 2018)	Crops cultivated in the state of Karnataka	Rotations systems of cereals, legumes and oilseed crops	NC	NM	Area [ha. yr]	Attributional	A	Different crops under typical rotation systems: rice, wheat, Sorgum , ragi , maize, bajra, pulse crops (red gram , black gram , green gram , horse gram and bengal gram),soybean , oil seed crops such as sunflower and groundnut and commercial crop as cotton	Cradle to farm gate	IPCC and Lal R (2004) (Sust. Index)	Global Warming Potential and Sustainability index (carbon accumulated in the biomass to a unit of carbon released during the cultivation)	NM
24	2017	(Diacono et al., 2018)	synergy combination of a set of agro-ecological techniques	Crop rotations and cover crops introduction (barley, vetch and their mixture);	Yes	NM	Area [ha. yr]	Attributional	C	different techniques (soil surface shaping, rotation, cover crops introduction, cover crop termination techniques, organic fertilization)	Cradle to farm gate	(Khojasteh pour et al. 2015)	. Energy efficiency (renewable and non-renewable categories)	NM
25	2017	(Ali et al., 2017)	Wheat and faba bean rotation	Wheat and faba bean rotation	Yes	NM	1 Kg of grain	Attributional	C	Management systems of wheat-faba bean rotation. Rotation every year for five years (two cycles of wheat and faba bean plus start-up year).	Cradle to farm gate	IPCC 2006	Global warming potential	NM
26	2016	(Kulak, Nemecek and Frossard, 2016)	Bread production cropping systems	Cereals rotation, including grassland mixture with alfalfa. Also,	Yes	NM	1 kg of bread	Attributional	C	bread from integrated crop and livestock production and bread from horse farming systems	Cradle to Industry gate (Bread)	Kulak et al. (2015)	Renewable energy demand; Global Warming Potential; Ozone Formation;	Not mentioned for agriculture phase

				barley and pea intercropping as a part of other crop rotation									Ozone Depletion; Eutrophication (Terrestrial and aquatic); Acidification; Terrestrial and Aquatic Ecotoxicity Human toxicity potential Phosphorus Use; Land competition	
27	2016	(Guardia et al., 2016)	Systems with different tillage treatment and crops (cereal and legume)	wheat -vetch -barley	Yes	Yes	Area (ha.yr)	Attributional	C	different crop and tillage treatments: wheat -vetch -barley and wheat in mono-cropping for each tillage system (NT, MT, CT)	Cradle to Farm gate	Myhre et al., 2013	Global Warming Potential	Not mentioned
28	2016	(Adewale et al., 2016, 2018)	hot spots of an organic farm and carbon footprint of vegetables	Vetch, potatoes, cauliflower, dry bush beans, winter squash, summer squash, chard, peppers, and onions grown in a crop rotation.	Yes	Yes	ha.yr or Whole Farm.yr, per dry or fresh yield and 1 metric tonne of fresh organic vegetables	Attributional	A	The rotation	Cradle to farm gate	IPCC 2007	Global Warming Potential	gasoline and diesel allocated among the crops based on the management practices for each crop;
29	2016	(Moretti et al., 2016)	combine biophysical and monetary sustainability assessment tools through farm system analysis	Both farm types, cereals and legumes crop rotations; livestock activities are characterized by the presence of mainly sheep and to a lesser extent both sheep and cows.	NC	NM	Area: Farm with 40 ha of Utilized Agricultural Area (UAA)	Attributional	C	7 mixed farms and 7 specialized crop farms	Cradle to farm gate	ReCiPe (Goedkoop et al., 2012 CML-IA (Guinée et al., 2002) Eco-indicator 99 (Goedkoop and Spriensma, 2001).	terrestrial acidification; freshwater eutrophication; soil and freshwater ecotoxicity; natural land transformation; damage ecosystems quality aggregated index; Sustainable Value approach (SVA)	Not mentioned

30	2016	(Rodrigues et al., 2016)	Agro mining: Recovery of nickel from serpentine soils and producing ammonium nickel sulphate hexahydrate (ANSH) from the resulting ashes using hydrometallurgical processes	Alyssum murale – hyper accumulator (HA) rotations with forage, legumes, corn	NC	No	1 kg of HA plant ashes produced and processed into 353 g of ANSH	Attributional	C	(i) Alyssum murale + fallow (ii) A. murale is sown and harvested every year, while the vegetation already in place is still growing. (iii) A. murale is part of a diverse cropping system. (forage, legumes, corn)	Cradle to Product (synthesis of Ni-salts from biomass ashes)	ILCD 2011 (EC - JRC - IES, 2011)	climate change, ozone depletion, human toxicity (both cancer and nonn cancer effects), particulate matter, ionizing radiation, photochemical ozone formation, acidification, terrestrial and aquatic eutrophication, ecotoxicity, land use, water mineral resource depletion	If other crops species are harvested at the beginning of A. murale growth, only 10 months of the cropping cycle are allocated to A. murale in terms of impacts
31	2016	(Röös et al., 2016)	oat drink instead of cow's milk and alternatives for diary protein	Cereals and legumes rotations (for feed), grass–clover crop rotations in the different scenarios for energy (biogas)	Yes	Yes	880 t of a drink (function of milk) + 5 t of protein for human consumption (35 t on the high protein scenario) +14t rapeseed oil and protein feed (142 t of legumes + grazing of 49 ha of semi natural grassland.)	Attributional	C	Reference of cow milk with oat drink. Protein alternatives: 1) beef from sucker herds; 2) chicken 3) plant-based protein 3) plant-based protein, i.e. a combination of cereals and grain legumes	Cradle to Farm + energy to produce the oat drink at the factory and the energy needed in dairy industries + Avoided emissions	Guinée et al. (2002) and IPCC 2013	Eutrophication Acidification potential Ecotoxicity impacts; Global Warming;	All products leaving the farm were included in the functional unit to avoid allocation of impacts between products, which was not necessary
32	2016	(Hauggaard-Nielsen et al., 2016)	Grass–forage legume: intercropping strategies	Spring barley followed by intercrops of forage legumes and grasses and subsequent winter wheat	Yes	Yes	1 t DM of harvested biomass	Attributional	C	Rotations managements, with high and low N treatments	Cradle to Farm Gate	IPCC 2007	Global Warming Potential	NM

33	2016	(Arunrat, Wang and Pumijumnong, 2016)	Rice rotations	crop rotations (rice, corn, mung bean, soybean and watermelon)	NC	NM	Area [ha. yr]	Attributional	C	10 combinations of 2 and 3 years rice rotations with corn, mung bean, soybean and watermelon	Cradle to farm gate	IPCC 2007	Global warming potential	NM
34	2016	(Xia et al., 2016)	Rice rotations	Rice-cropping systems with wheat; fava bean, and fallow	NC	Yes	Area [ha. yr] and per kg of grain equivalent	Attributional	C	Rice rotations: rice-wheat ; rice-bean; rice-fallow	Cradle to farm gate	IPCC 2006	Global warming potential	NM
35	2015	(Ashworth et al., 2015)	Feedstock production by intercropping systems	switchgrass and legumes intercropped	Yes	Yes	Mg dry matter of switchgrass	Attributional, consequential scenario of comparison with gasoline	C	Comparison of ethanol production by switchgrass and switchgrass intercropped with legume	Cradle to farm gate	TRACI 2.0	global warming; acidification; carcinogens and non-carcinogens toxicity; respiratory effects ; eutrophication; ozone depletion; ecotoxicity; photochemical ozone creation; global warming	allocation of input data per time of the crop (Diesel and seeds)
36	2015	(Karlsson et al., 2015)	Faba Beans cropping systems	Faba Beans in the crop rotation	Yes	Yes	Area (ha)	Attributional and Consequential	C	• Reference (I): The current use of FB beans as protein feed, with the remaining biomass returned to the soil. • Biorefinery (II): All aboveground biomass harvested and processed in a biorefinery to produce ethanol, protein concentrate feed and fuel briquettes. • Roughage (III): All aboveground biomass harvested, ensiled and used as roughage feed.	Cradle to Industrial phase Gate (final product) + avoided emissions	IPCC inventory (ecoinvent)	Global Warming Potential; Arable land use; Primary fossil energy use	System Expansion + Area
37	2015	(Nemecek et al., 2015)	introducing legumes on typical rotations	Two crop rotations without pea and three alternatives crop rotations with pea	Yes	NM	Land management (cultivation ha per year) Financial function (Per Euro)	Attributional	C	Rotations with Pea in three regions - A total of 64 crop rotations were defined for the three regions	Cradle to farm gate	SALCA (Gaillard and Nemecek, 2009)	Demand for non-renewable energy resources; Global Warming Potential; Ozone Formation; Eutrophication; Acidification; Terrestrial and	No coproducts and therefore no allocation

													Aquatic Ecotoxicity Human toxicity; Biodiversity and Soil Quality	
38	2015	(Jakobsen et al., 2015)	Organic pig production systems	Grass-clover (lowest integration of forage) or a combination of lucerne, grass-clover and Jerusalem artichokes (highest integration of forage)	Yes	Yes	kg live pig weight.	Attributional	C	Indoor Finishing ; Free-Range: Grass–clover; Free-Range Alternative Crops (lucerne- barley - Jerusalem artichokes) (barley-grass/clover-barley)	Cradle to farm gate	IPCC 2007	Global warming potential	NM
39	2014	(Pirlo et al., 2014)	Buffalo milk farms	legume hay rotations as a feed cultivated on the own farm	Yes	No	1 kg of fat and protein corrected milk (FPCM)	Attributional	C	6 Buffalo Farms	Cradle to Farm Gate	IPCC 2006	Global Warming Potential	Economic allocation
40	2014	(Knudsen et al, 2014b)	European rotation without and with legumes	pea and faba beans on cereal rotations	Yes	No	1 tonne harvested crop (DM)	Consequential	C	Grain rotations and rotations with more legumes (less cereal) and its consequences	Cradle to Farm Gate + Consequences analysis	IPCC 2007	Global Warming Potential	No allocation
41	2014	(Knudsen, et al,, 2014a)	Organic and Conventional rotations	Organic rotations (mulching, biogas, no input and slurry) and conventional rotations systems	Yes	Yes	1 kg of harvested crop DM and 1 ha	Attributional and Consequential scenario (biogas)	C	(1) Spring barley – green manure – potato – winter wheat- catch crop- wheat- catch crop ; (2) Spring barley – catch crop - faba beans - catch crop - potato – winter wheat- catch crop;	Cradle to Farm Gate + avoided emissions (biogas instead of natural gas)	IPCC 2007	Global Warming Potential	Catch crops and green manure were divided equally on all other crops in the rotation on an area basis
42	2014	(Barton et al., 2014)	Wheat production	Wheat-Wheat (W-W); Lupin-Wheat (L-W)	Yes	NM	1) Area (ha.yr); 2) 1 tonne of wheat	Attributional	C	2 years rotation Wheat-Wheat (W-W); Lupin-Wheat (L-W)	Cradle to port	IPCC 2006	Global Warming Potential	Factor calculated by dividing the total amount of fertilizer avoided (i.e., saved) by the amount of N in the crop (AG; BG)
43	2014	(Bevilacqua et al., 2014)	Cotton production	Cotton on rotation (cotton-wheat USA;	Yes	NM	1 kg of dyed cotton yarn	Attributional	A/C	providers in China, Egypt, India and USA	Cradle to factory gate	Ecoindicator99 and IPCC 2007	Global Warming Potential; toxicity carcinogenesis; ozone layer	90% of environmental impact has been allocated to

				Clover-cotton Egypt)									depletion; Ionizing; radiation; Ecotoxicity; Acidification and eutrophication; Land Use; mineral resources, fuels, energy demand	cotton fibres and 10% to cotton seeds and for oil obtained from the cotton seeds is used energy allocation
44	2014	(Vries, Ven and Ittersum, 2014)	first and second biofuel generation	Biodiesel by 1 and 2 generation for different crops	Yes	Yes	per ha gross energy(GJ−1)	Attributional	C	1st generation: rapeseed and sugar beet under rotation 2nd generation : Miscanthus (rotation w potato) and Black locust (short rotation coppice/ willow)	Cradle to Conversion	IPCC 2006	net energy yield; GHG emissions, N leaching, soil organic carbon and soil erosion, and resource use efficiencies	No GHG emission credits were allocated to the generated co-products.
45	2014	(Macwilliam et al, 2014)	Pulses in crop rotations	dry pea or lentil replaced a spring wheat crop in a canola – spring wheat – spring wheat – spring wheat rotation	Yes	NM	grain for human consumption: one tonne of 14% protein-corrected grain	Attributional	C	oilseed-cereal rotation; lentil-cereal rotation; dry pea-cereal rotation;	Cradle to Storage	IMPACT 2002+ midpoint method (Jolliet et al., 2003)	carcinogens, non-carcinogens, respiratory inorganics and organics, ionizing radiation, ozone depletion; terrestrial and aquatic ecotoxicity, (atm and aquatic) acidification, land use, global warming potential and resource, non-renewable energy use and mineral extraction	N fixing N2O emission calculated through AB and BG biomass. Not mentioned co products and N-fix benefit attributed to reduced fertilization of wheat
46	2014	(Naudin, Werf and Jeuffroy, 2014)	LCA methods for co products	Pea-wheat intercrops	NC	NM	1 kg of grain (of either wheat or pea) Area [ha]	Attributional	C	comparison of co-product handling methods to estimate impacts of Sole Crops and Intercropping per kg of grain and per ha	Cradle to Farm Gate	CML 02 baseline	Global Warming Potential; eutrophication; acidification; terrestrial ecotoxicity; cumulative energy demand; land occupation;	-Economic and Mass -“Nitro” allocation was based on the N yield in grains. - System expansion (Syst)

47	2014	(Yang et al., 2014)	Crop Rotations	peanut rotations	NC	Yes	area kg biomass economic output	Attributional	C	Crop rotations with sweet potato, cotton, wheat, maize, ryegrass an peanut	Cradle to Farm Gate	IPCC 2006	Global Warming Potential	Not mentioned
48	2014	(Tidåker et al., 2014)	Integrated grass grain rotation for biogas production	2-year grass/clover ley in combination with spring barley and winter wheat	Yes	Yes	1 t of grain.	Attributional + Consequential scenario (biogas substitution of diesel)	C	(1) spring barley and winter wheat; (2) 2-year grass/clover ley in combination with spring barley and winter wheat	Cradle to Farm. Cradle to Biogas use (scenario)	IPCC (2007) Guinée et al. (2002)	Primary energy use, global warming potential (GWP), potential eutrophication potential acidification. Land use Indirect land use change affecting greenhouse gas (GHG) emissions was considered in the sensitivity analysis.	Digestate allocated for barley and the second year of winter wheat. The entire N requirement was assumed to be covered by the digestate.
49	2014	(Gan et al., 2014)	Wheat production systems	Rotations with wheat (mono-cropping, fallow and lentil)	Yes	Yes	Area [ha] per kg of grain produced (defined as per-yield carbon footprint)	Attributional	C	(i) fallow-flax-wheat; (ii) fallow-wheat-wheat; (iii) continuous wheat; (iv) Lentil-Wheat.	Cradle to farm gate	Rochette, P. et al.; IPCC	Global warming potential	NM
50	2013	(Yan, Humphreys and Holden, 2013)	Milk production systems	Rotational grazing systems (clover-pasture)	Yes	No	1 kg of ECM from herd in 1 yr.	Attributional	C	pasture under N fertilization and White Clover management in low-cost, grass-based systems	Cradle to Farm Gate	IPCC 2007	Global Warming Potential	Economic allocation
51	2013	(Cadoux et al., 2014)	Greenhouse gas balance of annual and perennial bioenergy crops	Six crops (perennial, semi perennial, annual; C4, C3, and legume crops).	Yes	No	Ethanol by: Conversion yields of biomass to ethanol on a DM basis ;Conversion yields of biomass to ethanol on a carbon basis	Attributional + GHG emissions saved by replacing fossil fuel by lignocellulosic ethanol	C	triticale grown after fibre sorghum and vice versa; alfalfa grown after fescue and vice versa	Cradle to farm gate	Modified version of Crutzen et al. (2008).	Global warming potential	NM

52	2012	(Spugnoli et al., 2012)	Sunflower systems for biodiesel	Alfalfa; wheat-tomato-sunflower-wheat-tobacco; Sunflower-clover-bell bean-wheat	NC	No	1 MJ of biodiesel; 1 ha per year of cultivated land and 1 kg of grain on dry matter (DM).	Attributional	C	5 farms with different sunflower rotations	Cradle to Process and Transport	IPCC 2006	Global Warming Potential	Energy content
53	2012	(Tuomisto et al., 2012a)	Approach towards weighting in LCA, based on the concept of a planetary safe operating space for human welfare as propounded by Rockström et al. (2009b).	Grass-clover; potatoes; winter wheat + under sown overwinter cover crop; spring beans; spring barley undersown Grass-clover.	Yes	NM	460 potatoes + 88t winter wheat + 60t field beans +66 t spring wheat	Planetary boundaries	C	1. Organic farm without biogas 2. Organic farm with biogas production (OB). The GC, CC and CR (straw of wheat and bean crops) were harvested for biogas production. Ploughing was used. 3. Conventional farm (C). Used mineral fertilizers and non-organic pesticides. 4. Integrated farm (IF). The crop rotation and biogas production were similar to the OB system, but non-organic pesticides were used. 5. Integrated special (IFS). As IF but instead of GC municipal biowaste was used as a fertilizer. Crop rotation consisted of potatoes, winter wheat, spring beans and spring barley.	Cradle to Farm Gate + Planetary boundaries Change according to the impact category	Planetaru boundaries: Rockström et al. (2009b) Biodiversity: adapted from De Schryver et al. (2010).	Climate change, rate of biodiversity loss, interference with nitrogen and phosphorus cycles, stratospheric ozone depletion, ocean acidification, global freshwater use, change in land use, chemical pollution and atmospheric aerosol loading.	Not mentioned
54	2012	(Hakala et al., 2012)	Clover grass leys (biomass for energy)	Clover grass leys –spring wheat; barley as cover crop;	Yes	NM	Mg of DM and for achieved energy from combustion or	Attributional	C	organic and mineral fertilizer	Cradle to Farm gate	IPCC 2006	Global Warming Potential	Emissions from organic matter of the manure allocated to the 1st yr crop

							anaerobic digestion (AD)							
55	2012	(Ma et al., 2012)	Maize rotations	Maize-legumes rotations	Yes	NM	[Area : ha] kg grain harvested;	Attributional	C	Maize annual rotation with soybean, maize with forage (alfalfa or red clover) and monoculture maize.	Cradle to farm gate	Gan et al. (2011a, b).	Global warming potential	Based on the yields
56	2012	(Tuomisto et al., 2012b)	Wheat from organic, conventional and integrated farming systems.	Wheat rotations with grass-clover; spring beans; potatoes; oats;	Yes	No	1 (t, 1000 kg) of wheat with 86% dry matter; area [ha]	Attributional	C	1.Organic farm without biogas production; 2. Organic farm with biogas production; 3. Conventional farm; 4. Integrated farm; 5. Integrated special;	Cradle to cooling and drying	IPCC 2006, (ISO 14040, 2006)	energy use; land use; Global warming potential;	Economic
57	2011	(Kristensen et al., 2011)	Dairy farms	Feed and legumes pastures under rotation with cereals	Yes	NM	1 kg energy corrected milk (ECM)	Attributional	C	Organic and Conventional	Cradle to Farm	IPCC 2006	Global Warming Potential	Casual relation (Milk and meat). No feed allocation was mentioned
58	2011	(Cooper, Butler and Leifert, 2011)	Rotation (organic and Conventional)	Conventional : wheat (2x) wheat - barley - Potato- wheat - barley- Grass/clover (2x) Organic: Wheat- Potato -Beans- Cabbages - barley- Grass/clover (3x)	NC	NM	1 t of crop; 1 unit of livestock feed; 1MJ human energy	Attributional + Consequential (GHG emissions avoided due to fossil fuel substitution were included and feed by-products)	C	Rotation (organic and Conventional) Comparison trial were compared with alternatives with varying end uses of agricultural by-products	Cradle to Farm Gate + Avoided emission according to the products use	IPCC 2007	Global Warming Potential	All livestock feed sold off the farm was to pig feeding. This was converted to human food energy using the digestible energy values for pigs
59	2011	(Nemecek et al., 2011)	Comparing farming systems	Potatoes, wheat, beetroot, barley and grass-clover ley wheat / silage maize – barley – sugar beet –wheat – protein peas	NC	NM	Area (ha .yr) financial (Swiss Franc return (CHF); kg dry	Attributional	C	Management under different systems (bio-dynamic, bio-organic, and conventional/ integrated	Cradle to Farm gate	(Frischknecht et al., 2004a); (IPCC, 2001); EDIP97; Hauschild and	non-renewable energy resources; global warming potential; ozone formation; eutrophication; acidification; terrestrial	Not mentioned

							matter yield;					Wenzel, 1998; CML01, Guinée et al., 2001; (Jeanneret et al., 2006); (Oberholzer et al., 2006).	ecotoxicity; aquatic ecotoxicity; human toxicity; biodiversity, Soil quality	
60	2011	(Gan *et al.*, 2011)	Wheat rotation systems	Rotation systems which had different combinations of oilseed, pulse, and cereal crops	Yes	NM	Area (ha.yr); 1 kg of wheat grain;	Attributional	C	Cereal-cereal- wheat Cereal-oilseed-wheat Oilseed-cereal-wheat Cereal-pulse-wheat Pulse-Cereal-wheat Pulse-Oilseed-Wheat Oilseed-Oilseed-wheat Oilseed-pulse-Wheat Pulse-Pulse-Wheat	Cradle to Farm gate	(IPCC, 2006) adapted for Canadian conditions (Rochette et al., 2008	Global Warming Potential	Wheat received the benefit of N off the previous legume plant
61	2011	(Nikiema et al., 2011)	Switchgrass system for energy	Alfalfa, silage corn, small grain rotation for 30-40 years, and introducing switchgrass	NC	Yes	area (ha)	Attributional	C	different doses of N on switchgrass after rotation with legumes	Cradle to Farm gate	IPCC 2006	Global Warming Potential	Not mentioned
62	2010	(Müller-lindenlauf, Deittert and Köpke, 2010)	Dairy farms	Feed (including legumes) produced in crop rotation	Yes	NM	kg of milk Area (ha) Per whole System	Attributional	C	Intensive tilth based farm Low-input; grassland based farm; Intensive grassland based farm; Low-input tilt farm	Cradle to Farm gate	(Geier et al., 1999; Haas et al.,2000; Geier, 2000; Wetterich, 2004)	Energy Consumption; Global Warming; Land demand; Nitrogen Emission; Soil fertility; Conservation, Biodiversity, Animal welfare and Milk Quality (rating)	No allocation to single crops
63	2010	(Hayer et al., 2010)	Rotation of introducing legume into traditional rotations	Introducing peas into standard rotations	NC	NM	Area (ha.yr), kg DM, € gross margin	Attributional	C	Rotation options - with legume and cover crops and reduced fertilisations	Cradle to Farm Gate	SALCA (Nemecek et al., 2010, 2011)	non-renewable energy demand, global warming potential, eutrophication, acidification and the eco- and human toxicity	NM

64	2010	(Halberg et al., 2010)	organic pig production systems with different levels of integration of livestock and land use	Integration of grass-clover in the organic crop rotations	Yes	Yes	kg live weight pig ; per ha (feed level)	Attributional	C	(i) Grassland with huts + fattening indoor (2) free range: grassland all year round (moving according to rotation) (3) one-unit pen system: pigs have access to grazing when suitable.	Cradle to farm gate	EDIP 97 (Wenzel et al., 1997, updated version 2.3)	eutrophication, acidification, global warming ; ozone depletion and land use	Feed: Scandinavian Feed Units =Barley equivalents were used in the 3 models
65	2008	(Nemecek et al., 2008)	Cereal and legumes rotations	crop rotations of cereals with legumes (Pea and Soybean) and without legumes	Yes	NM	1. Area (hectare. year) 2. Gross energy of products (MJ) 3. Financial function (total receipts minus the production costs)	Attributional	C	Comparison of cereals rotation system with legumes and without it	Cradle to Farm gate	SALCA, CML 01, (ecotoxicity simulation)	Global warming; Acidification; Eutrofication; Ozone formation; Energy Demand; Terrestrial and Aquatic ecotoxicity; Human toxicity; Soil quality and Biodiversity	no co-products therefore no allocation
66	2007	(Adler, Del Grosso and Parton, 2007)	Bioenergy cropping systems	Corn, soybean, alfalfa rotations	Yes	Yes	Conversion of biomass to ethanol or biodiesel [MJ]	Attributional	C	(1) switchgrass, (2) reed canarygrass, (3) corn–soybean rotation, (4) corn–soybean–alfalfa rotation and (5) hybrid poplar	cradle-to-grave	DAYCENT (Del Grosso et al. 2001a)	Global warming potential	Alfalfa co products: mass and substitution for energy co-products
67	2006	(Gronroos et al., 2006)	Organic milk and rye bread production	For the Milk: Grass for - Barley + grass seed - Oats + grass seed - Grass for pasture - Grass for silage - Barley + grass seed - pea-oats For the Rye: Oats - Set aside - Rye - Grass with clover (Green manuringand hay - Oats - Oats + grass seed	Yes	NM	1000 l of milk (1.5% of fat) + 1000 kg of rye bread	Attributional	C	Typical Finnish farm: conventional and organic systems.	Cradle to Retail	ISO standards 14040 and 14041 (ISO, 1997, 1998).	Primary Energy Use (Partial LCA)	Mass

68	2006	(Dalgaard et al., 2006)	National agricultural model to estimate resource use, production and emissions	Consider the main typologies to Danish farm types - grass-clover	Yes	NM	Area (ha)	Attributional	A	Different farms	Farm level	(IPCC 2000), C-TOOL (Petersen et al., 2002).	Nutrient Balance based on Life Cycle Thinking and emissions of global warming potential	Not mentioned
69	2006	(Castellini *et al.*, 2006)	Poultry	Legumes for feed – consistent with farm activities in Italy	NC	NM	Productive Cycle	Emergy	C	Poultry by conventional and organic rearing systems	Cradle to Farm gate	Emergy	transformity, environmental loading ratio (ELR) and emergy yield ratio (EYR)	energy
70	2005	(Cederberg et al., 2005)	Pig feed systems	Feed systems: (1) oats-winter wheat- barley - winter wheat - Triticale (+ imported soy-meal) (2) W.Rapeseed -Winter Wheat-Barley + catch crop- Peas - Winter Wheat+ Catch Crop-Oats -Barley	NC	NM	‘1 kg of bone- and fat-free meat	Attributional	C	(1) oats-winter wheat-barley - winter wheat - Triticale (+ imported soy-meal) (2) W.Rapeseed - Winter Wheat- Barley + catch crop- **Peas** - Winter Wheat+ Catch Crop-Oats -Barley	Cradle to farm gate	ISO 14040 and as described by (Cederberg and Flysjo 2004).+ Pri-Farm to model farm level pesticides (Bergkvist, P. 2004)	Eutrophication, Energy Use, Global warming potential, PRI-Farm Model	Economic: The environmental burden was allocated between main products and coproducts (e.g. in feed production) according to the price of the products

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3 **Chapter three:** Legume-modified rotations deliver nutrition with lower environmental impact

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Highlights

- Life Cycle Assessment was undertaken for 10 cropping sequences across 16 impact categories
- Two functional units were applied to rotation outputs: human and animal nutrition potential
- Legume-modified rotations were compared with conventional baseline rotations
- Legume-modified rotations deliver nutrition at lower environmental cost
- Legume-modified rotations derive maximum benefit when crops go direct to human nutrition

Abstract

Introducing legumes to crop rotations could contribute towards healthy and sustainable diet transitions, but the current evidence base is fragmented across studies that evaluate specific aspects of sustainability and nutrition in isolation. Few previous studies have accounted for interactions among crops, or the aggregate nutritional output of rotations, to benchmark the efficiency of modified cropping sequences. We applied life cycle assessment to compare the environmental efficiency of ten rotations across three European climatic zones in terms of delivery of human and livestock nutrition. The introduction of grain legumes into conventional cereal and oilseed rotations delivered human nutrition at lower environmental cost for most of the 16 impact categories studied. In Scotland, the introduction of a legume crop into the typical rotation reduced external nitrogen requirements by almost half to achieve the same human nutrition potential. In terms of livestock nutrition, legume-modified rotations also delivered more digestible protein at lower environmental cost compared with conventional rotations. However, legume-modified rotations delivered less metabolisable energy for livestock per hectare-year in two out of the three zones, and at intermediate environmental cost for one zone. Our results show that choice of functional unit has an important influence on the apparent efficiency of different crop rotations, and highlight a need for more research to develop functional units representing multiple nutritional attributes of crops for livestock feed. Nonetheless, results point to an important role for increased legume cultivation in Europe to contribute to the farm and diet sustainability goals of the European Union’s Farm to Fork strategy.

Keywords: legumes, nutritional functional unit, rotation systems, animal feed, human food.

3.1 Introduction

Agricultural practices must evolve to deliver food security whilst reducing environmental impact. On the one hand, modern technologies have been developed and adopted to apply inputs such as fertilisers and water with more precision, producing crops more efficiently within "conventional" intensive systems. On the other hand, there are efforts to break the current state of technological lock-in of intensive mono-cropping by promoting "agro-ecological" intensification in order to reduce high dependence on finite resources such as phosphorus fertilizers and fossil energy whilst reducing greenhouse gas (GHG) emissions, loss of reactive nitrogen and soil degradation (Rockström et al., 2020). Such agro-ecological intensification may include more biological nitrogen fixation by legumes, extended rotations, intercropping and possible introduction of livestock into crop rotations. The European Green Deal Farm to Fork strategy aims to develop a "fair, healthy, and environmentally-friendly food system", with specific objectives to reduce GHG emissions and chemical pesticide use by 50% and synthetic fertiliser use by 20% by 2030 (European Union, 2020).

Legumes are arable crops from the Leguminosae family, which have the ability to fix nitrogen from the atmosphere and therefore avoid the use of other external sources of nitrogen fertilisers (Peoples et al., 2019). These crops provide a significant quantity of nitrogen to following crops, reducing mineral fertilizer requirements and GHG emissions across entire rotations (Rochette and Janzen, 2005; Watson et al., 2017). Legume cultivation has been associated with other benefits, including diversification of crop rotations (Hufnagel et al., 2020, Nemecek et al., 2008) which can break pest and disease cycles (Macwilliam et al., 2014), improved soil quality and drought resistance through deep root systems, and support for pollinating insects (Peoples et al., 2019). Legumes are mainly grown for food and feed purposes (Watson et al., 2017; Nemecek et al., 2008), but they also supply value chains for, inter alia, alcoholic beverages (Lienhardt et al., 2019), biorefineries (Karlsson et al., 2015) or green manures (Baddeley et al., 2017).

From a human nutritional perspective, legumes are a source of macro- and micro-nutrients providing protein, fibre, folate, iron, potassium, and magnesium and vitamins (Chaudhary et al., 2018b), delivering a richer nutrient profile than cereals or meat alternatives. Substituting meat with protein-rich legume-derived foods has the potential to simultaneously decrease environmental impact whilst improving nutritional profile (Jensen et al., 2012; Peoples et al., 2019; Saget et al., 2020). The EAT-Lancet Commission 'planetary healthy' diet recommends a lower daily intake of red meat and an increase of legume intake to deliver a diet which is simultaneously more nutritious and sustainable (Willett et al., 2019). Saget et al. (2021) has shown that replacing just 5 % of meatballs in Germany with pea protein balls could resut in climate mitigation of 8 million tonnes CO2 eq. annually, 1% of Germany’s annual GHG emissions.

Despite these pertinent benefits, legumes are not widely cultivated in Europe, covering only 1.5% of European arable land, compared to 14.5% worldwide (Watson et al., 2017). Meanwhile, large quantities of soybean are imported into Europe as protein-rich animal feed, from countries where its production may drive deforestation (Watson et al., 2017). Therefore, the introduction of legumes to European crop rotations could play a key role in Europe’s Farm to Fork strategy, but the current evidence base is fragmented across studies that typically evaluate specific aspects of environmental sustainability and nutrition in isolation. There is an urgent need for more holistic Life Cycle Assessment (LCA) approaches to evaluate the environmental sustainability of increased legume cropping in Europe, using complex functional units (FU) or more sophisticated biophysical allocation across crop products (Brankatschk and Finkbeiner, 2014) in order to represent: (i) the dynamics of particular cropping sequences; (ii) functional output in relation to balanced nutritional requirements.

Cultivating new crops incurs changes to rotation systems (cropping sequences) that have environmental and productivity implications beyond the specific inputs and outputs of the new crop in question. Yet, with few exceptions (MacWilliam et al., 2014; Nemecek et al., 2008), most LCA studies are designed to investigate one isolated crop rather than the whole crop rotation, often missing important nutrient cycling (via crop residues) and crop sequence effects that can strongly influence comparative environmental efficiency (Costa et al., 2020). Numerous authors encourage analysis of entire systems rather than individual crops (Brankatschk, 2018; Brankatschk and Finkbeiner, 2015; Peter et al., 2017). Analysing whole rotation sequences from cradle-to-gate introduces the challenge of selecting an appropriate functional unit (FU) to represent multiple crop outputs. Previous rotation LCA studies have often related environmental burdens to highly simplified FU such as tonnes of dry matter or ha.yr (hectare per year) cultivated (e.g. (Plaza-Bonilla et al., 2018)). Such FU can be misleading, through disregard for the nutritional value of different crops and via the implication that less agricultural activity (and thus potentially productivity) per unit area is always environmentally favourable (Brankatschk, 2018). Brankatschk and Finkbeiner (2014) propose the Cereal Unit (CU), a metric based on the digestible energy content of each crop, to aggregate multiple crop outputs across rotations intended to produce animal feed. An alternative FU is the amount of protein provided for feed (Karlsson et al., 2015). Reflecting the lack of consensus regarding the FU for rotational systems, and the potentially diverse end uses of crops, it may be prudent to apply more than one FU when benchmarking environmental efficiency across different systems (Goglio et al, 2018).

Meanwhile, food (rather than farm) LCA studies have applied FUs defined by single or multiple aspects of human nutrition. Sonesson et al. (2017) propose a quality-adjusted protein metric which considers essential amino acids. Notarnicola et al. (2017) highlight the importance of looking at the wider nutritional composition of products, in terms of fat, protein, and energy content amongst other relevant nutrients. Recently, other authors have combined multiple nutrients within a single functional unit, such as the Nutrient Balance Score (Chaudhary et al., 2018a,b), or the Nutrient Density Unit, a simplified FU that considers the balance of protein, fibre, essential fatty acids, and energy content in a certain product (Van Dooren, 2017). These innovations have been applied in recent LCA studies to better represent the nutritional functionality of different foods (McAuliffe et al., 2020). However, with few exceptions (Li et al., 2018; MacWilliam et al., 2014), these more complex metrics of human nutrition have not yet been applied to compare the efficiency of different crop rotations.

In this modelling study, we apply three FUs to benchmark the environmental efficiency of legume-modified crop rotations against counterpart conventional rotations across three climatic regions of Europe, considering potential nutrition delivery to livestock and directly to humans.

3.2 Material and methods

3.2.1 Rotations across Europe

This study compares the environmental impact of ten crop rotations across three contrasting geo-climatic arable regions in Europe (Table 5). Rotations are categorised into three typologies: cereal-cereal [C-C], cereal-oilseed [C-O], and cereal-oilseed-legume [C-O-L] systems. The first region analysed was Calabria, southern Italy (IT), representing Mediterranean Europe. The second was Sud-Muntenia in Romania (RO), representing continental Europe, and the last region was eastern Scotland (SC), representing Atlantic Europe. Simulated rotations were adapted from Reckling et al. (2016a), modelled using a rotation generator (Reckling et al., 2016b) in which the following aspects were considered: (i) Crop rotations spanning between 3 and 6 years, (ii) suitable crop sequences (iii) frequency of a crop in rotation (iv) minimum break between the same crops and (iv) maximum frequency of crops of the same crop types. Management of the rotations and further assumptions are available in Table 10. (Supplementary Information (SI)), whilst details of nutrient cycling and emission factors are summarised in Inventory and Impact Assessment framework.

Table 5: Crop sequences of each rotation in Scotland (SC), Italy (IT), and Romania (RO). [C-C] is cereal-cereal, [C-O] is cereal-oilseed and [C-O-L] is cereal-oilseed-legume rotation system.

Scotland rotations	SC [C_O #1] cereal-oilseed option 1	Rapeseed - Wheat - Wheat- Barley - Barley
	SC [C_O #2] cereal-oilseed option 2	Rapeseed - Barley - Oats- Spring Barley - Barley
	SC [C_O_L] cereal-oilseed-legume	Rapeseed - Barley - Oats- Peas - Barley
Italy rotations	IT [C_C] cereal-cereal	Oats- Barley-Oats- Barley
	IT [C_O] cereal-oilseed	Rapeseed- Barley-Rapeseed- Barley
	IT [C_O_L] cereal-oilseed-legume	Rapeseed- Barley-Rapeseed- Barley -Fava Bean
Romania Rotations	RO [C_O #1] cereal-oilseed option 1	Sunflower - Maize -Wheat
	RO [C_O #2] cereal-oilseed option 2	Rapeseed - Maize - Barley
	RO [C_O_L #1] cereal-oilseed-legume option 1	Common Bean - Maize - Barley - Rapeseed
	RO [C_O_L #2] cereal-oilseed-legume option 2	Soybean - Maize - Barley - -Rapeseed

3.2.2 The Life Cycle Assessment method

3.2.2.1 Goal and Scope

An attributional cradle-to-farm-gate LCA was used to benchmark the environmental efficiency of legume-modified rotations against typical rotations that they may replace in different regions of Europe, in relation to provision of feed and food, using novel nutrition-based FUs. The target audience for this study comprises researchers and policymakers with an interest in more sustainable cropping systems for food and feed nutrition. Since our main goal concerns entire rotations and not individual products, we chose FUs to represent potential nutrition for human food and animal feed. Use of crops for bioenergy systems or direct livestock grazing are outside the current scope.

3.2.2.1.1 Functional Unit for Human Food (FU_{Food})

The first sub-goal was to quantify the potential contribution of crude grain rotation outputs to human nutrition. Human food nutritional FUs are commonly applied to processed food rather than farm-level LCA studies (McAuliffe et al., 2020). FUs based on nutrient scores aggregate quantities of different nutrients, ranging from 3 nutrients as proposed by van Dooren (2017) for the Nutrient Density Unit (NDU) to 27 nutrients as applied by Chaudhary et al. (2018b). The latter metric is particularly relevant to assess food prepared for final consumption, often containing many ingredients. However, the former metric is simpler, especially for crude agricultural grains that have not yet been processed into final products and therefore cannot be assessed at high resolution. Additionally, the 3-nutrient and energy score correlates well with the nutrient-rich foods index (NRF 12:3) as shown by Saget et al. (2020). Thus, we adapted the formula proposed by van Dooren (2016), accounting for protein, fibre, and energy content of the crude grains compared to the daily recommended intake values (Equation 1). We omitted the essential fatty acid owing to lack of comparable data.

Equation 1: The Nutrient density Unit, adapted from van Dooren (2016):

$$\mathrm{NDU}_{P\text{-}F} = \frac{\left(\frac{Protein}{DV_{prot}}\right) + \left(\frac{Fibre}{DV_{fibre}}\right)}{2 \times \left(\frac{S_i}{SDRI}\right)}$$

Protein is the amount of protein in 100g of the product, expressed in grams.
Fibre is the amount of fibre in 100g of the product, expressed in grams.
DV_{prot} is the recommended daily value intake of protein, expressed in grams.
DV_{fibre} is the recommended daily value intake of fibre, expressed in grams.
S_i is the kilocalorie energy content in 100g of the product.
SDRI is the recommended daily intake of energy, expressed in kilocalories.

DVprot and DVfibre were set at 50 and 25 respectively based on a 2000 kcal dietary reference intake (SDRI) as proposed by van Dooren (2017). In order to use readily available and consistent data for both food and feed FUs in this ‘proof-of-concept’ study, human-digestible protein, fibre, and energy values were taken from (Heuzé et al., 2017), using values for pigs as proxies. Implications of data availability are discussed later. The composition of nutritional values calculated for each crop can be found in Table 12, SI.

3.2.2.1.2 Functional Unit for Animal Feed (FU_{Feed})

For the second sub-goal, to evaluate the efficiency of rotations to deliver animal feed, we analysed two FU:

(i) Cereal unit (CU) (Brankatschk and Finkbeiner, 2014), representing the sum of metabolisable energy in all macronutrients (crude protein, crude lipids, crude fibre, and nitrogen-free extracts containing hydrocarbons) – calculated as weighted average energy across the German livestock profile (pigs, poultry, cattle, and horses). The final value is converted into 1 kg of barley feed energy equivalent.

(ii) Total digestible protein (DP) content, considering values for ruminants, of each grain crop and straw under the rotations.

The values for crude protein were taken from (Heuzé et al., 2017), while values for the cereal unit were adopted from Brankatschk and Finkbeiner (2014). The values for final DP and CU for each crop and straw were calculated firstly per kilo of product, then multiplied by the yields of that product, and finally aggregated by summing all products across each rotation. The final output of each rotation was then divided by the time length (years) of the rotation. To ensure transparency, the calculation of each crop under each rotation is recorded in Table 12, SI. No variation of the nutrient content was considered for the crop according to fertilization rates or regional aspects. The final input and output of all rotations per FU analysed can be observed in Table 14, SI.

3.2.2.2 System boundaries

The LCA was completed from cradle to farm gate. All processes from the extraction of raw materials, manufacturing, use, and all farm operations up to the harvesting of the grains were considered. Since the main goal was to study crop rotation sequences, downstream processes such as transportation, drying, and storage of grains, were excluded from the analysis. System boundaries are described in Figure 5.

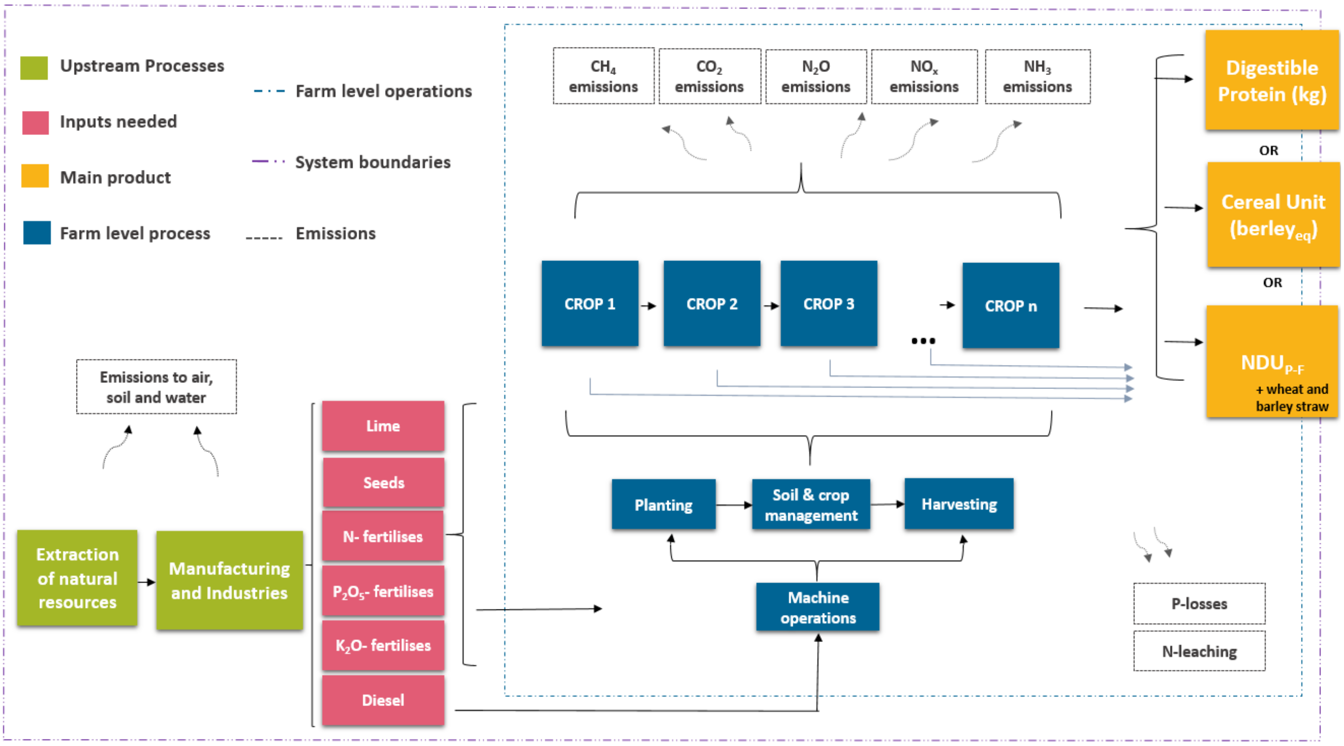

Figure 5: LCA boundaries of the rotation systems to deliver nutrition to animals (DP and CU) and to humans (NDU$_{P-F}$).

3.2.2.3 Inventory and Impact Assessment framework

Modelling was undertaken in Open LCA v1.9 (GreenDelta, 2006), using Ecoinvent v.3.5 database for background data (Moreno-Ruiz et al., 2018). Activity data and crop performance all originate from crop sequence simulations published previously (Reckling et al., 2016a). All field emissions were re-calculated in the present study based on the most recent emission factors, with the exception of nitrate (NO_3^-) leaching which was calculated using an N balance approach in Reckling et al., (2016a). In this study, ammonia (NH_3), nitrous oxide (N_2O), and carbon dioxide (CO_2) emissions were calculated according to Intergovernmental Panel on Climate Change (IPCC) (2006; 2019) emission factors (Table 11,SI), whilst phosphorus (P) runoff was calculated according to a 1% loss factor applied in a previous crop LCA study (Styles et al., 2015) (Table 11,SI). The inventory was generated using assumptions and allocations fully described in the Supplementary Information.

Life Cycle Impact Assessment (LCIA) was performed using the method recommended by the European Commission - Product Environmental Footprint (PEF) guidelines (European Environmental Bureau et al., 2018). This method was selected because it is comprehensive and aligns with the aim to harmonise European environmental footprint studies. The method recommends the calculation of 16 environmental impact categories (Table 13, SI) and is appropriate to the geographic location of the analysed rotations (i.e. Europe). PEF guidelines were also followed for normalisation. After presentation in their specific units, indicator values for each impact category were divided by average annual EU27 per capita burdens to generate normalised scores. Normalised scores (expressed as person.year^{-1}) for all categories were summed up to calculate total environmental impact with an assumption of equal weighting, an optional step in PEF guidelines (European Environmental Bureau et al., 2018) that can facilitate simplified communication and reporting. Categories with the largest normalised scores, cumulatively responsible for at least 80% of the total environmental impact, were investigated in more detail in the results section. The human toxicity categories were not reported in detail because (i) there was no primary or secondary data about crop protection application to the rotations, and (ii) of the uncertainty related to these categories, classified as interim categories within the PEF method (European Environmental Bureau et al., 2018).

3.2.2.4 Sensitivity analysis

We decided to test the robustness of the apparent efficiency of legume rotations for the NDU_{P-F} FU by simulating more efficient N-fertiliser use across all non-legume crops in each rotation. The simulation assumed use of nitrification inhibitors (NI) and urease inhibitors (UI). We varied the N_2O Emission Factors, yields, and N application based on published metaanalyses (Abalos et al., 2014; Gilsanz et al., 2016; Li et al., 2017; Thapa et al., 2016) to understand how this would affect the results on overall impact categories. The specific factors adopted are elaborated in the supplementary information.

3.3 Results

Overall, the legume-modified rotations delivered more DP per ha per year (animal feed) and more NDU_{P-F} (human food) across the regions studied (Table 6). This was not the case for CU (animal feed). These results are explained further in sections for human nutrition and for animal nutrition below.

Table 6: Outputs of the rotations in terms of DP, CU, and NDU_{P-F} per hectare per year of each rotation in Scotland (SC), Italy (IT), and Romania (RO). The highest output (ha.yr^{-1}) for each FU (per column) is shaded dark green and the lowest in shaded in red.

Rotation	Digestible Protein (kg) (grain +straw)	CU total (grain +straw)	Crude NDU_{P-F}
SC [C_O #1] cereal–oilseed option 1	664	8,956	682
SC [C_O #2] cereal–oilseed option 2	585	7,926	896
SC [C_O_L] cereal–oilseed -legume	681	7,469	950
IT [C_C] cereal–cereal	202	3,259	370
IT [C_O] cereal–oilseed	303	3,543	299
IT [C_O_L] cereal–oilseed-legume	320	3,101	313
RO [C_O #1] cereal–oilseed option 1	281	3,302	285
RO [C_O #2] cereal–oilseed option 2	344	4,245	357
RO [C_O_L #1] cereal–oilseed- legume option 1	392	3,633	370
RO [C_O_L #2] cereal–oilseed- legume option 2	468	4,034	385

3.3.1 Impact category results

The results for all 16 impact categories across each impact category and for each nutritional FU are displayed in radar charts (normalised scores) and tables (indicator values) below, and in Supplementary Information Figure 10. Six impact categories were responsible for at least 80% of the total environmental impact: climate change, terrestrial eutrophication, marine eutrophication, land use, terrestrial and freshwater acidification, and respiratory inorganics (Table 17, SI). The results for these impact categories are described below.

3.3.2 Process contributions

For each of the six priority impact categories, we investigated process contributions greater than 1% of the impact for each rotation. Five of the six priority impact categories relate to synthetic nitrogen fertilisers (SNF) and associated field emissions. We found that NH_3 emission into the air due to volatilization from N-based fertilisers was the main driver for terrestrial and freshwater acidification and respiratory inorganics. Climate change potential is driven by N_2O emissions after SNF application, followed by CO_2 emitted by urea and lime application and by nitric acid production (Figure 6). The latter emission is derived from a market dataset for this fertiliser formulation from the Ecoinvent database (Moreno-Ruiz et al., 2018). In this study, at least 95% of overall land use relates to direct land occupation by each rotation sequence (Table 16, SI). The land use category is therefore inversely related to land efficiency, i.e. how many hectares are needed to deliver the FU (Table 6). Marine eutrophication potential is mostly linked with NO_3^- leaching (Figure 6) and this data was calculated for each crop under each rotation from the model of Reckling et al. (2016a).

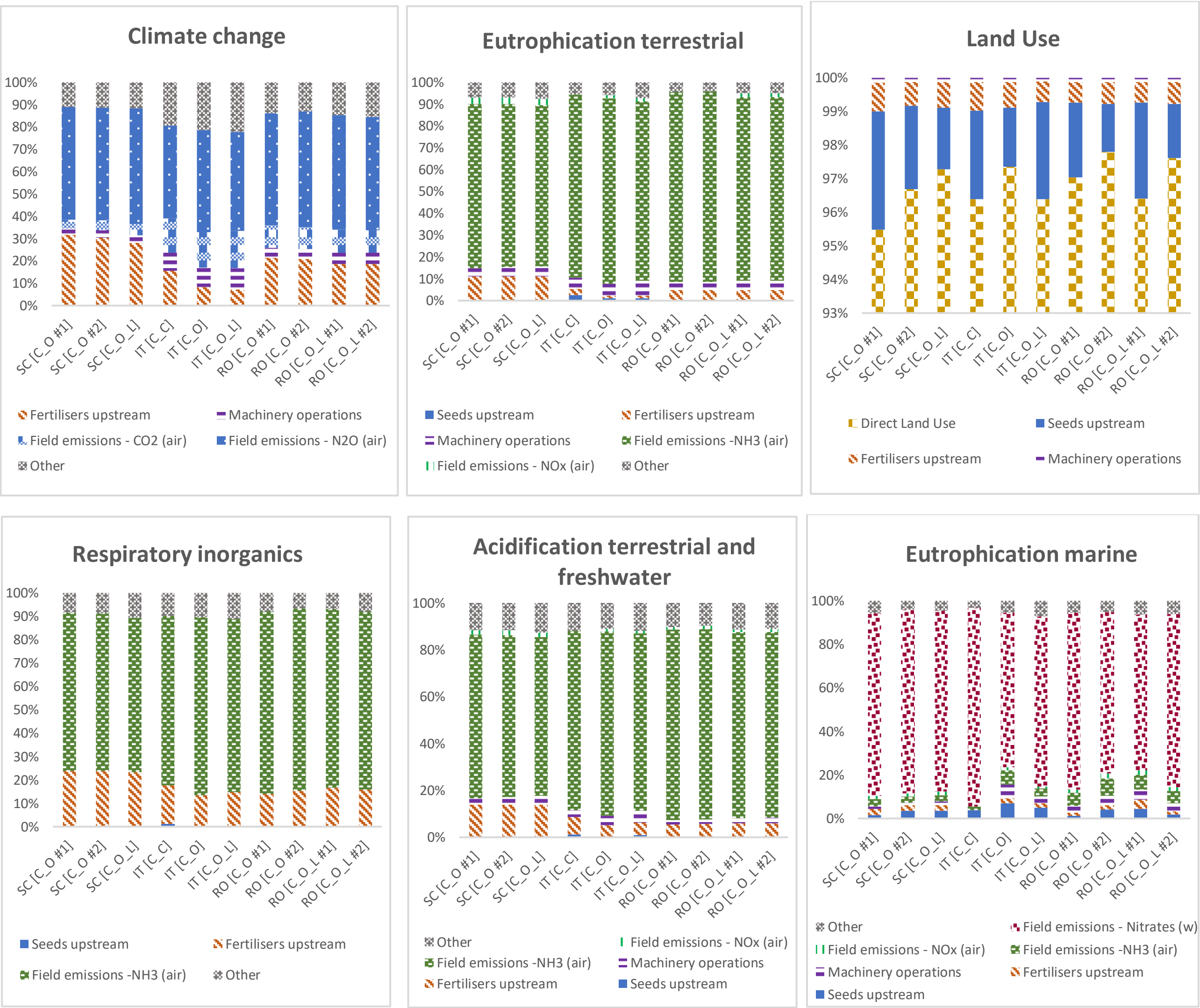

Figure 6: Process contributions for the six priority impact categories across the ten rotations of cereal (C_), oilseed (_O_), and legume (_L) in Scotland (SC), Italy (IT), and Romania (RO) for the NDU$_{P-F}$ FU.

3.3.3 Human nutrition footprints

The greatest amount of (potential) human nutrition per hectare year was delivered by Scottish rotations (NDU$_{P-F}$ 682–950), followed by Romanian (285-385) and Italian (299-370) rotations, respectively. The highest NDU $_{P-F}$ values are associated with higher-yielding legume-modified rotations in Scotland (Table 6). The SNF applications per one NDU$_{P-F}$ for each rotation can be observed in Table 15, SI, as a useful metric of nutrient use efficiency from a nutrition perspective and as a proxy for wider resource and environmental efficiency. Italian rotations had the lowest SNF requirement per NDU$_{P-F}$ followed by Scotland and Romania. However, the introduction of a legume crop into the Scottish rotation was highly beneficial, reducing the SNF requirements per NDU$_{P-F}$ by almost half, from 0.28 kg N per NDU$_{P-F}$ for cereal-oilseed rotation (SC [C_O #1]) to 0.14 kg N per NDU$_{P-F}$ for the legume-modified option

(SC [C_O_L]). The Romania legume-modified rotation incurred a reduction of 0.15 kg N per NDU$_{P\text{-}F}$, from 0.36 kg N/NDU$_{P\text{-}F}$ for the cereal-oilseed rotation (RO [C_O #1]), to 0.21 kg N/NDU$_{P\text{-}F}$ for the legume-modified option (RO [C_O_L #2]) (Table 15, SI). Italian rotations presented both the smallest requirement of SNF per NDU$_{P\text{-}F}$ (0.04 kg N and 0.11 kg N for C_O and C_O_L rotations, respectively) and the smallest reduction of SNF attributable to the legume-modified rotation (0.04 kg N per NDU$_{P\text{-}F}$).

For the FU$_{Food}$, all the legume rotations across all regions incurred lower environmental impacts across the majority of the 16 environmental impact categories assessed (Table 7) Scottish legume-modified rotations performed better across all impact categories. A few trade-offs were found for Romania, where the legume-modified rotation scored better in 14 impact categories but worse in two categories (Ecotoxicity freshwater and marine eutrophication) relative to non-legume rotations (Table 7). For Italy, more trade-offs were observed, where the legume-modified rotation scored better across 10 out of 16 impact categories compared with both the rapeseed and cereal rotations. The Romanian legume-modified rotations showed a slightly better performance for soybean than the common bean. Despite the yields of soybean being slightly lower, the NDU$_{P\text{-}F}$ of the grain is higher. The radar chart for Romanian rotations is available below (Figure 7), while the equivalent figures for Scottish and Italian rotations can be found in Figure 10, SI.

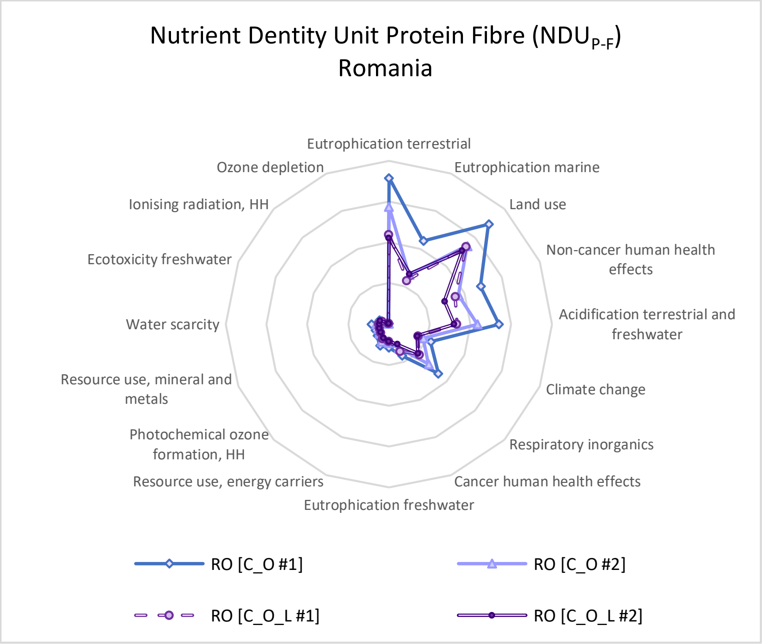

Figure 7: Normalised environmental scores per unit of protein and fibre nutritional output (NDU$_{P\text{-}F}$) across Romanian crop rotations. RO [C_O #1] refers to cereal-oilseed rotation option 1, RO [C_O #2] refers to cereal-oilseed rotation option 2, RO [C_O_L #1] refers to cereal-oilseed-legume rotation option 1 (with common bean) and [C_O_L #2] refers to cereal-oilseed-legume rotation option 2 (with soybean).

Table 7: Heat map of impact scores across all impact categories for all rotations analysed in Scotland (SC), Italy (IT), and Romania (RO), expressed per unit of protein, fibre, and energy nutritional output (NDUP-F). For each impact category and each region, the result for the rotation configuration with the highest impact is shaded darker red and the result for the rotation with the lowest impact is shaded darker green.

	Scotland			Italy			Romania				
Impact Category	SC [C_O #1]	SC [C_O #2]	SC [C_O_L]	IT [C_C]	IT [C_O]	IT [C_O_L]	RO [C_O #1]	RO [C_O #2]	RO [C_O_L#1]	RO [C_O_L#2]	**Unit**
	cereal-oilseed option 1	cereal-oilseed option 2	cereal-oilseed-legume	cereal-cereal	cereal-oilseed	cereal-oilseed-legume	cereal-oilseed option 1	cereal-oilseed option 2	cereal-oilseed-legume option 1	cereal-oilseed-legume option 2	
Eutrophication terrestrial	2.85E-01	1.79E-01	1.44E-01	3.08E-01	3.66E-01	2.68E-01	6.35E-01	5.10E-01	3.89E-01	3.73E-01	mol N eq
Resource use, mineral and metals	1.57E-05	1.00E-05	8.88E-06	1.54E-05	1.71E-05	1.38E-05	2.10E-05	1.69E-05	1.47E-05	1.42E-05	kg Sb eq
Climate change	6.34E+00	4.12E+00	3.56E+00	3.97E+00	4.61E+00	3.95E+00	8.57E+00	7.07E+00	5.96E+00	5.83E+00	kg CO_2 eq
Eutrophication freshwater	1.02E-03	6.60E-04	6.10E-04	1.48E-03	1.55E-03	1.24E-03	1.47E-03	1.18E-03	1.10E-03	1.08E-03	kg P eq
Photochemical ozone formation, HH	1.11E-02	7.39E-03	6.46E-03	1.01E-02	1.15E-02	1.05E-02	1.64E-02	1.32E-02	1.18E-02	1.13E-02	kg NMVOC eq
Land use	1.87E+03	1.42E+03	1.36E+03	3.48E+03	4.27E+03	4.16E+03	4.61E+03	3.62E+03	3.58E+03	3.39E+03	Pt
Respiratory inorganics	4.99E-07	3.12E-07	2.53E-07	5.49E-07	6.39E-07	4.66E-07	1.09E-06	8.77E-07	6.70E-07	6.45E-07	disease inc.
Water scarcity	3.02E+00	1.67E+00	1.30E+00	3.74E+00	4.41E+00	3.35E+00	4.89E+00	3.57E+00	2.83E+00	2.76E+00	m^3 depriv.
Ozone depletion	2.50E-07	1.63E-07	1.40E-07	2.57E-07	2.91E-07	2.51E-07	4.13E-07	3.29E-07	2.87E-07	2.70E-07	kg CFC11 eq
Ionising radiation, HH	1.22E-01	7.90E-02	7.15E-02	1.28E-01	1.51E-01	1.28E-01	1.83E-01	1.47E-01	1.30E-01	1.23E-01	kBq U-235 eq
Acidification terrestrial and freshwater	6.91E-02	4.34E-02	3.53E-02	7.53E-02	8.86E-02	6.53E-02	1.50E-01	1.21E-01	9.26E-02	8.89E-02	mol H^+ eq
Eutrophication marine	4.39E-02	3.25E-02	2.47E-02	1.09E-01	3.18E-02	4.10E-02	6.24E-02	3.69E-02	3.28E-02	3.77E-02	kg N eq
Resource use, energy carriers	2.31E+01	1.49E+01	1.29E+01	2.39E+01	2.75E+01	2.29E+01	3.73E+01	2.98E+01	2.55E+01	2.43E+01	MJ
Ecotoxicity freshwater	2.12E+00	1.39E+00	1.23E+00	2.53E+00	2.26E+00	1.95E+00	3.09E+00	2.42E+00	2.16E+00	2.73E+00	CTUe
Cancer human health effects	2.23E-08	1.45E-08	1.25E-08	2.32E-08	2.52E-08	2.75E-08	3.20E-08	2.45E-08	2.78E-08	2.04E-08	CTUh
Non-cancer human health effects	6.35E-07	4.11E-07	3.73E-07	8.21E-07	9.56E-07	8.95E-07	1.15E-06	8.77E-07	8.38E-07	7.04E-07	CTUh

The introduction of fava beans with a high NDU$_{P-F}$ into the Italian cereal-rapeseed rotation increased the DM yield of the following rapeseed crop by 20%, from 2275 kg ha^{-1} to

2730 kg ha^{-1} (Table 14, SI). However, in the Italian cereal-cereal rotations, the oat crop (twice in the rotation) contributed to a higher NDU$_{P-F}$ ha.yr^{-1} for this rotation compared to the cereal–oilseed and to the cereal–oilseed-legume options in the region, owing to the yield and nutritional composition (high fibre) of oats. In Italy, the amount of fertiliser required per NDU$_{P-F}$ was highest for the cereal-oilseed rotation, making it the worst performing of the Italian rotations across all impact categories except marine eutrophication. The Italian cereal-cereal rotation incurred high burdens in this category due to the high leaching values for winter oats.

The introduction of peas in the Scottish cereal-rapeseed rotation decreased the requirement for SNF whilst increasing the final output of NDU$_{P-F}$. This happens because peas have a higher NDU$_{P-F}$ per kilo of grain (Table 12, SI), and even whilst yielding 860 kg ha^{-1} less than spring barley, they deliver almost 180 more NDU$_{P-F}$ ha^{-1} (Table 14, SI). Additionally, peas need no SNF. Peas are also responsible for an increase of 94 NDU$_{P-F}$ ha^{-1} from the following barley crop due to a yield boost compared with the cereal-oilseed rotation in Scotland (Table 14, SI).Therefore, the Scottish legume modified rotation achieves the highest overall environmental efficiency per NDU$_{P-F}$ (Table 7). The Scottish cereal-oilseed rotation 2 with nutrient-dense oats scores better than the cereal-oilseed rotation 1 with a less-nutritionally-dense second wheat crop (SC [C_O #1]) (Table 14, SI).

Environmental burdens per NDU$_{P-F}$ are lower for Scottish rotations than Italian rotations, except for climate change. Despite the higher SNF requirements in Scotland than Italy (Table 15, SI), this is because of the N source used. According to the International Fertilisation Association information from 2015 to 2018 (IFASTAT, 2020), Italy consumes at least 72% of N in the form of urea. Urea fertiliser not only releases carbon when applied but also has a higher ammonia volatilization rate of 15% against 5% for ammonium nitrate used in Scotland (Table 11, SI). The climate change potential per NDU$_{P-F}$ is higher overall for the Scottish cereal-rapeseed rotation because of direct N_2O emissions derived from a large amount of total N applied and because of the upstream emissions from ammonium nitrate production (Moreno-Ruiz et al., 2018).

The Romanian sunflower-cereal rotation (RO [C_O #1]) requires more fertiliser to produce one NDU$_{P-F}$ than any other rotation. This rotation comprises three crops, two of which, wheat and maize, delivered low NDU$_{P-F}$. (Table 14, SI). In the first legume-modified Romanian rotation (RO [C_O_L#1]), common beans contributed to a slightly higher NDU$_{P-F}$ and also increased the yield of the following crop (maize). The second legume-modified rotation (RO [C_O_L#2]) introduced soybean, which has one of the highest protein contents of all crops, contributing to a slightly higher rotation level NDU$_{P-F}$ than for the common bean rotation and therefore scoring better across impact categories.

3.3.4 Animal nutrition footprints

3.3.4.1 Cereal Unit

Using the CU as a FU, legume-modified rotations scored better in most regions compared with cereal-cereal and cereal-oilseed rotations. The exception occurred in Italy, where the cereal-oilseed rotation was more environmentally efficient across 9 of the 16 impact categories and where the cereal-cereal rotations incurred the largest environmental burdens (Table 8). Scottish rotations produced the most CU per hectare year (Table 6), delivering 2-3 times more than Italian and Romanian rotations. Legume-modified rotations delivered 17% lower CU scores in Scotland compared with the cereal-oilseed rotation SC [C_O #1]. In Italy, IT [C_O_L] delivered 12% lower than IT [C_O] (Table 6). However, the soybean-modified rotation in Romania (RO [C_O_L #2]) had a 23% higher CU than the cereal-oilseed rotation 1 (RO [C_O #1) as can be seen in Table 8.

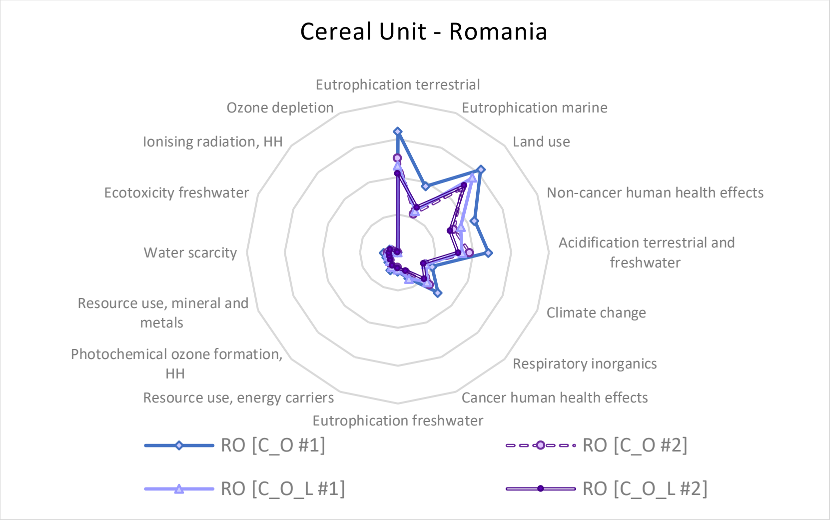

Figure 8: Normalised environmental scores per cereal unit (CU) of animal feed energy output across Romanian crop rotations. RO [C_O #1] refers to cereal-oilseed rotation option 1, RO [C_O #2] refers to cereal-oilseed rotation option 2, RO [C_O_L #1] refers to cereal-oilseed-legume rotation option 1 (with common beans) and [C_O_L #2] refers to cereal-oilseed-legume rotation option 2 (with soybeans).

Table 8: Heat map of impact scores across all impact categories for all rotations analysed in Scotland (SC), Italy (IT), and Romania (RO), expressed per cereal unit. For each impact category and each region, the result for the rotation configuration with the highest impact is shaded darker red and the result for the rotation with the lowest impact is shaded darker green.

Indicator	Scotland			Italy			Romania				**Unit**
	SC [C_O #1]	SC [C_O #2]	SC [C_O_L]	IT [C_C]	IT [C_O]	IT [C_O_L]	RO [C_O #1]	RO [C_O #2]	RO [C_O_L #1]	RO [C_O_L #2]	
	cereal-oilseed option 1	cereal-oilseed option 2	cereal-oilseed-legume	cereal-cereal	cereal-oilseed	cereal-oilseed-legume	cereal-oilseed option 1	cereal-oilseed option 2	cereal-oilseed-legume option 1	cereal-oilseed-legume option 2	
Eutrophication terrestrial	2.33E-02	2.15E-02	1.94E-02	3.67E-02	3.23E-02	2.84E-02	5.62E-02	4.42E-02	4.08E-02	3.67E-02	mol N eq
Resource use, mineral and metals	1.29E-06	1.20E-06	1.19E-06	1.84E-06	1.52E-06	1.47E-06	1.86E-06	1.47E-06	1.54E-06	1.40E-06	kg Sb eq
Climate change	5.19E-01	4.96E-01	4.76E-01	4.73E-01	4.08E-01	4.16E-01	7.60E-01	6.15E-01	6.25E-01	5.73E-01	kg CO$_2$ eq
Eutrophication freshwater	8.40E-05	7.90E-05	8.18E-05	1.80E-04	1.40E-04	1.30E-04	1.30E-04	1.00E-04	1.20E-04	1.10E-04	kg P eq
Photochemical ozone formation, HH	9.10E-04	8.90E-04	8.60E-04	1.20E-03	1.02E-03	1.10E-03	1.45E-03	1.15E-03	1.24E-03	1.11E-03	kg NMVOC eq
Land use	1.53E+02	1.71E+02	1.80E+02	4.17E+02	3.80E+02	4.38E+02	4.09E+02	3.16E+02	3.74E+02	3.33E+02	Pt
Respiratory inorganics	4.08E-08	3.75E-08	3.39E-08	6.54E-08	5.65E-08	4.94E-08	9.63E-08	7.60E-08	7.02E-08	6.33E-08	disease inc.
Water scarcity	2.50E-01	2.05E-01	1.77E-01	4.58E-01	4.01E-01	3.65E-01	4.41E-01	3.17E-01	3.03E-01	2.76E-01	m^3 depriv.
Ozone depletion	2.05E-08	1.97E-08	1.87E-08	3.06E-08	2.59E-08	2.65E-08	3.66E-08	2.86E-08	3.00E-08	2.65E-08	kg CFC11 eq
Ionising radiation, HH	9.99E-03	9.51E-03	9.56E-03	1.53E-02	1.34E-02	1.35E-02	1.63E-02	1.28E-02	1.36E-02	1.21E-02	kBq U-235 eq
Acidification terrestrial and freshwater	5.65E-03	5.21E-03	4.73E-03	8.97E-03	7.82E-03	6.91E-03	1.33E-02	1.05E-02	9.70E-03	8.73E-03	mol H$^+$ eq
Eutrophication marine	3.59E-03	3.90E-03	3.27E-03	1.25E-02	2.87E-03	4.31E-03	5.51E-03	3.20E-03	3.42E-03	3.67E-03	kg N eq
Resource use, energy carriers	1.89E+00	1.80E+00	1.73E+00	2.85E+00	2.44E+00	2.42E+00	3.31E+00	2.59E+00	2.67E+00	2.38E+00	MJ
Ecotoxicity freshwater	1.74E-01	1.67E-01	1.64E-01	3.00E-01	2.02E-01	2.06E-01	2.75E-01	2.10E-01	2.26E-01	2.66E-01	CTUe
Cancer human health effects	1.83E-09	1.74E-09	1.67E-09	2.76E-09	2.25E-09	2.88E-09	2.86E-09	2.14E-09	2.90E-09	2.01E-09	CTUh
Non-cancer human health effects	5.21E-08	4.95E-08	4.98E-08	9.80E-08	8.50E-08	9.43E-08	1.03E-07	7.65E-08	8.77E-08	6.94E-08	CTUh

Scottish rotations incurred smaller environmental impacts per CU than Italian rotations, except for climate change (Table 8). Scottish rotations deliver the most CU $ha.yr^{-1}$. However, the SNF requirement per CU produced was higher than Italian rotations (Table 15, SI). Therefore, the N_2O emissions were higher for Scottish than for Italian rotations. In Italy SNF was mainly applied as urea, with high volatilization rates (Table 11, SI), leading to high NH_3 emissions for Italian rotations and higher burdens for terrestrial and freshwater acidification, respiratory inorganics, and terrestrial eutrophication compared with Scottish rotations.

Romanian rotations delivered slightly more CU $ha.yr^{-1}$ than Italian rotations (Table 6). The Romanian cereal-oilseed rotation (RO [C_O #2]) delivers more CU than the common bean-modified rotation (RO [C_O_L #1]), and even though the cereal-oilseed rotations needed more SNF than legume-modified rotations, the impact of RO [C_O #2] per CU is lower for climate change (Table 8). Marine eutrophication potential was mostly linked to nitrate leaching to water (Figure 6). For Romanian rotations, the highest leaching per FU occurred in maize and soybean followed by winter wheat and sunflower crops. The RO [C_O_L #2] included both soybean and maize, scoring higher for marine eutrophication than the cereal-oilseed rotation RO [C_O #2] and the common bean-modified rotation RO [C_O_L #1] (Table S.5). However, RO [C_O #1] scored higher worst among them for the same impact (marine eutrophication), combining sunflower, wheat, and maize in the rotation. The Italian cereal-cereal (IT [C_C]) rotation also scored high on marine eutrophication due to the high nitrate leaching associated with winter oats.

3.3.4.2 Digestible Protein

When FU_{Feed} is measured in terms of DP (protein) rather than CU (energy) delivered, introducing legumes into typical rotations appears more beneficial. This can be observed for Romania (Figure 9). Per kg DP, all legume-modified rotations scored lower environmental impacts across the majority of 16 impact categories compared with the cereal-cereal and cereal-oilseed rotations within their regions (Table 9). Despite sometimes having lower yields than other cereal crops, legumes have two main advantages: a high protein content (Table 12, SI) and no requirement for SNF. All legume-modified rotations produced more DP per hectare-year of rotation than the other options in their regions (Table 6). Scottish rotations produced the most DP per hectare, followed by Romanian then Italian rotations. In Scotland, the legume-modified rotation (SC [C_O_L]) was only slightly better than the first cereal-oilseed rotation (SC [C_O #1]) in terms of DP production per ha owing to the very high yields of wheat and barley (Table 14, SI).

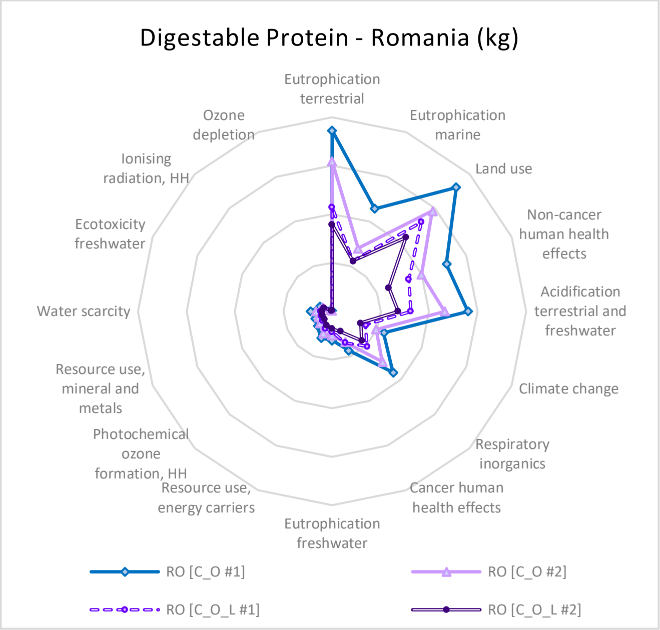

Figure 9: Normalised environmental scores per kg digestible protein (DP) animal feed nutritional output across Romanian crop rotations. RO [C_O #1] refers to cereal-oilseed rotation option 1, RO [C_O #2] refers to cereal-oilseed rotation option 2, RO [C_O_L #1] refers to cereal-oilseed-legume rotation option 1 (with common beans) and [C_O_L #2] refers to cereal-oilseed-legume rotation option 2 (with soybeans).

Table 9: Heat map of impact scores across all impact categories for all rotations analysed in Scotland (SC), Italy (IT), and Romania (RO), expressed per DP. For each impact category and each region, the result for the rotation configuration with the highest impact is shaded darker red and the result for the rotation with the lowest impact is shaded darker green.

	Scotland			Italy			Romania				
Indicator	SC [C_O #1]	SC [C_O #2]	SC [C_O_L]	IT [C_C]	IT [C_O]	IT [C_O_L]	RO [C_O #1]	RO [C_O #2]	RO [C_O_L #1]	RO [C_O_L #2]	**Unit**
Eutrophication terrestrial	3.14E-01	2.91E-01	2.12E-01	5.90E-01	3.78E-01	2.76E-01	6.60E-01	5.46E-01	3.78E-01	3.16E-01	mol N eq
Resource use, mineral and metals	1.74E-05	1.63E-05	1.30E-05	2.96E-05	1.78E-05	1.42E-05	2.19E-05	1.81E-05	1.43E-05	1.20E-05	kg Sb eq
Climate change	7.01E+00	6.72E+00	5.22E+00	7.61E+00	4.77E+00	4.04E+00	8.93E+00	7.59E+00	5.80E+00	4.94E+00	kg CO$_2$ eq
Eutrophication freshwater	1.13E-03	1.07E-03	9.00E-04	2.85E-03	1.62E-03	1.28E-03	1.53E-03	1.27E-03	1.07E-03	9.10E-04	kg P eq
Photochemical ozone formation, HH	1.23E-02	1.21E-02	9.48E-03	1.94E-02	1.19E-02	1.07E-02	1.71E-02	1.42E-02	1.15E-02	9.53E-03	kg NMVOC eq
Land use	2.07E+03	2.32E+03	1.98E+03	6.71E+03	4.44E+03	4.25E+03	4.81E+03	3.90E+03	3.47E+03	2.87E+03	Pt
Respiratory inorganics	5.51E-07	5.08E-07	3.72E-07	1.05E-06	6.60E-07	4.79E-07	1.13E-06	9.39E-07	6.52E-07	5.46E-07	disease inc.
Water scarcity	3.37E+00	2.78E+00	1.95E+00	7.37E+00	4.69E+00	3.54E+00	5.19E+00	3.91E+00	2.81E+00	2.38E+00	m^3 depriv.
Ozone depletion	2.76E-07	2.66E-07	2.06E-07	4.93E-07	3.02E-07	2.57E-07	4.30E-07	3.54E-07	2.78E-07	2.28E-07	kg CFC11 eq
Ionising radiation, HH	1.35E-01	1.29E-01	1.05E-01	2.46E-01	1.57E-01	1.31E-01	1.91E-01	1.58E-01	1.26E-01	1.04E-01	kBq U-235 eq
Acidification terrestrial and freshwater	7.63E-02	7.06E-02	5.19E-02	1.44E-01	9.15E-02	6.70E-02	1.56E-01	1.29E-01	9.00E-02	7.53E-02	mol H$^+$ eq
Eutrophication marine	4.85E-02	5.28E-02	3.59E-02	2.01E-01	3.35E-02	4.18E-02	6.48E-02	3.95E-02	3.17E-02	3.17E-02	kg N eq
Resource use, energy carriers	2.55E+01	2.44E+01	1.90E+01	4.58E+01	2.85E+01	2.35E+01	3.89E+01	3.20E+01	2.48E+01	2.05E+01	MJ
Ecotoxicity freshwater	2.34E+00	2.27E+00	1.80E+00	4.83E+00	2.36E+00	2.00E+00	3.23E+00	2.60E+00	2.10E+00	2.30E+00	CTUe
Cancer human health effects	2.46E-08	2.36E-08	1.83E-08	4.45E-08	2.63E-08	2.80E-08	3.36E-08	2.64E-08	2.69E-08	1.73E-08	CTUh
Non-cancer human health effects	7.03E-07	6.70E-07	5.46E-07	1.58E-06	9.94E-07	9.15E-07	1.21E-06	9.44E-07	8.14E-07	5.98E-07	CTUh

The SNF required to produce 1 kg of DP was considerably higher for cereal-cereal and cereal-oilseed rotations than for legume-modified rotations across all regions (Table 16, SI).

Consequently, cereal-cereal and cereal-oilseed rotations incurred larger burdens per kg DP for terrestrial and freshwater acidification, respiratory inorganics, and terrestrial eutrophication. Marine eutrophication burden was greatest overall for the Italian cereal-cereal rotation (IT [C_C]) because of the high nitrate leaching from the oat crop. Additionally, marine eutrophication burdens were greater for legume-modified rotations in Italy than cereal-oilseed (IT [C_O_L]) rotations because of leaching from fava bean residues (Reckling et al., 2016).

3.3.5 Sensitivity Analysis

Values for SNF application, yields (DM), Nitrogen Use Efficiency (NUE), leaching, and emission factors before and after the sensitivity analysis can be observed in Table 18, SI for each crop under each of the ten rotations across all regions studied. The results of the sensitivity analysis for NDU$_{\text{P-F}}$ (Table 19, SI) did not show significant changes to the major conclusions on the comparative environmental efficiency of legume and non-legume rotations across different regions in Europe. However, the simulation of the use of nitrification inhibitors resulted in a reduction in climate change impacts from entire rotations of 20% on average for non-legume rotations and 18% on average for legume-modified rotations, as can be observed in, SI.

3.4 Discussion

3.4.1 Assessing sustainable human nutrition

The NDUP-F FU applied here provides a unique perspective on the comparative efficiency of legume-modified rotations to deliver key components of human nutrition (protein, fibre, and energy) – factors rarely considered in farm- or rotation-level LCA studies. MacWilliam et al. (2014) and Li et al. (2018) evaluated rotations in terms of protein and essential nutrient outputs, but did not apply the NDU considered here nor evaluate the full PEF suite of impact categories. According to McAuliffe et al. (2020), nutritional footprint studies are not yet taken to their full potential, and commodity-level LCA results are sometimes confused with diet-level results. Critical details about farm management and rotations often get overlooked in diet-level LCA, compromising results, and limiting their value in informing food system transitions that necessitate changes in practices at the farm level – e.g. changes to cropping sequences. Results in this study show that choice of FU can change the comparative performance of rotations for some impact categories, and that nutritional FUs have an important role to play in farm level LCA – bridging the gap between state-of-the-art studies in food LCA and crop rotation LCA (Costa et al., 2020) to provide a more robust evidence base for integrated solutions to food chain sustainability. However, NDUP-F remains a relatively crude proxy for human nutrition because (i) the nutritional content of grains changes according to farm practices, choice of varieties, and fertilisation management (AHDB, 2019), (ii) grain processing and preparation influences the final nutritional value (Saget et al., 2020), and (iii) the NDU focus only on few elements of human nutrition – protein, fibre, and energy. More refined estimates of human nutrition consider different aspects, such protein quality via, for example, the amino acid profile (Leinonen et al., 2019), or other bioavailable micronutrients (which may be enhanced by cultivation and biofortification strategies). Biofortification can be achieved through different methods, such as conventional plant breeding, genetic engineering, agronomics tactics, and more recently plant growth-promoting bacteria (PGPB) strategies (Roriz et.al 2020). The latter, for instance, improves crop yields and also iron availability for human diets (an aspect not assessed in this study).

Here, pig digestibility values were used as a proxy for human digestibility, owing to a lack of alternative, universally applicable data. Another limitation of the NDUP-F is the residual need for some allocation or system expansion because not all outputs are used for human food. Here, economic allocation was used to partition the main grain products and straw. Despite these limitations, we propose the application of a nutritional FU to assess the environmental efficiency of rotations whose outputs are primarily destined for human food, in order to generate more coherent evidence for sustainable food system transitions. Our results also highlight the importance of looking at impact categories other than climate change, such as respiratory inorganics, marine eutrophication, and terrestrial and freshwater acidification (European Commission, 2017) to fully reflect impacts from e.g. fertiliser use and to provide a fuller picture of environmental sustainability.

3.4.2 Assessing sustainable animal nutrition

From an animal feed perspective, energy intake is often adopted as a FU because it represents the primary component of ruminant diets (Huws et al., 2018; AHDB, 2020). Nevertheless, digestible protein is a critical aspect of animal nutrition, not least because Europe currently imports soybean from other countries where its production may drive deforestation (Watson, et al 2017). To reflect current limitations of LCA methods for rotational systems, the adoption of more than one FU has been recommended (Nemecek et al, 2011; Brankatschk, 2017; Goglio et al, 2018). Results here show that the choice of energy or protein as the primary functional unit leads to different conclusions on the environmental efficiency of different crop rotations. Integration of multiple components of nutrition into a single NDU as for human nutrition is complicated in the case of livestock owing to different requirements and consequences across species. For example, lipid contents are important and can reduce methane emissions from cattle (Belanche et al., 2012; Newbold et al., 2004). Further research is needed to develop a more integrated FU for animal nutrition, analogous to the NDU for human nutrition. In the meantime, applying multiple functional units provides a useful sensitivity analysis and may avoid the inference of false precision that can arise when using a single metric oriented towards a particular aspect of nutrition. This study did not evaluate agroforestry systems, livestock grazing on temporary leys nor non-food-or-feed uses of crops (bioenergy, textiles, cosmetics, etc). Functional units may need to broadened out further to consider more complex integrated systems.

3.4.3 Implications for European cropping systems

Results from this study highlight that legume-modified rotations generally deliver nutrition to humans and livestock more environmentally sustainably than typical cereal rotations across different European regions. The main benefits of legume incorporation were reduced SNF requirements, enhanced yields in following crops, and improved nutritional profile of outputs. Legume-modified rotations also exhibit a greater degree of autarchy (reduced need for external inputs) – an important characteristic of food system sustainability (Pretty, 2008). Whilst previous studies indicated that legumes could increase N leaching (Nemecek et al., 2008), this was not a significant trade-off in our study when considered across the higher nutritional output of legume-modified rotations. For example, in some rotations, winter cereals cultivated after legumes “mopped up” much of the N in legume residues, reducing fertiliser requirements (Reckling et al., 2016a). Furthermore, technical options to improve the efficiency of synthetic fertiliser use cannot match the environmental advantage conferred by incorporation of legumes into rotations, and previous studies have shown the feasibility of replacing imported soy-based feeds with local legumes (Hörtenhuber et al., 2011; Smith et al., 2013; White et al., 2015). Thus, legumes could play a crucial role in improving the sustainability of cropping systems at farm level. However, high availability of inexpensive external resources (e.g. synthetic fertilisers and imported protein-rich feeds, alongside marginally competitive annual gross margins (excluding multi-annual rotation effects) for legumes (Preissel et al., 2015; Zander et al., 2016) deter widespread farmer uptake. There is also a lack of incentive through public policies which tend to favour alternative crops for bioenergy and biodiesel production (Watson et al., 2017; Zander et al., 2016).

Nonetheless, legumes also have an important role to play in the more radical food system change required to avoid critical exceedance of planetary boundaries (Lynch et al., 2020;

Springmann et al., 2018; Willett et al., 2019). Such dietary change may involve legume substitution of not just cereal and oilseed crops within rotations, but the livestock that feed off those crops (Chaudhary et al., 2018a; Goldstein et al., 2017; Saget et al., 2020; Tilman and Clark, 2014; Willett et al., 2019). Indeed, this study highlights the value of legumes in delivering protein and fibre for human nutrition directly from cropping systems. Proper accounting for the nutritional outputs of cropping systems could strengthen the evidence base for a demand (diet) driven shift in food system configuration to improve overall sustainability.

3.5 Conclusions

It is increasingly recognised that evaluation of food system sustainability should account for interactions among crops in rotation cycles, not just the inputs and outputs of single crops cultivated within such systems. In this study, we applied three functional units to aggregate multiple crop outputs and compare the environmental efficiency of ten crop rotations in terms of delivery of human and livestock nutrition. Across three European climatic zones, the introduction of legumes into conventional cereal and oilseed rotations increased protein production and overall nutritional output whilst reducing synthetic fertiliser inputs. Thus, for most of the 16 impact categories studied, legume-modified rotations delivered animal, and especially human, nutrition at a lower environmental cost than conventional rotations. Our results show that choice of functional unit has an important influence on the apparent efficiency of different crop rotations. Application of a nutrient density unit representing energy, protein and fibre highlighted the value of introducing legumes into rotations for the purpose of direct human nutrition. This study also points to the need to develop functional units capable of representing multiple (species specific) nutritional attributes of livestock feed. In the meantime, applying multiple functional units (e.g. based on metabolisable energy and digestible protein) can provide a more balanced picture of crop system efficiency with respect to animal nutrition. Evaluating entire crop rotations using nutritional indices as functional units highlights the important role for more legume cultivation in Europe to improve the sustainability of cropping systems. Legumes have high potential to underpin the transition to healthy and sustainable diets targeted by, *inter alia*, the European Green New Deal Farm to Fork strategy.

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3.8 Supplementary Information

3.8.1 Crop Rotations information

3.8.2 Farm Data

Sequence data in each region, fertiliser requirements, number of fertiliser applications, main crop yields, straw yields, and leaching potential considering the preceding crop and crop management, were taken directly from Reckling et al. (2016) and are summarised in Table 10 for Scotland, Italy, and Romania. For all rotations, tillage and ploughing were considered and a rainfed regime. No livestock manure, biosolids, compost or digestate were added to any of the rotations.

Table 10: Values for fertilisers applied, number of fertilisers applications, and yields (grain and straw) under each rotation in Scotland (SC), Italy (IT) and Romania (RO).

Crop	Dry Matter Yields (kg)	Straw (kg)	No. fertiliser applications	N (kg) applied	P_2O_5 (kg) applied	K_2O (kg) applied	N leaching (kg) $N\text{-}NO_3$
SC [C_O #1] - cereal-oilseed option 1							
Rapeseed	4,095	-	3	203.55	49.05	49.8	31.55
Wheat	8,600	5,200	3	193.2	67.50	72	21.47
Wheat	8,170	5,000	3	202.86	67.50	72	25.13
Barley	6,880	4,500	3	181.13	67.50	72	28.13
Barley	6,880	4,500	3	181.13	67.50	72	28.13
SC [C_O #2] - cereal-oilseed option 2							
Rapeseed	4,095	-	3	203.55	49.05	49.8	31.55
Barley	7,740	5,000	3	163.88	67.5	72.0	19.09
Oats	7,310	5,500	2	120.75	58.5	60	25.49
Spring Barley	5,590	3,500	2	110.45	55.25	55.25	25.72
Barley	6,880	4,500	3	181.13	67.5	72	28.13
SC [C_O_L] - cereal-oilseed- legume							
Rapeseed	4,095	-	3	203.55	49.05	49.8	31.55
Barley	7,740	5,000	3	163.88	67.50	72	19.09
Oats	7,310	5,500	2	120.75	58.50	60	25.49
Peas	4,730	-	1	-	49.05	49.80	5.97
Barley	7,740	5,000	3	163.88	67.50	72	19.09
IT [C_C] - cereal-cereal							
Oats	1,720	1,800	2	62	92	-	70.55
Barley	3,010	3,000	1	36	92	-	3.47
Oats	1,720	1,800	2	62	92	-	70.55
Barley	3,010	3,000	1	36	92	-	3.47
IT [C_O] - cereal-oilseed							
Rapeseed	2,275	-	2	59	66	48	5.29
Barley	2,838	3,000	1	32.4	82.8	-	9.13
Rapeseed	2,275	-	2	59	66	48	5.29
Barley	2,838	3,000	1	32.4	82.80	-	9.13
IT [C_O_L] - cereal-oilseed- legume							
Rapeseed	2,730	-	2	48	44	32	-
Barley	2,838	3,000	1	32	82.8	-	9.13
Rapeseed	2,275	-	2	59	66	48	5.29
Barley	2,838	3,000	1	32.4	82.8	-	9.13

Fava Bean	1,376	-	1	-	19	-	28.40
RO [C_O #1] - cereal-oilseed option 1							
Sunflower	2,227	-	2	95	60		11.08
Maize	3,612	-	2	120	50		21.39
Wheat	3,096	-	2	90	40		11.69
RO [C_O #2] - cereal-oilseed option 2							
Rapeseed	2,730	-	2	95	60		4.63
Maize	5,160	-	2	130	60		18.43
Barley	3,612	-	2	85	50		6.91
RO [C_O_L #1] - cereal-oilseed- legume option 1							
Common Bean	2,228	-	1	-	40		3.72
Maize	6,020	-	2	140	70		20.12
Barley	3,612	-	2	85	50		6.91
Rapeseed	2,730	-	2	95	60		4.63
RO [C_O_L #2] - cereal-oilseed- legume option 2							
Soybean	2,150	-	1	-	55		15.15
Maize	6,020	-	2	140	70		20.12
Barley	3,612	-	2	85	50		6.91
Rapeseed	2,730	-	2	95	60		4.63

3.8.3 Assumptions

Crop protection applications can vary hugely (across, inter alia, crop variety, specific local agro-climatic conditions and management practises), with few reliable data sources for specific quantities which in mass terms are typically orders of magnitude smaller than fertiliser applications. Therefore, crop protection applications were not considered in the modelling. Applications vary considerably. Additionally, all crops were allocated an equal application of 400 kg/ha of lime (acidity corrector - $CaCO_3$) regardless of where in the rotation the crop was cultivated relative to periodic lime additions. Lime is commonly applied to soil to maintain a neutral pH in response to gradual acidification especially driven by ammonium-based fertiliser applications (ADHB, 2019). Therefore, attributing lime to each crop in rotation equally is a conservative assumption to evaluating the effect of legumes, and has no bearing on rotation-level results. The source of other fertilisers is described below.

3.8.3.1 Fertiliser compound origin

Nitrogen, phosphate and potash fertilisers can be applied to the soil through different commercial formulations. Each formulation contains different amounts and chemical forms of the main elements (N, P, and K), influencing environmental impact from both manufacturing and field application. One example is Urea, containing 46% N but also carbon in its formulation (CH_4N_2O). Once applied to the soil, this fertiliser is therefore responsible not only for N_2O emissions due to direct application but also for carbon dioxide (CO_2) release (IPCC, 2019), alongside much greater ammonia volatilization than other N compounds (IPCC, 2019).

Other commercial fertilisers may contain more than one element in its formulation, such as triple superphosphate ($Ca(H_2PO_4)_2.H_2O$), which contains on average 15% of Ca and 45% of P_2O_5; or monoammonium phosphate ($NH_4H_2PO_4$), providing N and P_2O_5 at the same time to the crop. Some commercial products blend N, P and K into a single product, e.g. NPK 15:15:15.

To define types of N, P_2O_5, and K_2O fertiliser applications for the aforementioned crops, we firstly prioritised primary specific information from Reckling et al. (2016). For Scottish crops, the following information was given by Reckling et al. (2016): nitrogen source was ammonium nitrate (AN), the potassium source was muriate of potash (MOP) and phosphorus source was triple superphosphate (TPS). All the formulations were available in the database.

For Italy, the main fertilisers used on the rotations were NPK formulated, such as NP 18-46, NPK 11-22-16 and nitrogen 26% (Reckling et al, 2016). These formulations, however, were not available in the database used, and therefore other formulations had to be assumed, such as Urea. The format of fertiliser compounds was equated to national average fertiliser consumption by country over three recent years (from 2015 to 2017) based on data in IFASTAT (2020). For Italy, urea represents 71% of N fertiliser consumption.

In Romania, the fertiliser used was 100% Nitrogen (Reckling et al, 2016). This formulation was also not available in the database. According to country statistics (IFASTAT, 2020), urea formulation was most applied (34%) followed by ammonium nitrate (28%). In this situation, both compounds were considered proportionally as a source of N applied to the crops in this region.

The formulations of phosphate (P_2O_5) and Potassium oxide (K_2O) used on Italian and Romanian rotations were not specified by Reckling et al, (2016) and they were also taken from national averages (IFASTAT, 2020). In Italy, P_2O5 was mostly applied in the form of ammonium phosphate, representing 49% of total consumption in the country. In Romania, the situation is similar - phosphate comes mostly from ammonium phosphate, with 44.5%.

Potassium oxide in Romania is from NPK-formulated products. Italy, on the other hand, presents a more divided market, where 47% of the K_2O originates from NPK compounds followed by 31% of KCL. In this last case, since the distribution is more even, both compounds were considered for the crops in this region.

3.8.3.2 Machine Operation

Machine operation impacts were taken from Ecoinvent database v.3.5 (Moreno-Ruiz et al, 2018). Field operations consist of tillage and ploughing, sowing, broadcast fertiliser application, and harvesting. According to the Ecoinvent database (Moreno-Ruiz et al, 2018), tillage and ploughing operations include preliminary work at the farm, like attaching the relevant equipment to the tractor; transfer to the field (with an assumed distance of 1 km); fieldwork (for a parcel of land of 1 ha surface); transfer to farm and concluding work, like uncoupling the equipment. A fertiliser broadcaster with 500l carrying capacity was modelled to be used twice, once for lime and once for spreading the NPK compounds. The harvesting process also includes the activities aforementioned.

3.8.3.3 Seeds

Quantities of seeds sown for all crops under all rotations analysed were taken from Redman, (2018). The processes regarding the production for seeds were adopted from Ecoinvent v.3.5 database (Moreno-Ruiz et al, 2018).

3.8.3.4 Field Emissions

In this study, we updated field greenhouse gas emissions with the latest IPCC Emission Factors (IPCC, 2019), now specified by region (wet and dry climates) and according to nitrogen fertiliser sources. Ammonia volatilization emission and phosphorus (P) losses to the water were also calculated as described in Table 11.

The following field emissions were calculated:

i) Direct emissions of nitrous oxide (N_2O) from crop residues that remain on-field and from synthetic N fertilised (SNF) applied based on IPCC, equation11.2 (IPCC, 2019);

ii) Nitrogen oxides (NOx) produced following SNF application – Calculated according to Nemecek and Kägi, (2007);

iii) Ammonia (NH_3) emission calculated based on the SNF fraction of N that volatilises. The fraction of N volatilization depends on the SNF formulation (Table 11) (IPCC, 2019);

iv) Indirect emission of N_2O due to volatilised SNF applied - calculated based on IPCC, equation 11.9 (IPCC, 2019);

v) Nitrate (NO_3^-) losses to water according to the calculation provided by Reckling et al., (2016);

vi) Indirect emissions of N_2O due to leaching from SNF applied and from crop residues that remain in the field – Calculated based on IPCC, equation 11.10 (IPCC, 2019);

vii) CO_2 emissions due to Lime or Urea application according to (IPCC, 2006).

viii) Phosphorus (P) losses to water due to synthetic P fertilisers added to the soil. Calculated based on cropping system loss coefficients applied in Styles et al. (2015).

The emission factors necessary for those calculations are recorded in Table 11. Reckling et al., (2016) calculated leaching considering the regional soil type, preceding crop and crop management as a function of the soil leaching potential. Essentially, the nitrogen surplus is calculated and multiplied by the winter leaching probability. This probability is a function of precipitation, water holding capacity at rooting depth and a crop-specific leaching coefficient. N surplus is calculated by the sum of N fertilisers, mineralization and N fixation, minus N accumulated by the crop.

Table 11: Field emissions and emission factors calculated for each crop under each rotation.

Emission/ Emission Factor	Reference /Source	Comment	Value
EF1= emission factor for N added from SNF	(IPCC, 2019)	SNF in wet climates	0.016
FracGASF = fraction of SNF that volatilises as NH_3 (ammonia) and NOx, kg N volatilised (kg of N applied)$^{-1}$	(IPCC, 2019)	Value for Urea	0.15
		Value for Ammonium based	0.08
		Value for Nitrate based	0.01
		Value for ammonium-Nitrate based	0.05
		Default	0.11
EF4 = emission factor for N_2O emissions from atmospheric deposition of N on soils and water surfaces, [kg N–N_2O (kg NH_3–N + NO_x–N volatilised)$^{-1}$]	(IPCC, 2019)	Wet climate	0.014
EF5 = emission factor for N_2O emissions from N leaching and runoff, kg N_2O–N (kg N leached and runoff)$^{-1}$	(IPCC, 2019)	IPCC default values	0.011
NO_x= Values of NOx emitted from N_2O	(Nemecek and Kägi, 2007)	default values	0.21
Carbon emission factor urea	(IPCC, 2006)	default values	0.2
Carbon emission factor limestone	(IPCC, 2006)	default values	0.12
Carbon emission factor dolomite	(IPCC, 2006)	default values	0.13
P emissions factor to water	LCAD Tool (Styles et al., 2015)	default values	0.01

3.8.3.5 Allocation

Allocation was avoided when the functional units related to animal feed were analysed, since all harvested grains and straws were converted to the final content of digestible protein or cereal unit. The only allocation performed was economic, for analysis under FUHF. Wheat and barley straw were considered to be co-products, to which a share of (rotation) system burdens were allocated based on relative economic values recommended for LCA (Nemecek and Kägi, 2007).

3.8.3.6 Nutrient values of each crop

The values of protein, fibre, energy and cereal unit for all crops analysed can be found in the Table 12 below.

Table 12: Values of protein, fibre, energy and cereal unit for all crops.

	Crude protein grain	Digestible protein N-digestibility pigs	Digestible Protein N-digestibility ruminants	Crude fibre grain	Gross energy grain	Digestible energy - digestibility for ruminants	Digestible energy - digestibility for pigs	Cereal Unit	NDU $_{P-F}$ (100g)
Unit	Content kg/kg	Content kg/kg	Content kg/kg	Content kg/kg	MJ/kg DM	DM/kg	DM/kg	Cereal Unit	NDU $_{P-F}$ (100g)
Barley grain	11.8	8.99	7.87	5.2	18.4	14.85	14.83	1.00	1.09
Barley straw	3.8	0	0.87	40.5	18.2	8.03	2.53	0.43	-
Wheat grain	12.6	10.52	8.87	2.6	18.2	15.6	15.91	1.04	0.83
Wheat Straw	4.2	0	0.15	41.5	18.5	8.36	2.28	0.43	30.48
Oat	11	8.35	7.03	13.9	19.5	14.72	12.66	0.84	2.39
Oat Straw	3.6	0	1.12	39.8	18	8.05	2.7	0.43	-
Rapeseed	20.9	15.32	15.59	10.1	28.8	25.03	23.47	1.30	1.27
Pea	23.9	20.29	18.64	6	18.3	16.52	16.16	0.79	1.67
Fava bean	29	23.78	22.88	9.1	18.7	16.79	15.5	0.54	2.27
Common Bean	24.8	21.63	21.63	5.2	18.6	16.85	16.85	0.39	1.59
Soybean	39.6	34.25	36.63	6.2	23.6	19.75	20.27	1.15	1.93
Sunflower	16.6	14.36	15.36	17.2	28.7	24.02	24.65	1.25	1.66
Maize	9.4	7.6	6.23	2.5	18.7	16.1	16.46	1.08	0.64

3.8.4 Impact Assessment

The 16 Environmental impact categories and respective indicators according to the PEF guidelines (European Environmental Bureau, 2018) are available below in Table 13.

Table 13: Life cycle impact assessment methods used in this study. Adapted from the European Environmental Bureau, (2018).

Impact category	Indicator	Unit	Recommended default LCIA method
Climate change	Radiative forcing as Global Warming Potential (GWP100)	kg CO_2 eq	The baseline model of 100 years of the IPCC (based on IPCC 2013)
Ozone depletion	Ozone Depletion Potential (ODP)	kg CFC-11 eq	Steady-state ODPs as in (WMO 1999)
Human toxicity, cancer*	Comparative Toxic Unit for humans (CTUh)	CTUh	USEtox model (Rosenbaum et al, 2008)
Human toxicity, non-cancer*	Comparative Toxic Unit for humans (CTUh)	CTUh	USEtox model (Rosenbaum
Ionising radiation, human health	Human exposure efficiency relative to U235	kBq U235 eq	Human health effect model as developed by Dreicer et al. 1995 (Frischknecht et al, 2000)
Photochemical ozone formation, human health	Tropospheric ozone concentration increase	kg NMVOC eq	LOTOS-EUROS model (Van Zelm et al, 2008) as implemented in ReCiPe 2008
Acidification	Accumulated Exceedance (AE)	mol H^+ eq	Accumulated Exceedance (Seppälä et al. 2006, Posch et al, 2008)
Eutrophication, terrestrial	Accumulated Exceedance (AE)	mol N eq	Accumulated Exceedance (Seppälä et al. 2006, Posch et al, 2008)
Eutrophication, freshwater	The fraction of nutrients reaching freshwater end compartment (P)	kg P eq	EUTREND model (Struijs et al, 2009) as implemented in ReCiPe
Eutrophication, marine	The fraction of nutrients reaching marine end compartment (N)	kg N eq	EUTREND model (Struijs et al, 2009) as implemented in ReCiPe
Ecotoxicity, freshwater*	Comparative Toxic Unit for ecosystems (CTUe)	CTUe	USEtox model, (Rosenbaum et al, 2008)
Resource use, minerals and metals	Abiotic resource depletion (ADP ultimate reserves)	kg Sb eq	CML 2002 (Guinée et al., 2002) and van Oers et al. 2002.
Resource use, fossils	Abiotic resource depletion – fossil fuels (ADP-fossil)	MJ	CML 2002 (Guinée et al., 2002) and van Oers et al. 2002
Land use	Soil quality index	Dimensionless (pt)	Soil quality index based on LANCA (Beck et al. 2010 and Bos et al. 2016)
Water use	User deprivation potential (deprivation-weighted water consumption)	m^3 world eq.	Available Water Remaining (AWARE) as Recommended by UNEP, 2016
Particulate Matter	Impact on human health	Disease incidence	PM method recommended by UNEP (UNEP 2016)

3.8.5 Crop Rotation per FU

Table 14: Values of fertilisers, yields, fibre, nutrient density unit, digestible protein, digestible energy and cereal unit per crop under rotation and per the total per rotations for Scotland (SC), Italy (IT) and Romania (RO).

Crop	Dry Matter Yields (kg)	Straw Yields (kg)	N (kg) applied	P_2O_5 (kg) applied	K_2O (kg) applied	Crude fibre (kg)	Crude NDU $_{P\text{-}F}$	DP ruminants (grain +straw) (kg)	DE ruminants (grain +straw) (MJ)	CU (grain +straw)
SC [C_O #1] cereal-oilseed option 1										
Rapeseed	4.10E+03	0.00E+00	2.04E+02	4.91E+01	4.98E+01	4.14E+02	5.19E+02	6.39E+02	1.02E+05	5.32E+03
Wheat	8.60E+03	5.20E+03	1.93E+02	6.75E+01	7.20E+01	2.24E+02	7.11E+02	7.76E+02	1.78E+05	1.12E+04
Wheat	8.17E+03	5.00E+03	2.03E+02	6.75E+01	7.20E+01	2.12E+02	6.76E+02	7.37E+02	1.69E+05	1.06E+04
Barley	6.88E+03	4.50E+03	1.81E+02	6.75E+01	7.20E+01	3.58E+02	7.53E+02	5.84E+02	1.38E+05	8.82E+03
Barley	6.88E+03	4.50E+03	1.81E+02	6.75E+01	7.20E+01	3.58E+02	7.53E+02	5.84E+02	1.38E+05	8.82E+03
Total:	3.46E+04	1.92E+04	9.62E+02	3.19E+02	3.38E+02	1.57E+03	3.41E+03	3.32E+03	7.26E+05	4.48E+04
SC [C_O #2] cereal-oilseed option 2										
Rapeseed	4.10E+03	0.00E+00	2.04E+02	4.91E+01	4.98E+01	4.14E+02	5.19E+02	6.39E+02	1.02E+05	5.32E+03
Barley	7.74E+03	5.00E+03	1.64E+02	6.75E+01	7.20E+01	4.02E+02	8.47E+02	6.56E+02	1.55E+05	9.89E+03
Oats	7.31E+03	5.50E+03	1.21E+02	5.85E+01	6.00E+01	1.02E+03	1.75E+03	5.72E+02	1.52E+05	8.51E+03
Spring Barley	5.59E+03	3.50E+03	1.10E+02	5.53E+01	5.53E+01	7.77E+02	6.12E+02	4.73E+02	1.11E+05	7.10E+03
Barley	6.88E+03	4.50E+03	1.81E+02	6.75E+01	7.20E+01	3.58E+02	7.53E+02	5.84E+02	1.38E+05	8.82E+03
Total:	3.16E+04	1.85E+04	7.80E+02	2.98E+02	3.09E+02	2.97E+03	4.48E+03	2.92E+03	6.59E+05	3.96E+04
SC [C_O_L] cereal-oilseed-legume										
Rapeseed	4.10E+03	0.00E+00	2.04E+02	4.91E+01	4.98E+01	4.14E+02	5.19E+02	6.39E+02	1.02E+05	5.32E+03
Barley	7.74E+03	5.00E+03	1.64E+02	6.75E+01	7.20E+01	4.02E+02	8.47E+02	6.56E+02	1.55E+05	9.89E+03
Oats	7.31E+03	5.50E+03	1.21E+02	5.85E+01	6.00E+01	1.02E+03	1.75E+03	5.72E+02	1.52E+05	8.51E+03
Peas	4.73E+03	0.00E+00	0.00E+00	4.91E+01	4.98E+01	2.84E+02	7.91E+02	8.80E+02	7.81E+04	3.74E+03
Barley	7.74E+03	5.00E+03	1.64E+02	6.75E+01	7.20E+01	4.02E+02	8.47E+02	6.56E+02	1.55E+05	9.89E+03
Total:	3.16E+04	1.55E+04	6.52E+02	2.92E+02	3.04E+02	2.52E+03	4.75E+03	3.40E+03	6.43E+05	3.73E+04
IT [C_C] cereal-cereal										
Oats	1.72E+03	1.80E+03	6.20E+01	9.20E+01	0.00E+00	2.39E+02	4.11E+02	1.40E+02	3.98E+04	2.22E+03
Barley	3.01E+03	3.00E+03	3.60E+01	9.20E+01	0.00E+00	1.57E+02	3.29E+02	2.65E+02	6.88E+04	4.30E+03
Oats	1.72E+03	1.80E+03	6.20E+01	9.20E+01	0.00E+00	2.39E+02	4.11E+02	1.40E+02	3.98E+04	2.22E+03
Barley	3.01E+03	3.00E+03	3.60E+01	9.20E+01	0.00E+00	1.57E+02	3.29E+02	2.65E+02	6.88E+04	4.30E+03
Total:	9.46E+03	9.60E+03	1.96E+02	3.68E+02	0.00E+00	7.91E+02	1.48E+03	8.10E+02	2.17E+05	1.30E+04
IT [C_O] cereal-oilseed										
Rapeseed	2.28E+03	0.00E+00	5.90E+01	6.60E+01	4.80E+01	2.30E+02	2.88E+02	3.55E+02	5.69E+04	2.96E+03
Barley	2.84E+03	3.00E+03	3.24E+01	8.28E+01	0.00E+00	1.48E+02	3.11E+02	2.51E+02	6.62E+04	4.13E+03
Rapeseed	2.28E+03	0.00E+00	5.90E+01	6.60E+01	4.80E+01	2.30E+02	2.88E+02	3.55E+02	5.69E+04	2.96E+03
Barley	2.84E+03	3.00E+03	3.24E+01	8.28E+01	0.00E+00	1.48E+02	3.11E+02	2.51E+02	6.62E+04	4.13E+03
Total:	1.02E+04	6.00E+03	1.83E+02	2.98E+02	9.60E+01	7.55E+02	1.20E+03	1.21E+03	2.46E+05	1.42E+04
IT [C_O_L] cereal-oilseed-legume										
Rapeseed	2.73E+03	0.00E+00	4.80E+01	4.40E+01	3.20E+01	2.76E+02	3.46E+02	4.26E+02	6.83E+04	3.55E+03
Barley	2.84E+03	3.00E+03	3.24E+01	8.28E+01	0.00E+00	1.48E+02	3.11E+02	2.51E+02	6.62E+04	4.13E+03
Rapeseed	2.28E+03	0.00E+00	5.90E+01	6.60E+01	4.80E+01	2.30E+02	2.88E+02	3.55E+02	5.69E+04	2.96E+03
Barley	2.84E+03	3.00E+03	3.24E+01	8.28E+01	0.00E+00	1.48E+02	3.11E+02	2.51E+02	6.62E+04	4.13E+03
Fava Bean	1.38E+03	0.00E+00	0.00E+00	1.90E+01	0.00E+00	1.25E+02	3.12E+02	3.15E+02	2.31E+04	7.43E+02
Total:	1.21E+04	6.00E+03	1.72E+02	2.95E+02	8.00E+01	9.26E+02	1.57E+03	1.60E+03	2.81E+05	1.55E+04
RO [C_O #1] cereal-oilseed option 1										
Sunflower	2.23E+03	0.00E+00	9.50E+01	6.00E+01	-	3.83E+02	3.69E+02	3.43E+02	5.35E+04	2.78E+03
Maize	3.61E+03	0.00E+00	1.20E+02	5.00E+01	-	9.03E+01	2.31E+02	2.24E+02	5.82E+04	3.90E+03
Wheat	3.10E+03	0.00E+00	9.00E+01	4.00E+01	-	8.05E+01	2.56E+02	2.76E+02	4.83E+04	3.22E+03
Total:	8.94E+03	0.00E+00	3.05E+02	1.50E+02	0.00E+00	5.54E+02	8.56E+02	8.42E+02	1.60E+05	9.90E+03
RO [C_O #2] cereal-oilseed option 2										
Rapeseed	2.73E+03	0.00E+00	9.50E+01	6.00E+01	-	2.76E+02	3.46E+02	4.26E+02	6.83E+04	3.55E+03
Maize	5.16E+03	0.00E+00	1.30E+02	6.00E+01	-	1.29E+02	3.31E+02	3.20E+02	8.31E+04	5.57E+03

Barley	3.61E+03	0.00E+00	8.50E+01	5.00E+01	-	1.88E+02	3.95E+02	2.85E+02	5.36E+04	3.61E+03
Total:	1.15E+04	0.00E+00	3.10E+02	1.70E+02	0.00E+00	5.93E+02	1.07E+03	1.03E+03	2.05E+05	1.27E+04
RO [C_O_L #1] cereal-oilseed-legume option 1										
Common Bean	2.23E+03	0.00E+00	0.00E+00	4.00E+01	-	1.16E+02	3.54E+02	4.82E+02	3.75E+04	8.69E+02
Maize	6.02E+03	0.00E+00	1.40E+02	7.00E+01	-	1.51E+02	3.86E+02	3.73E+02	9.69E+04	6.50E+03
Barley	3.61E+03	0.00E+00	8.50E+01	5.00E+01	-	1.88E+02	3.95E+02	2.85E+02	5.36E+04	3.61E+03
Rapeseed	2.73E+03	0.00E+00	9.50E+01	6.00E+01	-	2.76E+02	3.46E+02	4.26E+02	6.83E+04	3.55E+03
Total:	1.46E+04	0.00E+00	3.20E+02	2.20E+02	0.00E+00	7.30E+02	1.48E+03	1.57E+03	2.56E+05	1.45E+04
RO [C_O_L #2] cereal-oilseed-legume option 2										
Soybean	2.15E+03	0.00E+00	0.00E+00	5.50E+01	-	1.33E+02	4.14E+02	7.87E+02	4.25E+04	2.47E+03
Maize	6.02E+03	0.00E+00	1.40E+02	7.00E+01	-	1.51E+02	3.86E+02	3.73E+02	9.69E+04	6.50E+03
Barley	3.61E+03	0.00E+00	8.50E+01	5.00E+01	-	1.88E+02	3.95E+02	2.85E+02	5.36E+04	3.61E+03
Rapeseed	2.73E+03	0.00E+00	9.50E+01	6.00E+01	-	2.76E+02	3.46E+02	4.26E+02	6.83E+04	3.55E+03
Total:	1.45E+04	0.00E+00	3.20E+02	2.35E+02	0.00E+00	7.47E+02	1.54E+03	1.87E+03	2.61E+05	1.61E+04

Table 15: Synthetic-Nitrogen analysed per each crop and per rotation under each functional unit for Scotland (SC), Italy (IT) and Romania (RO).

Crop	Nitrogen per 1 crude NDU_{P-F}	Nitrogen per 1 kg of DP ruminants	Nitrogen per 1 MJ of DE for ruminants	Nitrogen per 1 CU
SC [C_O #1] cereal-oilseed option 1				
Rapeseed	3.92E-01	3.19E-01	1.99E-03	3.82E-02
Wheat	2.72E-01	2.49E-01	1.09E-03	1.73E-02
Wheat	3.00E-01	2.75E-01	1.20E-03	1.91E-02
Barley	2.41E-01	3.10E-01	1.31E-03	2.05E-02
Barley	2.41E-01	3.10E-01	1.31E-03	2.05E-02
Total:	2.82E-01	2.90E-01	1.32E-03	2.15E-02
SC [C_O #2] cereal-oilseed option 2				
Rapeseed	3.92E-01	3.19E-01	1.99E-03	3.82E-02
Barley	1.93E-01	2.50E-01	1.06E-03	1.66E-02
Oats	6.91E-02	2.11E-01	7.95E-04	1.42E-02
Spring Barley	1.81E-01	2.33E-01	9.94E-04	1.56E-02
Barley	2.41E-01	3.10E-01	1.31E-03	2.05E-02
Total:	1.74E-01	2.67E-01	1.18E-03	1.97E-02
SC [C_O_L] cereal-oilseed-legume				
Rapeseed	3.92E-01	3.19E-01	1.99E-03	3.82E-02
Barley	1.93E-01	2.50E-01	1.06E-03	1.66E-02
Oats	6.91E-02	2.11E-01	7.95E-04	1.42E-02
Peas	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Barley	1.93E-01	2.50E-01	1.06E-03	1.66E-02
Total:	1.37E-01	1.92E-01	1.01E-03	1.75E-02
IT [C_C] cereal-cereal				
Oats	1.51E-01	4.42E-01	1.56E-03	2.79E-02
Barley	1.09E-01	1.36E-01	5.23E-04	8.37E-03
Oats	1.51E-01	4.42E-01	1.56E-03	2.79E-02
Barley	1.09E-01	1.36E-01	5.23E-04	8.37E-03
Total:	1.32E-01	2.42E-01	9.02E-04	1.50E-02
IT [C_O] cereal-oilseed				
Rapeseed	2.05E-01	1.66E-01	1.04E-03	1.99E-02
Barley	1.04E-01	1.29E-01	4.89E-04	7.85E-03
Rapeseed	2.05E-01	1.66E-01	1.04E-03	1.99E-02
Barley	1.04E-01	1.29E-01	4.89E-04	7.85E-03
Total:	1.53E-01	1.51E-01	7.42E-04	1.29E-02
IT [C_O_L] cereal-oilseed-legume				
Rapeseed	1.39E-01	1.13E-01	7.02E-04	1.35E-02
Barley	1.04E-01	1.29E-01	4.89E-04	7.85E-03
Rapeseed	2.05E-01	1.66E-01	1.04E-03	1.99E-02
Barley	1.04E-01	1.29E-01	4.89E-04	7.85E-03
Faba Bean	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Total:	1.10E-01	1.07E-01	6.12E-04	1.11E-02
RO [C_O #1] cereal-oilseed option 1				
Sunflower	2.58E-01	2.77E-01	1.78E-03	3.41E-02
Maize	5.18E-01	5.36E-01	2.06E-03	3.08E-02
Wheat	3.51E-01	3.27E-01	1.86E-03	2.80E-02
Total:	3.56E-01	3.62E-01	1.91E-03	3.08E-02
RO [C_O #2] cereal-oilseed option 2				

Rapeseed	2.75E-01	2.23E-01	1.39E-03	2.68E-02
Maize	3.93E-01	4.06E-01	1.56E-03	2.33E-02
Barley	2.15E-01	2.98E-01	1.58E-03	2.35E-02
Total:	2.89E-01	3.01E-01	1.51E-03	2.43E-02
RO [C_O_L #1] cereal-oilseed-legume option 1				
Common Bean	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Maize	3.63E-01	3.75E-01	1.44E-03	2.15E-02
Barley	2.15E-01	2.98E-01	1.58E-03	2.35E-02
Rapeseed	2.75E-01	2.23E-01	1.39E-03	2.68E-02
Total:	2.16E-01	2.04E-01	1.25E-03	2.20E-02
RO [C_O_L #2] cereal-oilseed-legume option 2				
Soybean	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Maize	3.63E-01	3.75E-01	1.44E-03	2.15E-02
Barley	2.15E-01	2.98E-01	1.58E-03	2.35E-02
Rapeseed	2.75E-01	2.23E-01	1.39E-03	2.68E-02
Total:	2.08E-01	1.71E-01	1.22E-03	1.98E-02

Table 16: Direct land efficiency (m2.yr) per rotation under each functional unit for Scotland (SC), Italy (IT) and Romania (RO).

	hectares per 1 $NDU_{P\text{-}F}$	hectares per 1 digestible protein for ruminants	hectares per 1 digestible energy for ruminants	hectares per 1 CU
SC [C_O #1] cereal–oilseed option 1	1.47E-03	1.51E-03	6.89E-06	1.12E-04
SC [C_O #2] cereal–oilseed option 2	1.12E-03	1.71E-03	7.59E-06	1.26E-04
SC [C_O_L] cereal–oilseed -legume	1.05E-03	1.47E-03	7.78E-06	1.34E-04
IT [C_C] cereal–cereal	2.70E-03	4.94E-03	1.84E-05	3.07E-04
IT [C_O] cereal–oilseed	3.34E-03	3.30E-03	1.62E-05	2.82E-04
IT [C_O_L] cereal–oilseed-legume	3.19E-03	3.13E-03	1.78E-05	3.22E-04
RO [C_O #1] cereal–oilseed option 1	3.50E-03	3.56E-03	1.88E-05	3.03E-04
RO [C_O #2] cereal–oilseed option 2	3.62E-01	2.91E-03	1.46E-05	2.36E-04
RO [C_O_L #1] cereal–oilseed-legume option 1	2.70E-03	2.55E-03	1.56E-05	2.75E-04
RO [C_O_L #2] cereal–oilseed-legume option 2	2.60E-03	2.14E-03	1.53E-05	2.48E-04

3.8.6 Normalisation

The results of the normalisation steps described in the manuscript can be found in the Table 17 below.

Table 17: Contribution of each impact category to the aggregate normalised scores, equal weighting (European Environmental Bureau, 2018). In bold borders, there are the categories that sum up to 80% of the total impact for each rotation in Scotland (SC), Italy (IT) and Romania (RO) and for NDU$_{\text{P-F}}$ FU. The highest impacts within the rotation are shaded in darker red and the lowest are shaded in darker green.

	Scotland (SC)			Italy (IT)			Romania (RO)			
Indicator	SC [C_O #1]	SC [C_O#2]	SC [C_O_L]	IT [C_C]	IT [C_O]	IT [C_O_L]	RO [C_O#1]	RO [C_O#2]	RO [C_O_L#1]	RO [C_O_L#2]
	cereal-oilseed option 1	cereal-oilseed option 2	cereal-oilseed-legume	cereal-cereal	cereal-oilseed	cereal-oilseed-legume	cereal-oilseed option 1	cereal-oilseed option 2	cereal-oilseed-legume option 1	cereal-oilseed-legume option 2
Eutrophication terrestrial	14.5%	13.7%	13.1%	11.4%	14.3%	11.8%	17.4%	18.1%	15.9%	16.0%
Eutrophication marine	14.0%	15.5%	13.8%	25.2%	7.8%	11.2%	10.7%	8.2%	8.4%	10.1%
Land use	12.6%	14.3%	16.2%	17.0%	22.1%	24.1%	16.7%	17.1%	19.4%	19.3%
Non-cancer human health effects	12.1%	11.6%	12.4%	11.3%	13.9%	14.5%	11.7%	11.6%	12.7%	11.2%
Acidification terrestrial and freshwater	11.2%	10.5%	10.0%	8.9%	11.0%	9.1%	13.0%	13.6%	12.1%	12.1%
Climate change	7.4%	7.2%	7.3%	3.3%	4.1%	3.9%	5.4%	5.7%	5.6%	5.7%
Respiratory inorganics	7.0%	6.6%	6.4%	5.6%	6.9%	5.6%	8.3%	8.7%	7.6%	7.7%
Cancer human health effects	5.2%	5.1%	5.1%	3.9%	4.6%	5.5%	4.0%	4.0%	5.2%	4.0%
Eutrophication freshwater	3.6%	3.5%	3.8%	3.8%	4.2%	3.7%	2.8%	2.9%	3.1%	3.2%
Resource use, energy carriers	3.2%	3.1%	3.2%	2.4%	2.9%	2.7%	2.8%	2.9%	2.8%	2.8%
Photochemical ozone formation, HH	2.4%	2.4%	2.5%	1.6%	1.9%	2.0%	1.9%	2.0%	2.1%	2.1%
Resource use, mineral and metals	2.4%	2.3%	2.4%	1.8%	2.1%	1.9%	1.7%	1.8%	1.8%	1.9%
Water scarcity	2.3%	2.0%	1.8%	2.2%	2.6%	2.2%	2.1%	1.9%	1.8%	1.8%
Ecotoxicity freshwater	1.6%	1.6%	1.6%	1.4%	1.3%	1.2%	1.3%	1.3%	1.3%	1.7%
Ionising radiation, HH	0.3%	0.3%	0.3%	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%
Ozone depletion	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%

3.8.7 Additional footprint

The normalised environmental scores for animal feed nutritional output (CU and DP) and per human nutritional output (NDUP-F) across Scotland and Italian crop rotations results can be found in the Figure 10 below.

Figure 10: Normalised environmental scores for animal feed nutritional output (CU and DP) and per human nutritional output (NDUP-F) across Scotland and Italian crop rotations.

3.8.8 Sensitivity Analysis (SA): Simulation of Nitrogen Inhibitors use

As a sensitivity analysis, we decided to simulate the use of nitrogen inhibitors such as nitrification inhibitors (NI) and urease inhibitors (UI) within N-fertiliser applications. Based on meta-analysis studies (Abalos et al., 2014; Gilsanz et al., 2016; Li et al., 2017; Thapa et al.,

2016) of the main effects of the inhibitors, we considered an average yield increase of 3.5% (Abalos et al., 2014; Li et al., 2017), a reduction of the direct N2O-N emission factor (EF1) of 35% (Gilsanz et al., 2016; Thapa et al., 2016) and an N-use-efficiency (NUE) improvement of 10% (Abalos et al., 2014; Li et al., 2017). This resulted in a lower N fertilisation rate, and the leaching values were adjusted accordingly. The simulation was performed for every rotation across all regions studied. The values of N-fertiliser, yields (DM), straw yields, NUE, leaching values, and EF1 before and after the sensitivity analysis can be observed in Table 18.

Table 18: Values for N-fertiliser applied, yields (DM), straw yields, NUE, leaching values and EF1 for every rotation, per hectare year, in Scotland (SC), Italy (IT) and Romania (RO) before and after the sensitivity analysis simulation.

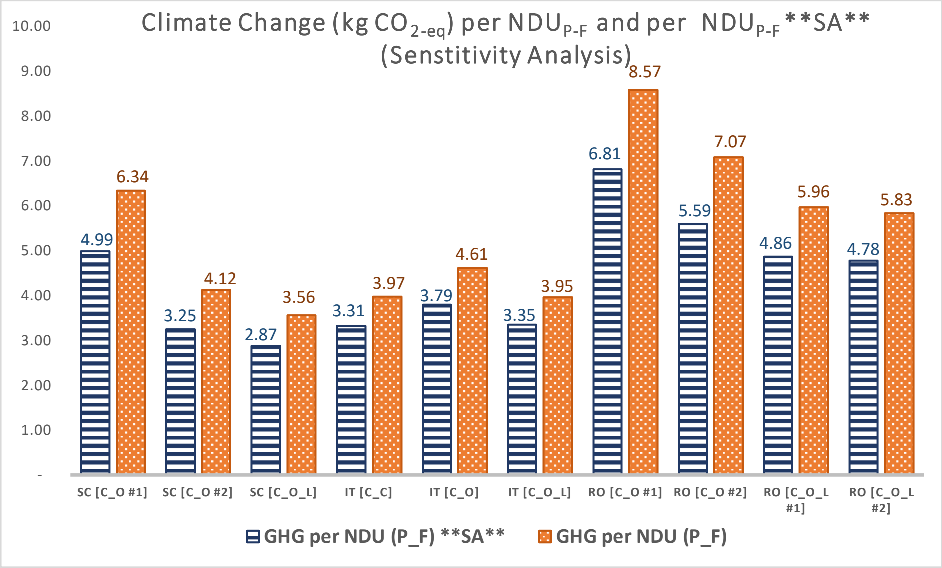
Crop	**Kg N-applied (kg/ha)**	**Yields DM (kg/ha)**	**Yields Straw (kg/ha)**	**NUE**	**Leaching (kg N-NO$_3^-$)**	**EF1**	**Sensitivity Analysis: kg N-applied (kg/ha)**	**Sensitivity Analysis: Yields (kg/ha)**	**Sensitivity Analysis: Straw DM (kg/ha)**	**Sensitivity Analysis: NUE**	**Sensitivity Analysis: Leaching (kg N-NO$_3^-$)**	**Sensitivity Analysis: EF1**
SC [C_O #1]												
Rapeseed	2.04E+02	4.10E+03	0.00E+00	4.97E-02	3.15E+01	1.60E-02	1.90E+02	4.24E+03	0.00E+00	4.47E-02	2.94E+01	1.04E-02
Wheat	1.93E+02	8.60E+03	5.20E+03	2.25E-02	2.15E+01	1.60E-02	1.80E+02	8.90E+03	5.38E+03	2.02E-02	2.00E+01	1.04E-02
Wheat	2.03E+02	8.17E+03	5.00E+03	2.48E-02	2.51E+01	1.60E-02	1.89E+02	8.46E+03	5.18E+03	2.23E-02	2.34E+01	1.04E-02
Barley	1.81E+02	6.88E+03	4.50E+03	2.63E-02	2.81E+01	1.60E-02	1.69E+02	7.12E+03	4.66E+03	2.37E-02	2.62E+01	1.04E-02
Barley	1.81E+02	6.88E+03	4.50E+03	2.63E-02	2.81E+01	1.60E-02	1.69E+02	7.12E+03	4.66E+03	2.37E-02	2.62E+01	1.04E-02
Total:	9.62E+02	3.46E+04	1.92E+04	-		-	8.96E+02	3.58E+04	1.99E+04	-	0.00E+00	-
SC [C_O #2]												
Rapeseed	2.04E+02	4.10E+03	0.00E+00	4.97E-02	3.15E+01	1.60E-02	1.90E+02	4.24E+03	0.00E+00	4.47E-02	2.94E+01	1.04E-02
Barley	1.64E+02	7.74E+03	5.00E+03	2.12E-02	1.91E+01	1.60E-02	1.53E+02	8.01E+03	5.18E+03	1.91E-02	1.78E+01	1.04E-02
Oats	1.21E+02	7.31E+03	5.50E+03	1.65E-02	2.55E+01	1.60E-02	1.12E+02	7.57E+03	5.69E+03	1.49E-02	2.37E+01	1.04E-02
Spring Barley	1.10E+02	5.59E+03	3.50E+03	1.98E-02	2.57E+01	1.60E-02	1.03E+02	5.79E+03	3.62E+03	1.78E-02	2.40E+01	1.04E-02
Barley	1.81E+02	6.88E+03	4.50E+03	2.63E-02	2.81E+01	1.60E-02	1.69E+02	7.12E+03	4.66E+03	2.37E-02	2.62E+01	1.04E-02
Total:	7.80E+02	3.16E+04	1.85E+04	-		-	7.26E+02	3.27E+04	1.91E+04	-		-
SC [C_O_L]												
Rapeseed	2.04E+02	4.10E+03	0.00E+00	4.97E-02	3.15E+01	1.60E-02	1.90E+02	4.24E+03	0.00E+00	4.47E-02	2.94E+01	1.04E-02
Barley	1.64E+02	7.74E+03	5.00E+03	2.12E-02	1.91E+01	1.60E-02	1.53E+02	8.01E+03	5.18E+03	1.91E-02	1.78E+01	1.04E-02
Oats	1.21E+02	7.31E+03	5.50E+03	1.65E-02	2.55E+01	1.60E-02	1.12E+02	7.57E+03	5.69E+03	1.49E-02	2.37E+01	1.04E-02
Peas	0.00E+00	4.73E+03	0.00E+00	-	5.97E+00	1.60E-02	0.00E+00	4.73E+03	0.00E+00	-	5.97E+00	1.60E-02
Barley	1.64E+02	7.74E+03	5.00E+03	2.12E-02	1.91E+01	1.60E-02	1.53E+02	8.01E+03	5.18E+03	1.91E-02	1.78E+01	1.04E-02
Total:	6.52E+02	3.16E+04	1.55E+04	-		-	6.07E+02	3.26E+04	1.60E+04	-		-
IT [C_C]												
Oats	6.20E+01	1.72E+03	1.80E+03	3.60E-02	7.06E+01	1.60E-02	5.78E+01	1.78E+03	1.86E+03	3.24E-02	6.57E+01	1.04E-02
Barley	3.60E+01	3.01E+03	3.00E+03	1.20E-02	3.47E+00	1.60E-02	3.35E+01	3.12E+03	3.11E+03	1.08E-02	3.23E+00	1.04E-02
Oats	6.20E+01	1.72E+03	1.80E+03	3.60E-02	7.06E+01	1.60E-02	5.78E+01	1.78E+03	1.86E+03	3.24E-02	6.57E+01	1.04E-02
Barley	3.60E+01	3.01E+03	3.00E+03	1.20E-02	3.47E+00	1.60E-02	3.35E+01	3.12E+03	3.11E+03	1.08E-02	3.23E+00	1.04E-02
Total:	1.96E+02	9.46E+03	9.60E+03	-		-	1.83E+02	9.79E+03	9.94E+03	-		-
IT [C_O]												
Rapeseed	5.90E+01	2.28E+03	0.00E+00	2.59E-02	5.29E+00	1.60E-02	5.50E+01	2.35E+03	0.00E+00	2.33E-02	4.93E+00	1.04E-02
Barley	3.24E+01	2.84E+03	3.00E+03	1.14E-02	9.13E+00	1.60E-02	3.02E+01	2.94E+03	3.11E+03	1.03E-02	8.51E+00	1.04E-02
Rapeseed	5.90E+01	2.28E+03	0.00E+00	2.59E-02	5.29E+00	1.60E-02	5.50E+01	2.35E+03	0.00E+00	2.33E-02	4.93E+00	1.04E-02
Barley	3.24E+01	2.84E+03	3.00E+03	1.14E-02	9.13E+00	1.60E-02	3.02E+01	2.94E+03	3.11E+03	1.03E-02	8.51E+00	1.04E-02
Total:	1.83E+02	1.02E+04	6.00E+03	-		-	1.70E+02	1.06E+04	6.21E+03	-		-
IT [C_O_L]												
Rapeseed	4.80E+01	2.73E+03	0.00E+00	1.76E-02	0.00E+00	1.60E-02	4.47E+01	2.83E+03	0.00E+00	1.58E-02	0.00E+00	1.04E-02
Barley	3.24E+01	2.84E+03	3.00E+03	1.14E-02	9.13E+00	1.60E-02	3.02E+01	2.94E+03	3.11E+03	1.03E-02	8.51E+00	1.04E-02

Rapeseed	5.90E+01	2.28E+03	0.00E+00	2.59E-02	5.29E+00	1.60E-02	5.50E+01	2.35E+03	0.00E+00	2.33E-02	4.93E+00	1.04E-02
Barley	3.24E+01	2.84E+03	3.00E+03	1.14E-02	9.13E+00	1.60E-02	3.02E+01	2.94E+03	3.11E+03	1.03E-02	8.51E+00	1.04E-02
Fava Bean	0.00E+00	1.38E+03	-	-	2.84E+01	1.60E-02	0.00E+00	1.38E+03	-	-	2.84E+01	1.60E-02
Total:	1.72E+02	1.21E+04	6.00E+03	-		-	1.60E+02	1.24E+04	6.21E+03	-		-
RO [C_O #1]												
Sunflower	9.50E+01	2.23E+03	0.00E+00	4.27E-02	1.11E+01	1.60E-02	8.85E+01	2.31E+03	0.00E+00	3.84E-02	1.03E+01	1.04E-02
Maize	1.20E+02	3.61E+03	0.00E+00	3.32E-02	2.14E+01	1.60E-02	1.12E+02	3.74E+03	0.00E+00	2.99E-02	1.99E+01	1.04E-02
Wheat	9.00E+01	3.10E+03	0.00E+00	2.91E-02	1.17E+01	1.60E-02	8.38E+01	3.20E+03	0.00E+00	2.62E-02	1.09E+01	1.04E-02
Total:	3.05E+02	8.94E+03	0.00E+00	-		-	2.84E+02	9.25E+03	0.00E+00	-		-
RO [C_O #2]												
Rapeseed	9.50E+01	2.73E+03	0.00E+00	3.48E-02	4.63E+00	1.60E-02	8.85E+01	2.83E+03	0.00E+00	3.13E-02	4.31E+00	1.04E-02
Maize	1.30E+02	5.16E+03	0.00E+00	2.52E-02	1.84E+01	1.60E-02	1.21E+02	5.34E+03	0.00E+00	2.27E-02	1.72E+01	1.04E-02
Barley	8.50E+01	3.61E+03	0.00E+00	2.35E-02	6.91E+00	1.60E-02	7.92E+01	3.74E+03	0.00E+00	2.12E-02	6.43E+00	1.04E-02
Total:	3.10E+02	1.15E+04	0.00E+00	-		-	2.89E+02	1.19E+04	0.00E+00	-		-
RO [C_O_L #1]												
Common Bean	0.00E+00	2.23E+03	0.00E+00	-	3.72E+00	1.60E-02	0.00E+00	2.23E+03	0.00E+00	-	3.72E+00	1.60E-02
Maize	1.40E+02	6.02E+03	0.00E+00	2.33E-02	2.01E+01	1.60E-02	1.30E+02	6.23E+03	0.00E+00	2.09E-02	1.87E+01	1.04E-02
Barley	8.50E+01	3.61E+03	0.00E+00	2.35E-02	6.91E+00	1.60E-02	7.92E+01	3.74E+03	0.00E+00	2.12E-02	6.43E+00	1.04E-02
Rapeseed	9.50E+01	2.73E+03	0.00E+00	3.48E-02	4.63E+00	1.60E-02	8.85E+01	2.83E+03	0.00E+00	3.13E-02	4.31E+00	1.04E-02
Total:	3.20E+02	1.46E+04	0.00E+00	-		-	2.98E+02	1.50E+04	0.00E+00	-		-
RO [C_O_L #2]												
Soybean	0.00E+00	2.15E+03	0.00E+00	-	1.52E+01	1.60E-02	0.00E+00	2.15E+03	0.00E+00	-	1.52E+01	1.60E-02
Maize	1.40E+02	6.02E+03	0.00E+00	2.33E-02	2.01E+01	1.60E-02	1.30E+02	6.23E+03	0.00E+00	2.09E-02	1.87E+01	1.04E-02
Barley	8.50E+01	3.61E+03	0.00E+00	2.35E-02	6.91E+00	1.60E-02	7.92E+01	3.74E+03	0.00E+00	2.12E-02	6.43E+00	1.04E-02
Rapeseed	9.50E+01	2.73E+03	0.00E+00	3.48E-02	4.63E+00	1.60E-02	8.85E+01	2.83E+03	0.00E+00	3.13E-02	4.31E+00	1.04E-02
Total:	3.20E+02	1.45E+04	0.00E+00	-		-	2.98E+02	1.49E+04	0.00E+00	-		-

Table 19: Values Impact scores across all impact categories for all rotations analysed in Scotland (SC), Italy (IT) and Romania (RO), expressed per NDUP-F with the economic allocation (EA) under the Sensitivity Analysis. For each impact category and each region, the highest impact is shaded darker red and the lowest impact is shaded darker green.

Indicator	SC [C_O #1]	SC [C_O #2]	SC [C_O_L]	IT [C_C]	IT [C_O]	IT [C_O_L]	RO [C_O #1]	RO [C_O #2]	RO [C_O_L #1]	RO [C_O_L #2]	**Unit**
Eutrophication terrestrial	2.55E-01	1.61E-01	1.30E-01	2.78E-01	3.30E-01	2.45E-01	5.71E-01	4.59E-01	3.53E-01	3.39E-01	mol N eq
Resource use, mineral and metals	1.46E-05	9.30E-06	8.33E-06	1.47E-05	1.63E-05	1.33E-05	1.97E-05	1.59E-05	1.40E-05	1.35E-05	kg Sb eq
Climate change	4.99E+00	3.25E+00	2.87E+00	3.31E+00	3.79E+00	3.35E+00	6.81E+00	5.59E+00	4.86E+00	4.78E+00	kg CO_2 eq
Eutrophication freshwater	9.70E-04	6.22E-04	5.86E-04	1.43E-03	1.49E-03	1.20E-03	1.40E-03	1.13E-03	1.06E-03	1.04E-03	kg P eq
Photochemical ozone formation, HH	9.77E-03	6.52E-03	5.78E-03	9.35E-03	1.06E-02	9.82E-03	1.47E-02	1.17E-02	1.08E-02	1.03E-02	kg NMVOC eq
Land use	1.81E+03	1.37E+03	1.32E+03	3.36E+03	4.12E+03	4.05E+03	4.45E+03	3.50E+03	3.48E+03	3.31E+03	Pt
Respiratory inorganics	4.51E-07	2.82E-07	2.30E-07	5.00E-07	5.81E-07	4.27E-07	9.84E-07	7.93E-07	6.12E-07	5.89E-07	disease inc.
Water scarcity	2.86E+00	1.58E+00	1.23E+00	3.56E+00	4.19E+00	3.21E+00	4.60E+00	3.35E+00	2.68E+00	2.61E+00	m^3 depriv.
Ozone depletion	2.31E-07	1.52E-07	1.31E-07	2.43E-07	2.75E-07	2.40E-07	3.85E-07	3.07E-07	2.71E-07	2.55E-07	kg CFC11 eq
Ionising radiation, HH	1.14E-01	7.41E-02	6.76E-02	1.21E-01	1.43E-01	1.22E-01	1.72E-01	1.38E-01	1.23E-01	1.17E-01	kBq U-235 eq
Acidification terrestrial and freshwater	6.22E-02	3.91E-02	3.20E-02	6.85E-02	8.04E-02	5.98E-02	1.35E-01	1.09E-01	8.43E-02	8.11E-02	mol H^+ eq
Eutrophication marine	3.95E-02	2.92E-02	2.24E-02	9.86E-02	2.89E-02	3.87E-02	5.62E-02	3.33E-02	3.01E-02	3.50E-02	kg N eq
Resource use, energy carriers	2.14E+01	1.39E+01	1.21E+01	2.26E+01	2.59E+01	2.18E+01	3.48E+01	2.78E+01	2.41E+01	2.29E+01	MJ
Ecotoxicity freshwater	1.97E+00	1.30E+00	1.15E+00	2.42E+00	2.16E+00	1.87E+00	2.90E+00	2.27E+00	2.06E+00	2.61E+00	CTUe
Cancer human health effects	2.08E-08	1.35E-08	1.18E-08	2.21E-08	2.40E-08	2.65E-08	3.02E-08	2.30E-08	2.66E-08	1.94E-08	CTUh
Non-cancer human health effects	6.07E-07	3.92E-07	3.59E-07	7.90E-07	9.20E-07	8.68E-07	1.11E-06	8.42E-07	8.11E-07	6.82E-07	CTUh

Figure 11: Climate Change (kg $CO_{2\text{-eq}}$) results for all rotations analysed in Scotland (SC), Italy (IT) and Romania (RO), expressed per $NDU_{P\text{-}F}$ with the economic allocation (EA) before and after the Sensitivity Analysis.



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4 **Chapter Four:** Environmental and land use consequences of replacing milk and beef with plant-based alternatives

Please note that this manuscript was submitted as described below:

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Highlights

- Substituting beef with pea protein can save 2.42 kg CO_2e per 100 g serving
- Afforestation of spared land increases saving to 7.3 kg CO_2e per serving
- Displaced calf production negates CO_2e mitigation by soy milk substitution of cow milk
- But carbon dioxide removal (CDR) on spared land could generate net CO_2e mitigation
- Plant protein diet transitions coupled with CDR support moves to climate neutrality

Abstract

The consumption of meat and dairy products raise enormous environmental concerns. Circa 80% of greenhouse gas emissions (GHG) from the livestock industry originate from beef, milk and pork production. Changing the production and consumption of meat and dairy products, is considered to offer an important contribution to achieving the Paris Agreement climate targets (UNFCCC, 2015), and could reduce the import of soybean meal to Europe from countries where it is linked with deforestation. However, individual diet substitutions may have indirect and unintended environmental consequences across interlinked livestock systems, hence a wider assessment of impacts of consumption changes is required using consequential life cycle assessment (cLCA). In this study, we investigated the environmental consequences of two independent but interconnected diet choices in a German context: (i) replacing dairy milk with soy milk, and; (ii) replacing beef meatballs with pea protein balls. We related commodity demand to detailed agricultural rotations and land use changes via farm scale economic modelling coupled with consequential LCA. The substitution of beef by pea-derived protein can result in GHG savings of 2.4 kg CO_2e per 100 g serving, and to 7.3 kg CO_2e per 100 g serving if spared land is afforested. Environmental problems related to nutrient leakage such as acidification and eutrophication are also mitigated. Unless accompanied by dramatic reductions in beef consumption, the substitution of cow milk with soy-based milk does not lead to significant GHG mitigation owing to the displacement of dairy-beef production to less efficient suckler-beef systems. Nonetheless, land sparing by cow milk substitution could support overall GHG mitigation if combined with afforestation. This study confirms that legumes can play an important role in diet transitions towards climate neutrality, especially via substitution of meat (as opposed to dairy) products.

Keywords: vegan, legumes, life cycle analysis, carbon opportunity cost, carbon footprint

4.1 Introduction

Demand for animal-products, such as meat and milk, continues to increase. According to FAO (2018), the global dairy herd has increased by 11%, and milk yields by 17% per cow, over the last ten years. Global meat consumption is expected to increase by 1.1% per year (AHDB, 2021). However, annual beef consumption in Europe is expected to decline from 10.6 kg to 9.7 kg per capita by 2030. The European suckler herd is forecast to follow this trend and contract. This reduction is partly due to sustainability concerns being a key factor in the European market (AHDB, 2021). Livestock production brings enormous environmental pressures (Poore and Nemecek, 2018; Willett et al., 2019), and animal-based foods such as meat and dairy products are major contributors to environmental damage (Chai et al., 2019; Choudhary and Kumar, 2017; Notarnicola et al., 2017). Beef, milk and pork account for 80% of greenhouse gases emissions (GHG) from the livestock industry (Weiss & Leip, 2012). According to Godfray et al. (2018), a considerable part of these emissions is related to bovine enteric fermentation (Beauchemin et al., 2009; Nguyen et al., 2010). Chadwick (2005) also highlights the significance of ammonia and nitrous oxide emission from manure management and fertilisation, and GHG emissions also arise from other life cycle stages of livestock systems, such as from manufacture of fertilisers, combustion of fossil fuels, and feed crop production (Soteriades et al., 2018).

Reducing the consumption of meat is seen as an important strategy to achieve ambitious emission reductions and carbon dioxide removal (CDR) targets established by the Paris agreement (UNFCCC, 2015). In a European context, reduced meat demand may be associated with a reduction in the demand for imported soybean feed, avoiding the environmental degradation arising from land clearing associated with production of this crop in Latin America (Lienhardt et al., 2019; Zander et al., 2016). The use of legume plant alternatives in diets could lead to a reduction of 62 % in meat consumption across Europe, as suggested by Hallström and Börjesson (2012) and Zander et al. (2016). Western diets are known to be energy-rich and nutrient-poor, leading to health problems such as obesity (Saarinen et al., 2017). Falcone et al., (2020) argues that there is already a consensus that plant-based diets can reduce problems caused by poor nutrition such as obesity, type 2 diabetes, and cardiovascular diseases (Joyce et al., 2012; Lynch et al., 2018; Rosi et al., 2017; Springmann et al., 2016) while also reducing pressure on the environment.

Nevertheless, with few exceptions such as the Danish food database (Goldstein et al., 2016; Schmidt et al., 2021), most of the carbon or environmental footprint studies of meat substitutes and vegetarian and vegan diets have applied an attributional Life Cycle Assessment (aLCA) approach (Chaudhary et al., 2018; Davis et al., 2010; Saget et al., 2021a, 2021b, 2021c). This means that these studies consider current or historical market averages for production factors, and environmental burdens are quantified by taking into account inputs and outputs at all stages of the product life cycle, from the extraction of raw materials to manufacturing, transport, use, and final disposal (ISO 14040, 2006). Allocation of burdens across co-products is performed in aLCA when a product is associated with co-products – across which production inputs and outputs cannot be biophysically separately (Dalgaard et al., 2014). For instance, the environmental pollution caused by dairy systems is typically split between milk (main product), meat and surplus calves (co-products). The allocation rules are defined by the LCA practitioner and it can vary, for example, it can be based on a physical relation (for example the mass of each by product), energetic (based on energy content), economic (based on the monetary value), or other relations. The choice of allocation procedures can generate biased results, and the final interpretation can vary substantially according to the allocation rule chosen.

Consequential Life Cycle Assessments (cLCA) can provide different results and interpretation compared with aLCA (Schaubroeck et al., 2021). cLCA tackles a specific change in demand of a product under study, which changes the supply according to cause–effect relationships where co-product activities are dealt with using substitution instead of allocation (Dalgaard et al., 2014), and the modelling of by-products entails substitution by including only unconstrained market suppliers (Schmidt, 2008a). Therefore, if there is an improvement in efficiency in dairy systems via higher milk yields per cow, the market demand for milk would be satisfied with a lower number of cows (Styles et al., 2018). This lower number of cows would consequently provide less meat in their end of life via slaughter and surplus calf production. The shortfall in beef production would have to be compensated by dedicated beef systems (Baldini et al., 2017; Mazzetto et al., 2020), with considerably higher emission intensity per kg of beef produced. This consequential approach is followed through the entire value chain in a cLCA. Similarly, a change in the demand for soybean meal for feed affects the production of soybean oil and other grain crops and their straw residues, affecting, inter alia, the oil market and possibly the energy market, depending on the type of straw and whether it is used for energy generation (Dalgaard et al., 2014; Schmidt and Weidema, 2008). There remains a need to comprehensively assess the wider implications of changes in demand for milk and meat products, accounting for complex "teleconnections" across systems (Styles et al., 2018).

In this study, we investigate the environmental consequences of replacing dairy milk and beef meatballs with legume-based options, namely soy milk and pea protein balls respectively, in a German context. These products were chosen owing to the increasing popularity of alternative milk products and high potential for environmental impact reduction via beef substitution (Eshel et al., 2014). Our analysis includes agricultural crop rotation changes and land use implications, estimated from economic viability in farm modelling. As far as we are aware, these product substitutions were never investigated through consequential LCA that simultaneously accounts for dairy-beef displacement, crop rotation changes and land carbon opportunity costs.

4.2 Methods

4.2.1 Goal and Scope

A consequential LCA was conducted to understand the environmental impact and land use implications of simple diet change based on direct substitution of animal-based products with plant-based products in Germany, specifically replacing dairy milk with soy milk and meatballs with protein pea protein balls. The target audience for this study comprises researchers and policymakers with an interest in the transition to more sustainable food systems. Two functional units were addressed: (i) the production of 1 litre of soy milk (ii) the production of a 100 g portion of pea-balls. It was considered that soy milk replaces semi skimmed milk, while pea protein balls replace beef meatballs on a 1:1 mass basis. Modelling was undertaken in Open LCA v1.9 (GreenDelta, 2006), using Ecoinvent v.3.7 consequential database for background data (Moreno-Ruiz et al., 2018). Life Cycle Impact Assessment (LCIA) was performed using the method recommended by the European Commission - Product Environmental Footprint (PEF) guidelines (European Environmental Bureau et al., 2018). This method was selected because it is comprehensive and aligns with the aim to harmonise European environmental footprint studies. The method recommends the calculation of 16 environmental impact categories and in this paper we focus interpretation on five categories which span the dominant environmental impacts incurred by agricultural systems in relation to planetary boundary exceedances (Steffen et al., 2015): Acidification, Climate Change, Eutrophication freshwater, Resources - fossil, and Water Scarcity.

Legume crops necessary for soy milk and pea protein ball production were assumed to be integrated into existing German crop rotations, consistent with recent efforts to increase legume production and consumption in Europe (TRUE legumes, 2021). Modified agricultural crop rotations were simulated by an Economic Farm Emission Model (EFEM) developed at the Hohenheim University (Petig et al, 2018, Petig et al., 2019), described in detail in section 4.2.2. This model identifies the conventional crop rotations likely to be replaced by legume-modified rotations incorporating soybean and pea as well as livestock production data including feed rations. This modelling is based on typical farms representing different structural and natural conditions in Germany. Crop rotation modelling was based on typical arable farms located in Southern Germany (Bavaria) and Eastern Germany (Brandenburg) (Petig et al, 2018, Petig et al., 2019). Dairy and beef system modelling was based on typical farms from the Baden-Württemberg region in Southern Germany (Petig et al. 2019). This farm level data is further described in sections 4.2.2 and 4.2.3. Milk (soybean and dairy) processing data assumptions are described in section 4.2.4 and beef/protein ball processing assumptions are described in section 4.2.5.

Fertiliser sources were assumed using data describing German consumption of fertiliser types, based on International Fertilizer Association information from 2015 to 2018 (IFASTAT, 2021). Germany consumes 52% of nitrogen (N) in the form of Calcium ammonium nitrate (CAN), 32% in the form of Urea, 8% as Ammonium sulphate (AS) and 5% as Monoammonium Phosphate (MAP). In this study, ammonia (NH3), nitrous oxide (N2O), and carbon dioxide (CO2) emissions arising from fertiliser application were calculated according to Intergovernmental Panel on Climate Change (IPCC, 2019a, 2006) emission factors, whilst phosphorus (P) runoff was calculated by assuming a 1% loss factor applied in a previous crop LCA study (Styles et al., 2015).

4.2.2 Economic Farm Emission Model (EFEM)

The Economic Farm Emission Model (EFEM) is a comparative static linear optimisation model based on a bottom-up approach and can be applied at farm- or regional-level. (Krimly et al. 2016, Petig et al. 2018 and Petig et al. 2019). It analyses farm management decisions and optimises the farm organisation with the aim of maximising the total gross margin (objective function) of the farm. Regionally typical conditions, such as climate, yields in arable farming, grassland and animal production are taken into account. The factor endowment of the farm models and regional typical crop rotation limits serve as constraints for the optimisation process. Producer and factor prices as well as the agricultural and environmental policy framework conditions are exogenous parameters.

In order to generate typical farms for different farm types and regions, individual farm data from the Farm Accountancy Data Network (FADN) of the EU Commission (EU-FADN - DG Agriculture, 2018) are used. Typical farm models are built based on average farm data for different farm types and NUTS2 regions. The classification of farm types is based on the FADN farm typologies.

The main part of the model is the production module. It unites all relevant agricultural production processes (Figure 12). With respect to plant production, EFEM distinguishes different food and feed production activities on arable land and grassland. Production processes vary in fertilisation and production intensities and soil management. In this study, EFEM was extended by incorporating new legume cultivation and legume feed systems (Zimmermann et al. 2020, TRUE final report). Legumes are well known to provide many pre-crop effects on a crop rotation (Costa et al., 2020; Nemecek et al., 2008; Reckling et al., 2016). In EFEM, N-fixation by legumes is assumed depending on the crop, and confers an average fertiliser-N saving of 30 kg of N per hectare for the following crop. Further pre-crop-effects such as a yield growth of about 10 % in the following crop are assumed in model scenarios.

The input data derived from FADN include a wide range of structural farm data such as capacities, land use and livestock, as well as economic farm data on yields, product-specific outputs and farm inputs. The values of these input data were based on three-year averages to compensate for year-to-year fluctuations. Gross margins were calculated for all relevant crop production activities based on FADN data. This is achieved through applying ARACOST, a programme developed by the EU Commission (DG VI) (1999) for estimating variable costs of production of arable crops. With respect to livestock production, the FADN data were supplemented by production specific costs such as performance related feed costs based on Petig et al. (2019).

The main results of the optimization process are economic variables such as farm total gross margin as well as production structures and quantities and the associated input of means of production such as fertilisers, pesticides and energy input. The latter are included in the LCA inventories.

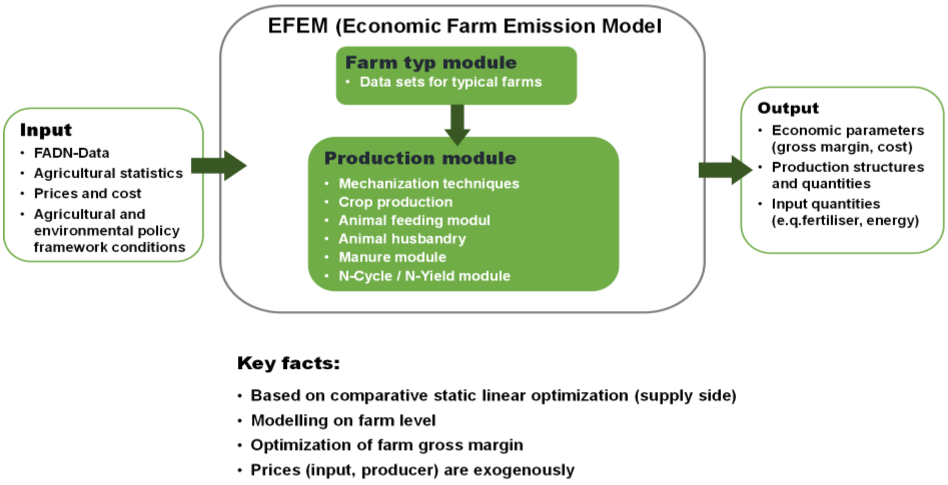

Figure 12: Structure, data sources and output of the Economic Farm Emission Model (EFEM).

4.2.2.1 Arable systems data

Typical arable farms in Germany were investigated regarding the economic viability of the inclusion of legume crops in the rotation (Table 20). The regions were characterized by different agro-climatic conditions and farm structures. Under a scenario where legume pre-crop effects increased yields in following crops by 10 %, the introduction of soybean and peas was considered, accounting for the grains those legumes would replace (Table 20). Net grain displacement depends on the changed demand for dairy and beef feed supply, and according to cLCA methodology, is compensated by an unconstrained supply chain in the market. In order to constrain scenario permutations and generate indicative results on land balance associated with diet change, this compensation was considered to arise within Germany. Therefore, conventional crop rotations modelled in EFEM (pre legume incorporation) were used to model the impact of any displaced production.

Table 20: Crop rotations without and with legumes on typical arable farms located in Eastern Germany (Brandenburg) and Southern Germany (Bavaria)

	Eastern Germany (Brandenburg)			Southern Germany (Bavaria)		
	Crop rotation without legumes ha	Yield (FM) t/ha	Incorpo-ration of legumes Ha	Crop rotation without legumes ha	Yield (FM) t/ha	Incorpo-ration of legumes ha
Winter wheat	147	5.7	-	75	7.6	-23.4
Spring wheat	28	4.4	-	15	4.4	-
Winter barley	35	5.1	-27.9	-	7	-
Rapeseed	105	4.4	-	15	4.4	-
Grain maize	31	8.0	-17.5	12	9.7	-12.0
Silage maize	3	35.2	-3.5	2	49.2	-2.1
Sugar beet	-	60.1	-	31	83.9	-
Soybean	-	1.8	-	-	2.2	37.5
Peas	-	2.1	48.9	-	3.2	-
Catch crops	31	-	14.0	31	-	3.3

4.2.3 Beef and Dairy Systems data

The typical dairy farm is based on FADN data from Oberland/Donau, an intensive livestock region in Baden-Württemberg with a typical grass and maize feed regime (Table 21). The dairy farm comprises 139 milking cows, 35 calves and 35 heifers for rearing, and exports 8000 litres of milk per milking cow per year, alongside 93 surplus calves. In addition to feed produced on the farm, 9 tonnes of purchased soybean meal are consumed from external sources per year. The dairy system was used to model the effects of avoided milk production and LUC induced by soybean production.

Table 21: Key characteristics of a typical German grass and maize based dairy farm located in Baden-Württemberg.

	Cultivated area	N input		yield		
	ha	kg N /ha	Use as feed (%)	t FM / ha	% Dry mass	t DM / ha
Arable land (total)	4.00					
Winter cereals (wheat)	1.20	160	100	6.3	0.86	5.4
Spring cereals	0.75	100	0	5.4	0.86	4.6
Grain Maize	0.20	186	0	10.6	0.86	9.1
Silage maize	0.50	180	100	39.2	0.35	13.7
Clover Grass (on arable land)	1.25	180	100	65	0.14	9.1
Rapeseed	0.10	220	0	3.9	0.91	3.5
Catch crops	1.00					
Permanent grassland (total)	26.00	100	100			4.8

The beef system represents a typical suckler beef farm in the German middle mountain region of Baden-Württemberg (Table 22), and comprises 20 suckler cows, 9 fattening bulls and 3 heifers. Six heifers were sold annually, and 16.5 t of cereal-based feed was imported to the farm. The beef system was used to model the effects of avoided beef production.

Table 22: Key characteristics of a typical German suckler-beef farm located in Baden-Württemberg.

	Cultivated	N input		yield		
	ha	kg N /ha	Use as feed (%)	t FM / ha	% Dry mass	t DM / ha
Arable land (total)	4.00					
Winter cereals	1.20	160	100	6.3	0.86	5.418
Spring cereals	0.75	100	0	5.4	0.86	4.644
Corn	0.20	186	0	10.6	0.86	9.116
Silage maize	0.50	180	100	39.2	0.35	13.72
Clover Grass (on arable land)	1.25	180	100	65	0.14	9.1
Rapeseed	0.10	220	0	3.9	0.91	3.549
Catch crops	1.00					
Permanent grassland (total)	26.00	100	100			4.8

Animal emissions were modelled according to the cattle system LCA tool developed by Styles et al. (2015), largely based on an IPCC Tier 2 methodology (IPCC, 2006) and activity-specific NH_3 emissions (Misselbrook et al., 2014). Parameters pertinent to emissions were: (i) German dairy cows grazed outdoors on average for 10% of the year, and suckler-beef cows for 55% of the year; (ii) slurry stored in tanks with natural crust covers; (iii) animal housing had open stalls with concrete floors; (iv) slurry was broadcast spread, with incorporation within 24 hours on arable land; (v) male and female animals were sold for slaughter at circa 20 months, at 680 kg and 610 kg live weight (LW) per animal, respectively.

The cLCA requires that co-products of a system need to be replaced by the unconstrained supply chains in the market. The dairy system produces milk as a main product, and surplus calves and meat from cow slaughter as co-products. When the production of the main product (milk) is avoided, the co-products are also avoided. Since it is assumed that there is no reduction in the market demand for those co-products, meat and calf production (for beef rearing) need to be compensated by the unconstrained market. Data from ecoinvent v3.7 consequential (Wernet et al., 2016) was used to assess the impact of the market for weaned calves and for cattle for slaughtered LW.

For the soymilk land balance calculations, two scenarios were modelled to reflect different crop displacement possibilities: from Germany country level (EFEM model) (Table 20) or on the avoided land on the dairy farm (Table 21). Land use change (LUC) is an important source/sink of emissions and occurs in the modelling if grassland is considered to be converted to cropland, or when there is potential for afforestation on 0-100% of spared land. Modelling of these potentially important "what if" LUC effects for scenarios of soymilk and pea protein ball production is based on a simple average carbon loss (positive emission) or gain (carbon sequestration) in temperate systems, from Searchinger et al., (2018). This approach is intended to indicate the biophysical potential for emissions and removals associated with diet transitions, and is therefore not constrained by current economics or laws around land management.

The avoidance of animal production also avoids the animal wastes and by-products (so-called C1, C2 and C3 category materials). These materials could be processed into pet food/animal feed, fat, biofuels, and fertilisers (Schmidt et al., 2021). In this study, we assumed that the demand for hides and skins is lower than the remaining production from cattle after pea protein ball substitution, so that hides, and skins were considered as a waste and no compensation was necessary. The waste treatment assumption is incineration with energy recovery; therefore, electricity from the national grid is avoided. However, according to the ecoinvent v.3.7.1 consequential database (Wernet et al., 2016), meat and bone meal are used partially as feed for animals, thus traded on the generic feed market with other protein. In the same database, the tallow displaces esterquats, quaternary ammonium compounds with two long fatty acid chains with weak ester linkages, commonly found in a new generation of fabric softening agents. The marginal market to replace this compound is palm kernel and oil. All these assumptions are contained in the ecoinvent database v3.7.1, consequential. Associated land balances (relevant to LUC) are reflected in the final results.

4.2.4 Soybean and Dairy milk Processing data

Data for soymilk processing were taken from Birgersson et al. (2009), including steaming, grinding, pasteurisation and homogenisation, modification and centrifugation, and sterilisation. During the modification and centrifugation stage, okara is generated. This co-product can be designated to livestock feed. Therefore, the consequence is that marginal feed is avoided i.e. barley (marginal feed for energy) and soybean meal (marginal feed for protein) (Schmidt and Weidema, 2008). To identify the quantity of soymeal and barley avoided, linear optimisation was used to balance out metabolisable energy and crude protein (Leinhardt et al., 2019). The values of energy and protein from Okara were taken from López (2018), while the soymeal and barley values were extracted from Feedpedia (Heuzé et al., 2017).

Data for the pasteurisation from raw milk was taken from the Agribalyse database (ADEME, 2020) and adapted to the Ecoinvent v. 3.7.1 consequential database (Wernet et al., 2016). Since the baseline scenario considers semi-skimmed milk, when semi-skimmed milk consumption is avoided (substituted) by soymilk, production of the co-product (fat) is also avoided and needs to be replaced by the market alternative, as the demand of fat remains unaltered. According to FAO statistics and increased production over the past decade, milk fat is most likely to be replaced by vegetable oil i.e., palm oil from Malaysia, a determining product (Schmidt, 2008b).

4.2.5 Beef meatballs and Pea proteins balls processing data

Life cycle activities associated with processing of pea protein balls and beef balls were taken from (Saget et al., 2021a), with transport from farm to processing adapted to the German context. The cattle slaughtering process was also taken from Saget et al. (2021a) based on an inventory from Agri-footprint 4.0 (Durlinger et al., 2017) adapted to processes found to ecoinvent v3.7.1 consequential (Wernet et al., 2016). The packaging, transportation, refrigeration and distribution of both pea protein balls and meatballs were not included in this study, as they were assumed to be the same, with no significant environmental consequences associated with the substitutions. However, environmental consequences during the cooking phase were considered as pea protein balls need less time in the oven, compared with meatballs (Saget et al., 2021a).

4.2.6 Uncertainty Analysis

Uncertainty analysis was conducted by error propagation. Uncertainty for specific process data extracted from LCA databases and for German farm systems (described above) was assumed to be +/- 15%. Much higher levels of uncertainty (+/- 50%) were applied to global average production data for beef systems, weaned calves, and afforestation. Aggregate errors were calculated as the square root of the sum of squared errors across major contributory processes.

4.3 Results

4.3.1 Soymilk replacing Dairy Milk

4.3.1.1 Land Balance

According to the EFEM model, the introduction of 1 kg of fresh matter (FM) of soybean production into an arable crop rotation replaces 2.2 kg FM of wheat, 1.4 kg FM of grain maize and 1.3 kg FM of silage maize. For the soybean milk production, two scenarios of farm displacement were considered. In the first scenario (Figure 13), the crops displaced from the arable rotation need to be compensated. Ceasing dairy farm production spares grassland and avoids emissions related to cows, but also reduces demand for the following feed crops: clover-grass, silage maize, and wheat. Avoided silage requirements were larger than the amount of silage displaced from the crop rotation, and the net spared area was converted to grain maize and wheat production (to compensate for their displacement from the arable rotation). Additional wheat displacement was compensated from the German market (data from EFEM model of arable farms without legumes), along with milk co-products i.e., beef live weight (LW) from culled cows and calves (Wernet et al., 2016). Those secondary data from ecoinvent 3.7.1 consequential were not represented in the foreground land balance results displayed here, however, they were presented in the final impact categories results, accounting for any emissions related to that land. The spared dairy grassland was entirely available for afforestation (0-100%).

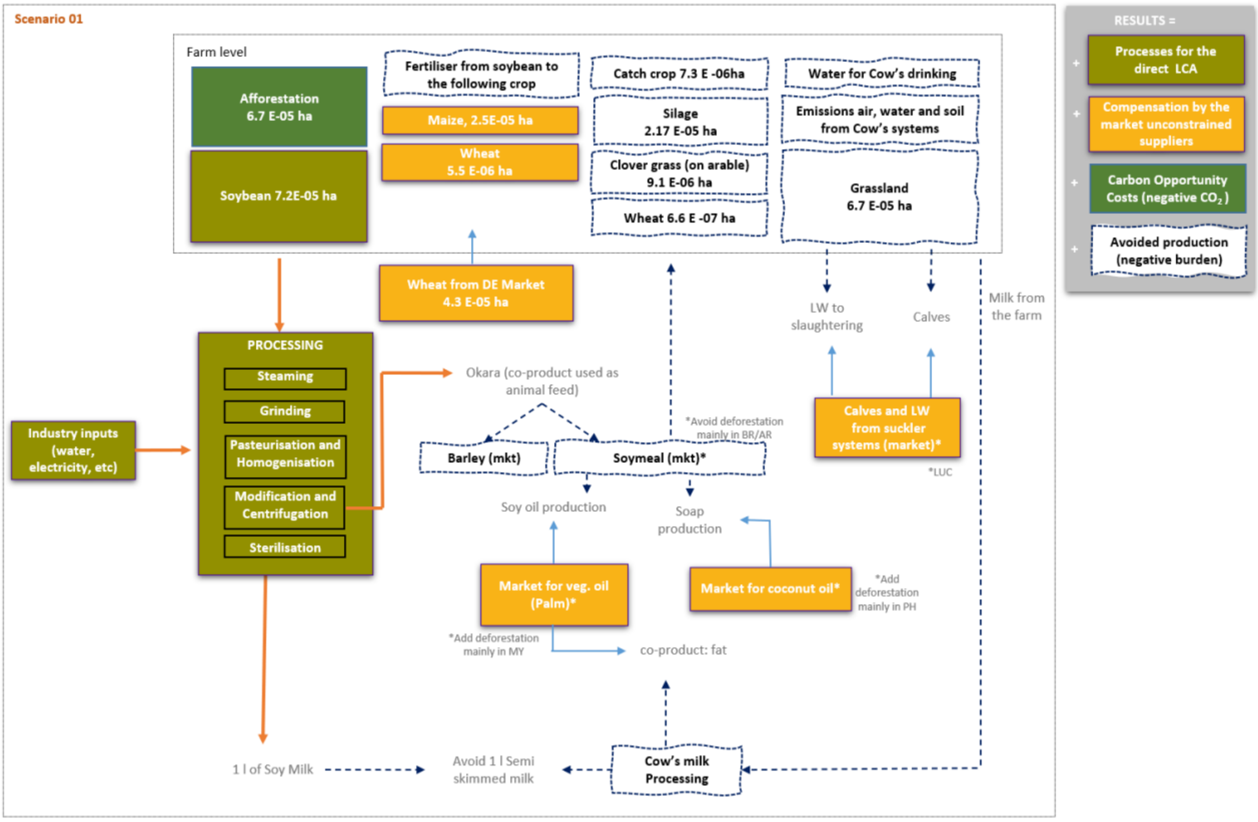

Figure 13: Scenario 1. Soybean cultivation displaces grain cultivation on the arable farms and on the spared dairy farmland. Some wheat, culled cattle live weight and calves need to be compensated by market alternatives.

In the second scenario (Figure 14), on the foreground land balance, the additional wheat displaced was not compensated by the average German market; instead it was modelled that part of the spared dairy grassland is considered to be converted into wheat cultivation (considering emissions from LUC) and the remainder is modelled for afforestation, of which 0-100% is afforested. There remains the necessity to compensate LW and calves with market alternatives from ecoinvent consequential database, v3.7.1 (Wernet et al., 2016).

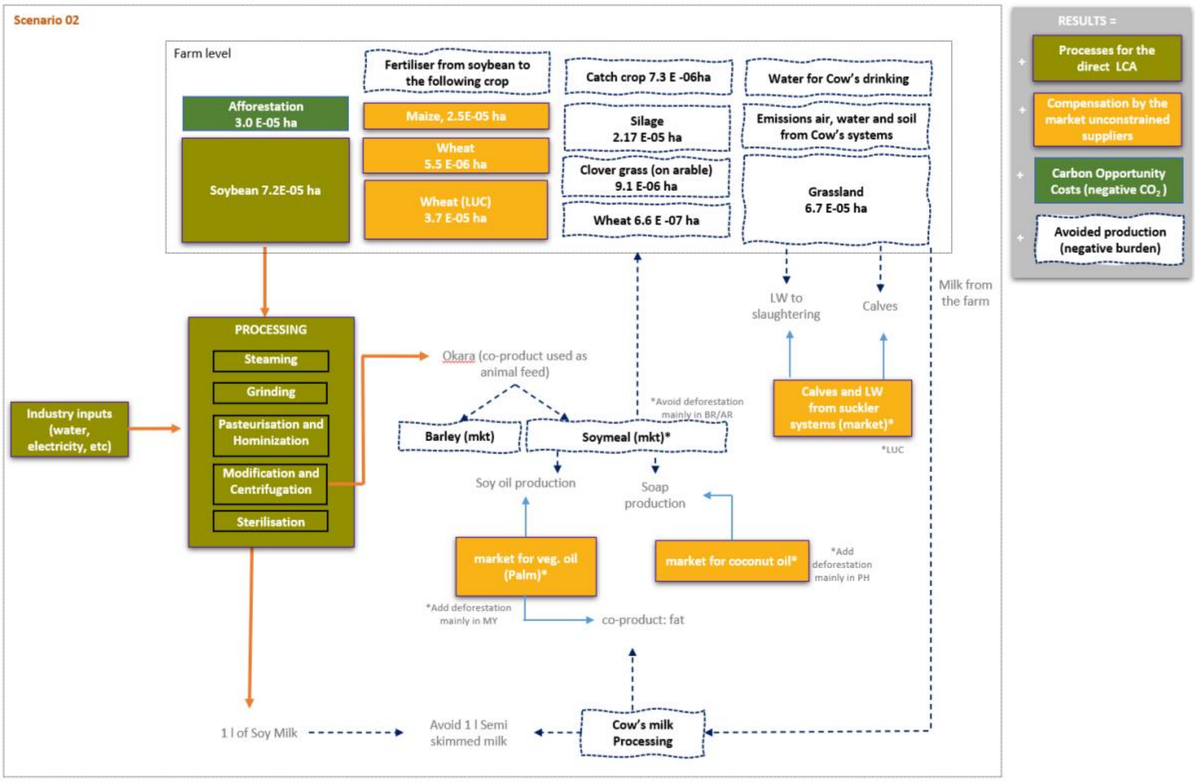

Figure 14: Scenario 2. Soybean cultivation displaces grain cultivation on the arable farms and on the spared dairy farmland. Some wheat production is displaced onto spared dairy grassland, whilst culled cattle live weight and calves need to be compensated by market alternatives.

4.3.1.2 Life Cycle Assessment Results

The results of five impact categories for both scenarios, expressed per 1 litre of dairy milk replaced, are presented below in Table 23. Under scenario 02, three categories displayed an environmental improvement when dairy milk is replaced by soymilk while two categories represent an environmental deterioration. For scenario 01, environmental improvements are recorded only in two categories out of five. For freshwater eutrophication, water scarcity and climate change under scenario 02, the uncertainty was high enough to vary the results between positive (burden) or negative (environment improvement).

Table 23: Net environmental balance and associated uncertainty ranges across five environmental categories for the replacement of 1 litre of dairy milk with soymilk under two land balance scenarios analysed. Red shaded cells (positive values) represent environmental deterioration while the green shaded cells represent environmental improvement (negative values).

Impact Category	Scenario 01	Scenario 02	Unit
Acidification	-1.74E-02 ± 4.17E-03	-1.71E-02 ±4.18E-03	mol H^+ eq
Climate change	-9.05E-01 ±5.78E-01	-2.34E-01± 3.86E-01	kg CO_2 eq
Eutrophication, freshwater	1.18E-05 ± 9.18E-05	1.10E-05 ± 9.19E-05	kg P eq
Resource use, fossils	9.98E-01 ± 1.83E-01	9.86E-01 ± 1.83E-01	MJ
Water use	3.9E-03 ± 3.21E-02	-2.4E-03 ± 3.22E-02	m^3 deprived.

Details about the processes in scenarios 01 and 02 that contribute most to the climate change cathegory either positively or negatively, are shown in Figure 15. The process that contributes the most to reducing net GWP burden is the conversion of 100% of spared land to forest, representing a saving of 0.89kg CO2e (scenario 01) and 0.23 kg CO2e (scenario 02) per litre of milk replaced. The second most important process is the avoidance of cows (saving 0.82kg CO2e per litre of milk replaced), largely reversed by the compensation of weaned calves, which adds emissions of 0.69 kg CO2e per litre of dairy milk replaced in scenarios 01 and 02.

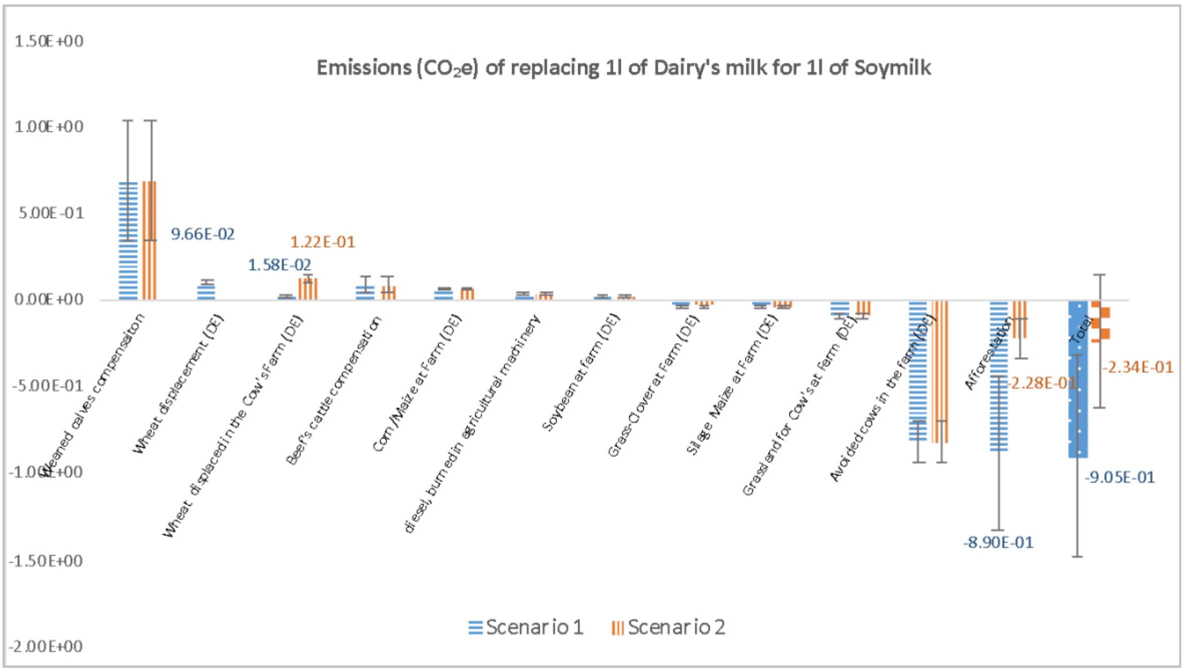

Figure 15: Milk scenario 1 and 2 results, expressed as net GWP balance (kg CO2e) per litre of soymilk produced, per main incurred or displaced process that accounts for more than 1% of the total emissions (positively or negatively). Indicative maximum 100% afforestation of spared farmland is illustrated.

For both scenarios, afforestation of the spared grassland area can lead to significant net GWP savings overall (Table 24). We highlight that displacement of surplus calf production associated with dairy systems means that a larger suckler herd is needed, generating substantial new emissions. Thus, excluding potential afforestation of spared grassland, displacing cow milk with soymilk results in almost no overall change in GHG emissions (Table 24). This "leakage" effect of dairy-calf displacement has previously been shown for dairy intensification transitions (Styles et al. 2018), but not, as far as we are aware, for diet transitions. Such leakage could be avoided if beef demand was reduced to a level that could be satisfied by dairy-beef production.

Table 24: Summary (aggregate) results for climate change for milk scenarios and related uncertainty values, based on different levels of afforestation on land spared from food production.

% Spared area converted to afforestation	Scenario 1	Uncertainty Scenario 1	Scenario 2	Uncertainty Scenario 2
	(kg CO_2e) per l milk replaced			
0%	- 0.01	± 0.37	- 0.01	± 0.37
25%	-0.24	± 0.39	- 0.06	± 0.37
50%	-0.46	± 0.45	- 0.12	± 0.37
75%	-0.68	± 0.50	- 0.18	± 0.38
100%	- 0.90	± 0.58	- 0.23	± 0.39

There were no benefits from afforestation across other impact categories assessed in this paper. For freshwater eutrophication and acidification, the main determining factor is the wheat displacement under each scenario. Even when wheat is displaced in the same country (Germany) (scenario 01, Figure 13), there were some adaptations regarding the yields and fertilisation where wheat is produced on avoided animal feed areas. The national average wheat yield in Germany was represented in the EFEM model while the yield of wheat cultivated on the spared dairy farmland was taken from the typical dairy farm as described in section 4.2.2. The wheat yield from the dairy farm was considerably higher than the national average, supporting a better environmental performance for scenario 2, where most of the wheat is produced on the land spared from dairy production.

There was a detrimental impact for freshwater eutrophication potential, measured in kg of P eq. (phosphorus equivalent to freshwater), meaning that there is an additional burden when dairy milk is replaced by soymilk. However, this interpretation is linked to a high uncertainty, and mainly arises from the compensatory market production of weaned calves. The second most contributing process to the results is the avoidance of soybean meal due to the co-production of Okara feed from soymilk (Figure 16).

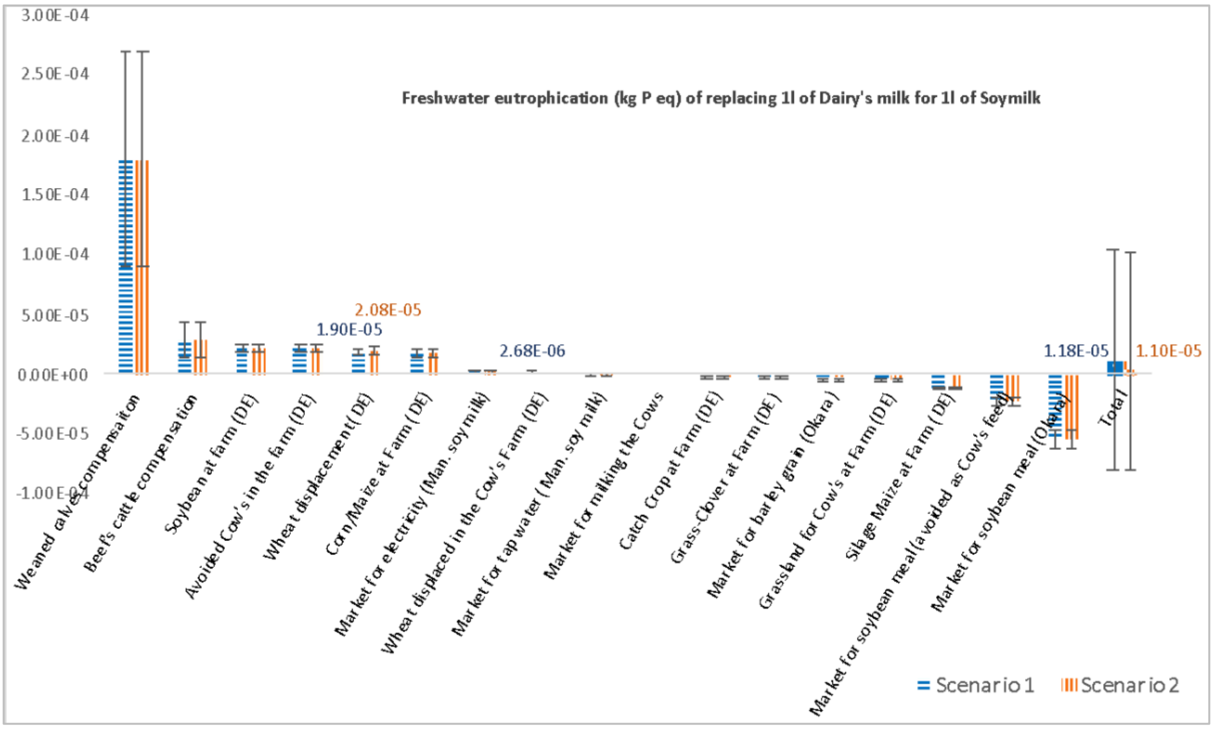

Figure 16: Results for scenario 01 and scenario 02 for freshwater eutrophication, expressed in kg P eq. per litre of soymilk produced, per main incurred or displaced process that accounts for more than 1% of the total emissions (positively or negatively). Scenario results are shown in blue for scenario 01 and in orange for scenario 02.

Acidification potential, measured in mol H^+ eq, demonstrated an environmental improvement from replacing cow milk. The benefit can be inferred even with the high uncertainty. The process that most contributed to this result was the avoidance of cattle emissions, somewhat offset by a burden from weaned calves (Figure 17).

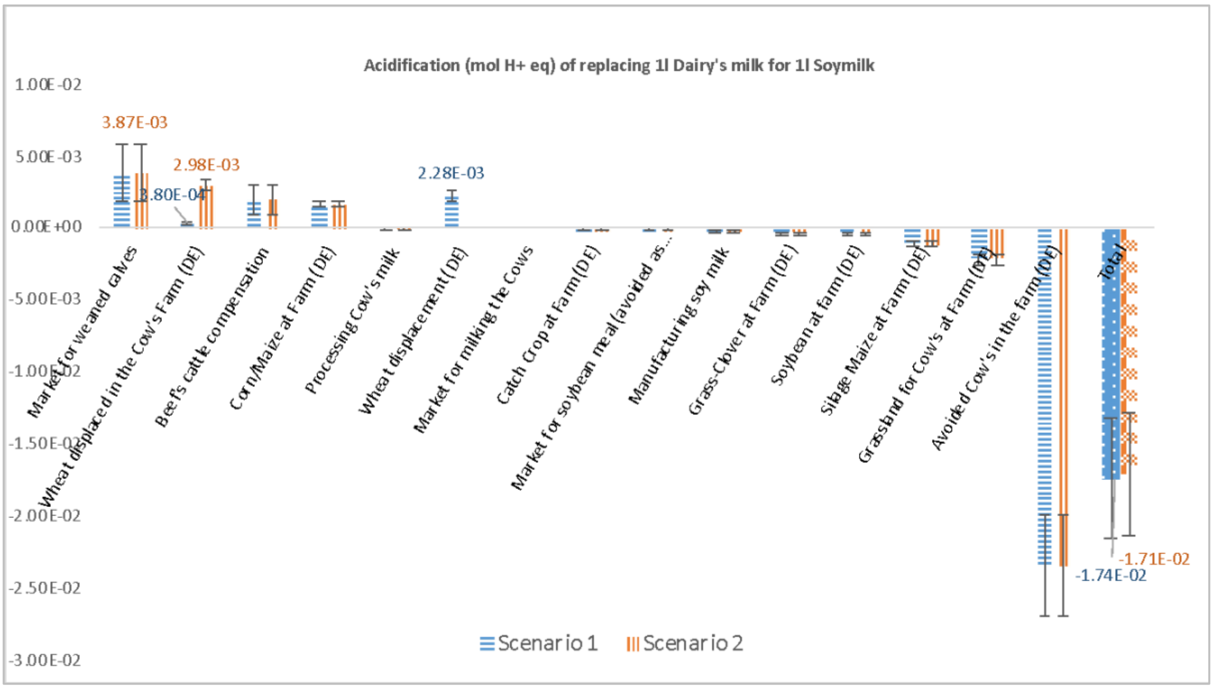

Figure 17: Results for scenario 01 and scenario 02 for the acidification potential, measured in mol H^+ eq. per litre of soymilk produced, per main incurred or displaced process that accounts for more than 1% of the total emissions (positively or negatively). Scenarios results are presented in blue for scenario 01 and in orange for scenario 02.

Resource depletion (fossil fuels), measured in MJ eq, demonstrated a deterioration under both scenarios. i.e. there was an environmental disadvantage of replacing cow milk. The process that most contributed to this result was the displaced wheat cultivation. The market for diesel burned in agricultural machines is the main factor that contributes to this category, as shown in Figure 18.

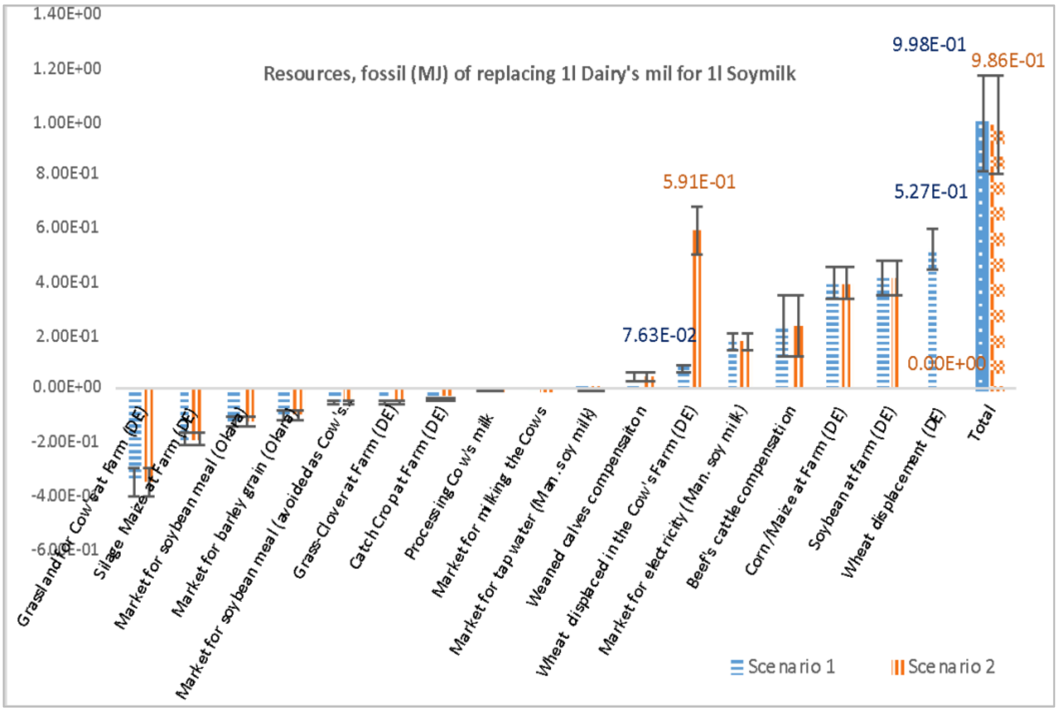

Figure 18: Results for scenario 01 and scenario 02 for the resources, fossil fuels depletion potential, measured in MJ eq. per litre of soymilk produced, per main incurred or displaced process that accounts more than 1% of the total emissions (positively or negatively). Scenario results are presented in blue for scenario 01 and in orange for scenario 02.

Water scarcity potential, measured in m^3 H_2O deprived eq., demonstrated an environmental disadvantage for scenario 1 and an improvement for scenario 2 (Figure 19). The process that contributed the most to water scarcity was the market for barley (marginal energy feed) avoided once Oraka, the soymilk processing co-product, was designated to cattle feed. The aspects that contributed the most to this category within barley cultivation were the seed production and irrigation. However, as in the aforementioned categories (acidification, freshwater eutrophication and resource use, fossil fuels), it was the wheat cultivation that influenced differences between scenarios. Despite wheat cultivation with no irrigation in Germany, the market for wheat seeds incurs an irrigation burden. The industrial phase of soymilk production has tap water as a main input, and this is reflected in results that indicate a greater water scarcity burden than the credit from avoided cow drinking water for dairy systems. There is a high uncertainty related to the results for water scarcity, therefore it is not possible to assure that there was a real benefit or burden under this category.

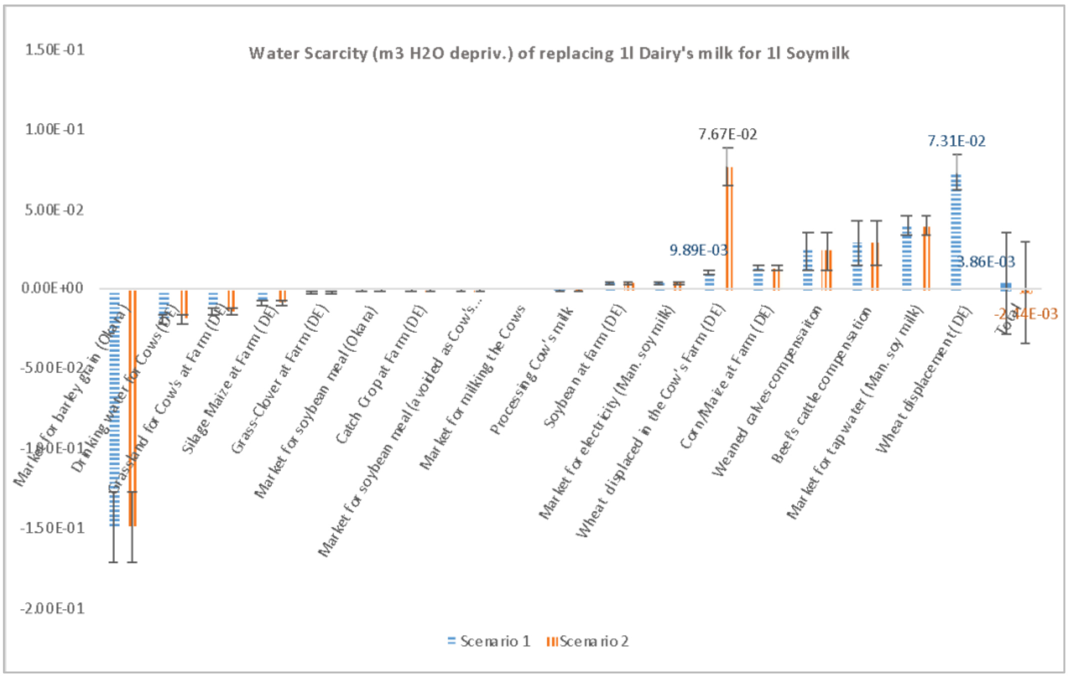

Figure 19: Results for both scenarios for the water scarcity potential, measured in m3 H2O deprived eq. per litre of soymilk produced, per main incurred or displaced process that accounts more than 1% of the total emissions (positively or negatively). In red and green there are the values of the processes that are more relevant to this category, for burdens and avoidances respectively (same value for both scenarios). Scenarios results are presented in blue for scenario 01 and in orange for scenario 02.

4.3.2 Pea Protein Balls replacing Meatballs

4.3.2.1 Land Balance

According to the EFEM model, the introduction of peas in the rotation replaces 1.4 kg FM of barley, 1.4 kg FM of grain maize and 1.2 kg FM of silage maize. For the pea protein balls, only one scenario was considered (Figure 20). The baseline before the pea protein balls was produced and consumed is represented by two main systems: (i) a suckler beef farm associated with annual cropland for cattle feed production, as well as a large area of permanent grassland; (ii) an arable cropping system. The introduction of pea cultivation into the arable rotation displaces barley, maize, and silage production previously used to produce cattle feed. The remaining spared arable land, and spared grassland, is available for other uses, such as afforestation (0-100% afforested in sensitivity analysis).

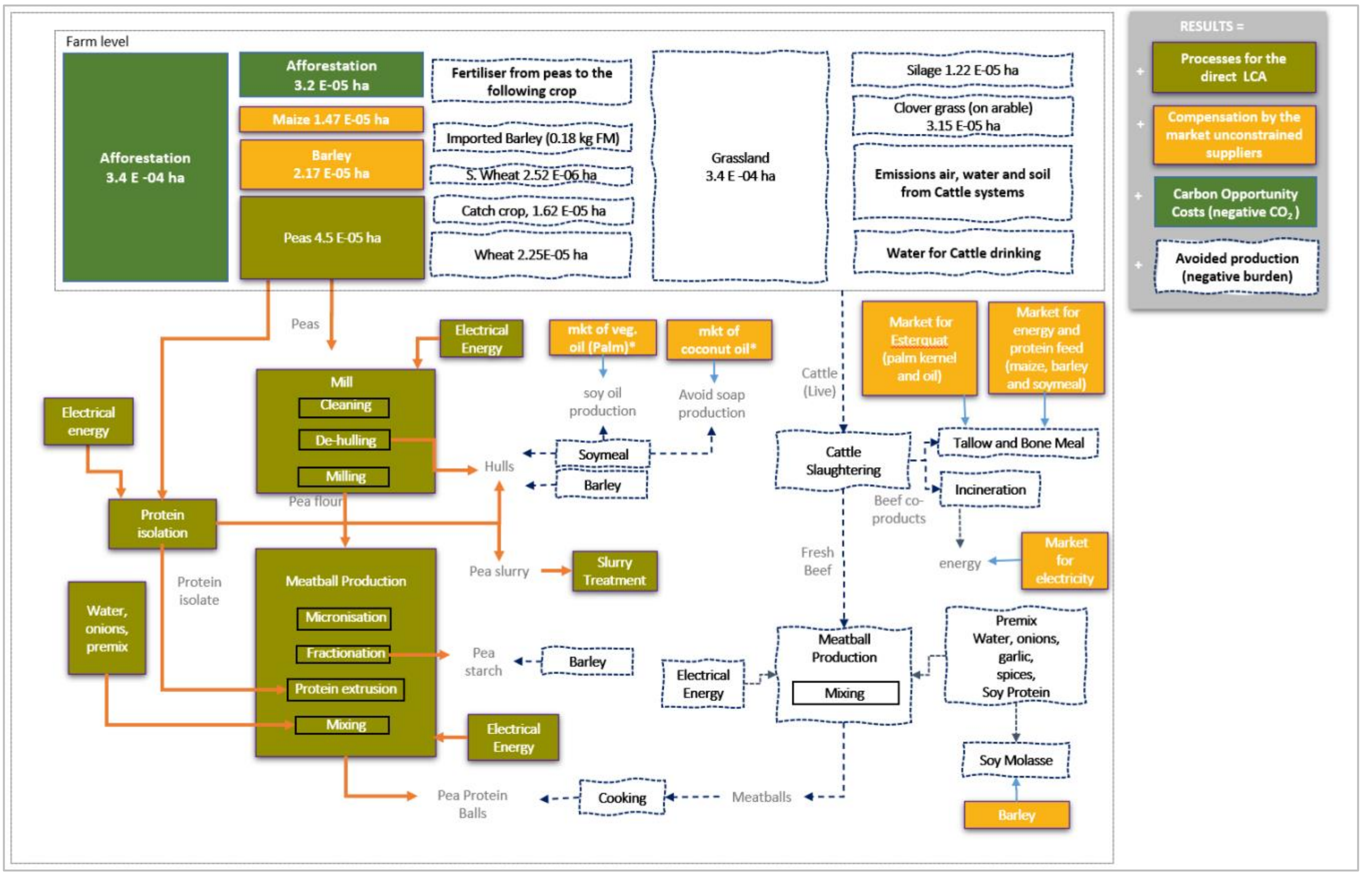

Figure 20: Flow diagram showing process changes when beef meatballs are substituted with pea protein balls, where pea cultivation replaces cultivation of cereals used for beef cattle feed, sparing large areas of arable and grassland for afforestation.

4.3.2.2 Life Cycle Assessment Results

Results are more clear-cut for pea protein balls substituting beef meatballs than for the substitution of dairy milk for soymilk, across most of the categories, and uncertainties do not interfere in the final interpretation (Table 25). There was an environmental disadvantage across one of the five categories analysed (resources use, fossil fuels, in MJ).

Table 25: Net environmental balance and related uncertainties across five environmental categories for pea protein balls substituting beef meatballs. Red shaded cells represent environmental deterioration while the green shaded cells represent environmental improvement.

Impact Category	Impact result	Unit
Acidification	-5.38E-02 ± 7.23E-03	mol H^+ eq
Climate change	-7.30E+00 ± 2.46E+00	kg CO_2 eq
Eutrophication, freshwater	-2.4E-04 ± 6.27E-05	kg P eq
Resource use, fossils	6.74E-02 ± 4.10E-01	MJ
Water use	-1.3E+01 ± 1.96E+00	m^3 depriv.

Details about the processes that most contributed to GWP mitigation can be observed in Figure 21. The process that most contributed to the results is the afforestation of spared land, representing a saving of up to 4.9 kg CO_2e per 100 g of meatballs replaced by pea protein balls. The second process that most contributed to the results was the avoidance of cattle production and meatball processing (-2.1kg CO_2e per 100g of pea protein balls). The highest additional burden arose from other ingredients, which added emissions burdens of 0.2kg CO_2e per 100 g of meatballs replaced.

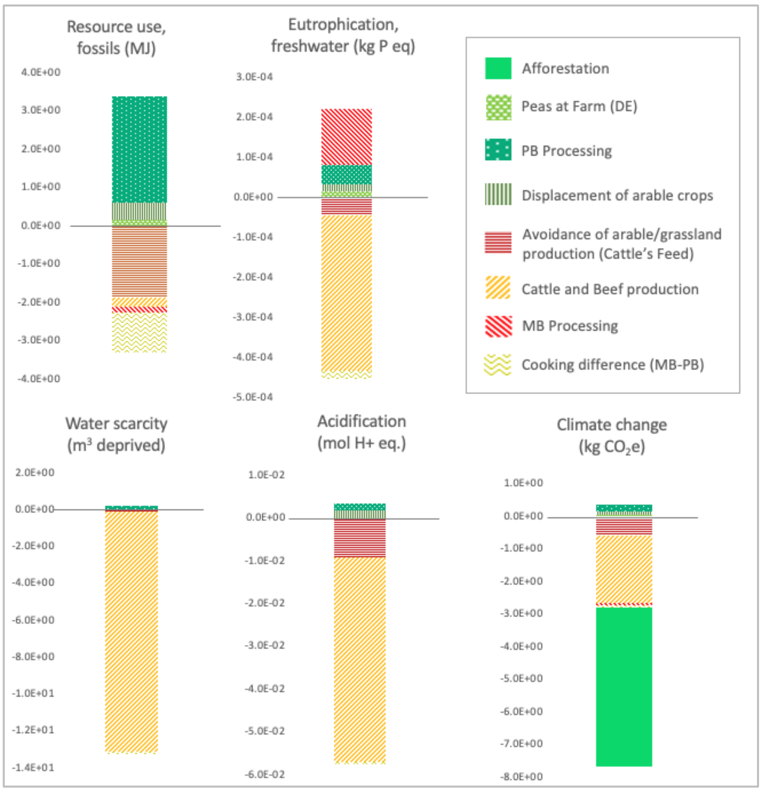

Figure 21: Results for the substitution of 100g of meatball (MB) by 100 g of pea protein ball (PB), across five environmental categories, broken down into main incurred or displaced processes accounting for more than 1% of positive or avoided emissions. Indicative maximum 100% afforestation of spared farmland is illustrated.

Table 26 shows that, even before accounting for possible afforestation of spared land, substitution of beef can avoid 2.42 kg CO_2e per 100 g serving of meatballs. In fact, in addition to sparing 3.4 m^2.yr of grassland from beef production (per 100 g serving), pea cultivation occupies a smaller area of arable land than would otherwise be required to produce the cereal portion of the suckler-beef diet. Thus, up to 3.7 m^2.yr is spared per 100 g portion of pea protein balls, resulting in a potential GWP saving of up to 7.3 kg CO_2e per serving portion.

Table 26: Summary (aggregate) results and related uncertainties of climate change potential of substituting 100g of beef meatball by pea protein balls, based on different levels of afforestation on land spared from food production.

% Spared area afforested	Results	Uncertainty
	(kg CO_2e per 100 g of beef meatball replaced for pea protein balls)	
0%	- 2.42	± 0.32
25%	-3.64	± 0.69
50%	-4.86	± 1.26
75%	-6.08	± 1.86
100%	-7.30	± 2.46

Similar to the soymilk replacement, there were no benefits from afforestation across the non-GWP impact categories modelled for the meatball substitution. Overall, there was an environmental improvement across the freshwater eutrophication potential category, measured in kg of P eq. (phosphorus equivalent to freshwater) when the meatballs are replaced (Figure 21). The avoidance was mainly due the avoided P emissions to water from cattle rearing. Most burdens to freshwater eutrophication arose from other ingredients for the meat- and protein-balls. On the meatball manufacturing, the impact arose from the vegetable oil compensation for the avoided use of soybean (ingredient to the meatball production). This resulted in additional wastewater from oil refining which affected the results. For pea protein balls, the eutrophication potential of other ingredients was associated with the crop cultivation needed for the premix production.

Acidification potential, measured in mol H^+ eq., demonstrated an environmental improvement from replacing meatballs (Figure 21). The process that most contributed to this result was the avoidance of cattle rearing ammonia emissions. The compensation of weaned calves by the market adds the highest burden. However, this value was considerably smaller than the avoidance impact mentioned above. There was an environmental deterioration for resource depletion, fossil, from replacing meatballs (Figure 21). The processes that most contributed positively to this result (burden) were other ingredients for the pea protein ball manufacturing followed by processing. The aspect that was responsible for this burden in other ingredients is the use of energy to fabricate the premix of pea protein balls. During the manufacturing phase, the energy used for the pea protein isolate and dehulling are the main contributors to the environmental impact. Looking at the environmental improvements, the main processes were the avoided grassland production due to the market for diesel burned in agriculture machines for fertilisation, followed by the cooking phase. The cooking phase represents a direct saving in energy, as the pea protein balls need less time in the oven to prepare, compared with meatballs.

In terms of water scarcity potential, there was an environmental improvement from replacing 100g of meatballs (Figure 21). The process that most contributed towards this saving was the avoidance of cattle rearing, avoiding 13 m^3 of water scarcity per portion of 100g of meatballs. This is mainly related to the dataset for the market for wastewater in Europe (ecoinvent 3.7.1 consequential) avoided during the slaughtering process. In other words, the generation of effluent is avoided. The aspects that most contributed towards water scarcity burdens for pea protein ball production were irrigation and seed production of ingredients such as potatoes, bell pepper, onions, etc. Only 15% of cattle drinking water is consumptive and not returned to the system, as it is incorporated in the cattle co-products or lost through evapotranspiration of the animals. This means that 85% of the water returns to the system through urine and faeces, not impacting the water scarcity category. However, animal excretion does affect water quality, addressed under the freshwater eutrophication impact category described above.

4.4 Discussion

4.4.1 Consequential LCA approach

The consequential LCA described in this paper provides new and detailed insight into the direct and indirect environmental effects associated with dietary substitution of cow milk and beef with soymilk and pea protein, including agronomic effects, dairy-beef interlinkages and potentially critical land use change. Costa et al. (2021) demonstrated the potential importance of agronomic benefits associated with the integration of legumes into conventional rotations. Such effects are not explicitly considered in most attributional LCA studies, which may result in an underestimation of the environmental benefits that could be attributed to wider legume production and consumption in Europe (Costa et al., 2020). Many sustainability evaluations and attributional footprint studies have been undertaken comparing legume alternatives with typical foods (Saget et al., 2020), or plant substitutes to meat protein, pointing to high improvement potential for human nutrition and sustainability in industrialised countries with excessive calories and protein intake (Jensen et al., 2011; Peoples et al., 2019; Saget et al., 2021b). Saget et al., (2021a) performed an attributional life cycle assessment of a 100 g serving of cooked pea protein balls with beef meatballs made from Irish or Brazilian beef. The authors reported higher GHG savings, including large avoided "carbon opportunity costs" (COC), for legume substitutes of popular products. Total GHG savings were almost double the values found in this study, in part because allocation of burdens within the attributional approach can underestimate consequences associated with replacing livestock co-products (Styles et al., 2018; Mazzetto et al., 2020). The consequential modelling proposed in this paper represents both crop rotation, wider land COC effects and co-product substitution effects as well as direct e.g. livestock production emission avoidance, associated with diet change in Europe, and therefore offers a more complete and accurate estimate of achievable environmental savings.

Consequential studies of some food and feed products have been undertaken previously, but typically these only looked at climate change burdens (Knudsen et al., 2014; Schmidt et al., 2021), or did not account for the full suite of co-product substitutions, such as co-products from the slaughtering house (Goldstein et al., 2016). The only consequential GWP results comparable to those in this study are consequential footprints contained in the Climate Change Database (Schmidt et al., 2021). In this database, comparable carbon footprints were: (i) 0.38 kg CO_2e for 1 kg soymilk; (ii) 0.61 kg CO_2e per kg of milk, semi-skimmed (1.5%); (iii) 0.61 kg CO_2e per kg of vegan mince (0.061kg per 100g of vegan /mince), pea-based; and (iv) 11.08 kg CO_2e per kg of meatball (1.1 kg CO_2e per 100g of meatball), without the cooking phase. Values for the meat/dairy alternatives are higher than the results encountered in this study, because the reported footprints don't account for substitution of alternative products (e.g., beef and milk) at the point of consumption. Without considering land sparing from cow milk substitution, the soymilk footprint calculated in this paper also has a positive carbon footprint. But that changes when potential GHG mitigation associated with land sparing is accounted for. Whilst we considered the cultivation of soybeans in German crop rotations, the climate change database considers cultivation across the main expanding source countries for soybean globally, such as Latin America and the US, as a marginal market composite. Similarly, the climate database gives positive footprints for meat substitutes, such as the vegan mince, because the database looks at the increase of that product demand, not relating it to a diet transition scenario as done in this study.

4.4.2 Role of legumes in diet transitions

The modelling undertaken here demonstrates that a dietary shift towards more legumes could result in substantial GHG emission savings and reduce leakage of reactive nitrogen, also leading to smaller acidification, eutrophication, and resource depletion burdens where beef consumption is reduced. Substitution of beef also spares large areas of land, making it available for carbon dioxide removal (CDR) activities such as afforestation, potentially doubling net GHG mitigation, and supporting the climate neutrality goal (Duffy et al., 2022; Huppmann et al., 2018).

When legumes replace dairy products, the picture includes more trade-offs. Dairy systems produce milk, beef, and surplus calves for beef fattening. Dairy-beef production is considerably more efficient than suckler-beef production (Nguyen et al., 2010). Thus, whilst milk substitution can reduce emissions from dairy systems, it may also displace beef production and calf production to less efficient suckler systems, unless demand for beef can be dramatically reduced – eutrophication and resource depletion burdens were actually increased when soymilk replaced cow milk in our results. This suggests that legume incorporation into European diets should prioritise substitution of meat, rather than dairy products, in the first instance to achieve maximum environmental savings. Dairy substitution may become more important as diet transitions progress, and could still play an important role in land sparing, and thus CDR deployment, in the medium term. This paper highlights the importance of complementing diet change strategies with land use planning to deliver effective CDR on spared land, in line with IPCC recommendations (IPCC, 2019b). The development of trading schemes in non-reversible, permanent carbon offsets could play an important role (Carbon Offset Guide, 2021) as part of the European Commission's "carbon farming" initiative. Other studies have recently demonstrated the importance of diet transitions in achieving the Paris Agreement target of limiting global average temperature rise to 1.5 °or 2 °C since the pre-industrial age (Clark et al., 2020). The European Union and multiple countries, including the United Kingdom, have committed to "net-zero" GHG emission targets by 2050, meaning huge reductions in emissions and scale up of CDR (Committee on Climate Change, 2019; Shepheard, 2020).

Diet transitions are also about human health, and it has been shown that there are a lot of complementarities between environmental and health objectives in shifting towards a more plant-based diet (Gerber et al., 2013; Richi et al., 2016). For example, the EAT-Lancet Commission proposed the 'planetary healthy' diet, which recommends limiting the consumption of red meat to 28 g a day, equivalent to 10 kg of red meat per person per year (Willett et al., 2019). In Europe, the intake of processed meat is 90% higher than recommended (Afshin et al., 2019), and nearly four times more than in developing countries (FAO, 2019). The EAT Lancet diet (Willett et al., 2019) also specifically proposes an increase in legume consumption, although Zander et al. (2016) argue that there is little evidence of sufficient shifts in European diets to significantly influence grain legume production. The two simple diet substitutions considered in this study, using plant protein analogues for popular animal-derived products, could represent scalable solutions to drive food system transformation without the need for dramatic shifts in food choices and preparation.

4.4.3 Limitations

According to FAO (McLaren et al., 2021), tools such as LCA have been extremely important to provide reliable information to policymakers seeking more sustainable food systems. However, they also recognise the limitations of LCA methods and the lack of guidance for researchers to use such tools. Furthermore, researchers have developed different frameworks and approaches to address the sustainability challenges and interlinkages of systems such as agricultural production, processing, health, energy and others. The consequential framework is complex, and requires a deep knowledge of the economy and markets (Dalgaard et al., 2014; Schmidt, 2008a). Such knowledge is required across interlinked agri-food value chains, from grains and animal feed production, through livestock systems, to fuel and energy production, cosmetics and clothing, among others. Whilst consequential LCA modelling can provide a more systemic view of global consequences, many assumptions need to be made in order to model market responses and co-product substitutions, even with consequential LCA databases available for background modelling. Results can vary considerably depending on assumptions made about interlinkages, and should be interpreted carefully. Soymilk substitution of cow milk involved many assumptions and secondary effects, some of which were difficult to parameterise and therefore somewhat uncertain. For example, this study does not consider the veal market. Additionally, suckler calf footprints were modelled based on a global average secondary database, therefore this could offer a very different impact when analysed specifically for the German context.

Another limitation of this study was the evaluation of nutritional trade-offs. This means evaluating the impact that the replacement of meatballs for pea protein balls or dairy milk for soymilk would have on human nutrition, and wider dietary choices. Legume alternatives such as the pea protein balls are known to have more fibre, but potentially less digestible protein, than the meat products they may substitute (Saget et al., 2021a). On one hand, vegetarian and vegan diets could necessitate higher gross intake of protein (by 20% and 30%, respectively) to satisfy human requirements, due to the lower protein digestibility (Davis et al., 2010, The Health Council of the Netherlands, 2001). On the other hand, this factor may not be significant for simple substitutions in typical Western diets associated with overconsumption of protein (Nijdam et al., 2012). The 1:1 mass substitution assumption in this paper is predicated on the latter, and disregards potential secondary diet change effects. Nevertheless, nutrition is an important aspect of diets transitions, and its consequences should be analysed further.

4.5 Conclusion

The substitution of beef by pea-derived protein can result in large GHG savings, of up to 2.42 kg CO_2e per 100 g serving. The associated land sparing of up to 3.7 m^2.yr per serving could support further mitigation via afforestation, more than tripling total GHG mitigation to 7.3 kg CO_2e per 100 g per serving. On the other hand, the substitution of cow milk with soymilk does not lead to significant GHG savings owing to the displacement of dairy-beef production to less efficient suckler-beef herds. Nonetheless, land sparing by cow milk substitution could lead to overall GHG mitigation if spared grassland is afforested, especially if beef consumption is simultaneously reduced.

This study confirms that legumes can play an important role towards realisation of the EAT-Lancet diet and support considerable land sparing, livestock emission avoidance and synthetic fertiliser displacement, promoting not only GHG mitigation, but also mitigation of other environmental problems such as acidification. Diet substitution should initially focus on replacing meat, rather than dairy products, to avoid environmental “leakage” via displacement of (surplus) calf production. Maximum benefit could be derived by coordinating plant protein substitution of animal protein with a land use strategy to ramp up carbon dioxide removal, e.g. via afforestation, in order to deliver climate neutrality.

4.6 Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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5 **Chapter Five:** Role of different life cycle assessment approaches in supporting a sustainable food system transition

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Abstract

Applying the appropriate LCA approach framed in appropriate context is imperative to inform relevant stakeholders on how to effectively engage with a successful transition to sustainable agri-food systems. Diet transitions mean product substitutions, which imply land use changes and crop rotation modifications. Diet change and agricultural system modifications have typically been addressed separately by the LCA community. In this paper, we explore how different approaches to LCA application can be useful to answer different questions relating to sustainable food systems, drawing on experience from a Horizon 2020 project (TRUE) evaluating the sustainability of legume-derived food and drink products, along with other recent peer-reviewed studies. Current state-of-the-art food system LCAs do not yet simultaneously capture rotational effects, human nutritional aspects, product substitution and indirect land use change. To align with international challenges, in particular the ambitious of Paris Agreement (UNFCCC, 2015) and SDGs (UN, 2016), the delivery of human nutrition and potential consequences for land based carbon dioxide removal should be included within the design of food system LCA. This could be achieved via adaptation of nutritional functional units (for foods and rotation outputs) within attributional LCA, and development of appropriate prospective scenarios in consequential LCA. Meanwhile, biophysical allocation of burdens and credits linked to specific crops produced within certain types of rotation could improve attributional footprints of food items (and diets), providing more robust evidence for consumers, industry, and policy makers.

Key words: Life Cycle Assessment, food systems, Diet Transitions, agricultural rotations, legumes

5.1 Introduction

The Farm to Fork Strategy under the European Green Deal aims to make food systems fair, healthy, and environmentally-friendly (EC, 2020). Legumes such as beans, peas, lentils, chickpeas, and others can make an important contribution to diet transitions in support of these objectives, and to achieve climate stabilisation under the Paris Agreement (UNFCCC, 2015). This is because the leguminous family is known to be beneficial in environmental and nutritional spheres (Röös et al., 2020). In terms of environmental attributes, legumes fix atmospheric nitrogen and do not need to rely on additional synthetic fertilization. Additionally, legumes can provide nitrogen to following crops in rotations, reducing fertiliser requirements of those crops and thus the emissions related to production and use of those fertilisers (Costa et al., 2020). Legumes also contribute to better nutrition, providing low-fat, high-fibre protein alternatives to livestock products which are linked with high environmental pollution (Röös et al., 2020).

There are clear prospective benefits of these grains in supporting a sustainable diet transition, with many scientific studies and environmental footprint calculations through Life Cycle Assessment (LCA) showing the benefits of planting legumes in agricultural rotations (Nemecek et al., 2008a; Plaza-Bonilla et al., 2017; Prechsl et al., 2017; Reckling et al., 2016; Watson et al., 2017) and including them in dietary change (Poore and Nemecek, 2018; Röös et al., 2022, 2020; Willett et al., 2019). However, evidence ise scattered in the literature, and often focused only on one part of the value chain such as agricultural phase or consumption. Additionally, there remains a lack of effective policies to encourage more widespread production and consumption of legumes in Europe (TRUE, 2018; Zander et al., 2016). The situation is a result of technological lock in (Magrini et al., 2016), with technologies and supply chains developed around specialisation in cereals and other crops with high commercial interest. The failure of effective public polices to encourage legume cultivation in Europe (Zander et al., 2016) may reflect lack of sufficient academic evidence that integrates scientific understanding with appropriate deployment scenarios to support clear decision making. Applying the appropriate LCA approach framed in (an) appropriate context(s) is imperative to adequately inform relevant stakeholders on how to effectively drive the sustainable agri-food system transition.

The application of LCA to evaluate the environmental sustainability of diets, foods, and food systems faces many drawbacks. Life cycle assessments for food systems include a variety of approaches, from simple assessment of a food ingredient or food item to assessment of complex meals and diets (McAuliffe et al., 2020). Many food ingredients and food items are commonly assessed via attributional LCA (aLCA). Attributional LCA is a descriptive approach, representing a context of the recent past and reflecting a static representation of (average) impacts at that moment (McLaren et al., 2021). However, a single simple ingredient can entail a complex supply chain, for instance, wheat flour from wheat cultivation produced in arable systems in a rotation of crops and specific farming practices and milled in a process generating other co-products. At the farm level, the sequence and management practices of crop cultivation would affect the growth of the following crop. If wheat is followed by a legume in the rotation, it can benefit from nitrogen from the legume and requires less mineral fertiliser application, potentially then reducing the footprint of wheat by 56% per hectare (Barton et al., 2014). Nevertheless, this result for wheat strongly depends on the boundaries and allocation procedures applied during the LCA modelling. In this specific case, boundaries are drawn around one cropping season, after the harvesting of the legume and before the wheat planting, therefore the pre crop benefits of the legume (i.e. nitrogen to the soil and next crop) are captured in the wheat cultivation cycle, while the burdens (impact related to the legume such as leaching) typically remain with the legume crop (Costa et al., 2020). The same issues arise across combinations of non-legume crops, for example allocation of burdens and credits arising in cereal crop sequences where residues may be left behind for some crops but harvested for use as animal bedding or fuel for others (Brankatschk, 2018; Goglio et al., 2018). Nevertheless, aLCA with boundaries drawn around one cropping period (e.g. one year in temperate climates) and with some type of allocation, is the typical approach underpinning the main LCI databases used for LCA studies (Durlinger et al., 2017; Moreno-Ruiz et al., 2018).

Notwithstanding the allocation issue above, it could also be argued that such crop or food footprint LCAs are too narrowly focussed on the comparative efficiency of food production, encouraging only incremental improvement of existing systems through new technologies, increased productivity or improved management. Such an approach risks locking in fundamentally unsustainable food system organisation and business models that do not consider a broader systemic view (Magrini et al., 2016), and therefore cannot provide solutions to achieve food security within planetary boundaries (Springmann et al., 2016). Other LCA practitioners, explore alternative consequential LCA scenario modelling or expansion of system boundaries, often to link with aggregate demand for land and possible land use change (LUC) associated with product footprints or system transitions. For example, pea residue by-products from gin made from pea starch can be designated to fish and cattle feed, and therefore avoid soymeal and the production impacts related to it, such as deforestation in South America (Lienhardt et al., 2019).

In this paper, we explore how different approaches to LCA application can be useful to answer different questions relating to sustainable food systems, drawing on experience from a Horizon 2020 project evaluating the sustainability of legume-derived food and drink products and wider transition scenarios (TRUE, 2018). In that project, LCA (attributional and consequential) was adapted to link land management with diet change to capture the wider environmental effects of prospective transitions towards greater production and consumption of legumes in Europe.

5.2 Methods

A number of recent contrasting LCA studies of food systems from the literature and from the recent TRUE project (TRUE, 2018), all of them published in international peer-reviewed journals, were selected to analyse how different LCA approaches can be used to inform sustainable food system transitions. Studies were broadly categorised according to their scope: (i) agricultural system attributional LCA (aLCA, terminology defined further) for one crop or one rotation; (ii) aLCA for food products, meals/ diets; (iii) consequential LCA (cLCA, terminology defined further) of agricultural systems, products or diet change. In addition, to improve understanding of different functional units (FUs) applied to assess entire rotations, we re-evaluated rotation aLCA data presented in Costa et al., (2021) by comparing different FUs – aggregated nutritional FUs (Costa et al., 2021), mass of dry matter (DM) output and area (ha.yr-1). Methodological details and results can be found in the Supplementary Information (SI). Thus, via review and re-analysis of recent rotation LCA studies, advantages, limitations and appropriate uses were identified for different LCA approaches. Categorisation of LCA studies analysed in this paper can be observed in Table 27.

5.3 Key Issues of LCA approaches on legumes food systems

The key issues of each LCA approach are discussed in the subtopics below, while main findings are summarised in Table 27.

Table 27: Main advantages and disadvantages of different LCA approaches to assess the environmental sustainability of agri-food systems.

		Examples of studies	Advantages	Disadvantages	Main uses/ Purposes
aLCA Agricultural phase	aLCA of primary crop products with boundaries set around one cropping cycle	(Barton et al., 2014)	○ Simpler to calculate ○ Less contextual info needed ○ Enables generic food footprints to be calculated;	○ Often ignores rotational effects ○ Often ignores nutritional aspects	○ International Databases ○ Simple footprint mapping of a product ○ Quick scan and hot spot understanding
	Aggregated aLCA of rotational systems	(Costa et al., 2021, 2018; Goglio et al., 2018; Knudsen et al., 2014)	○ Indicates overall system efficiencies ○ Include synergic effects of rotations ○ It can include nutritional perspective	○ Generates results for a sequence of crops ○ Difficult to relate to product footprints without allocation	○ Land management and land production efficiency
aLCA Foods, Meals, and Diets	aLCA Food items	(Birgersson et al., 2009; Saget et al., 2021b, 2020)	○ Indicates product efficiency and can help to identify product enhancement opportunities ○ It can include nutritional perspective	○ Often calculated with average secondary information ○ Often ignores rotational effects and land use change implications of diet transitions ○ Often ignore a wider meal or diet change impacts	○ Development of novel products ○ Process optimization ○ Value chain optimisation (transport, packaging) ○ Ecolabeling ○ Benchmarking
	aLCA Meal or Diets	(Chaudhary et al., 2018; Davis et al., 2010; Willett et al., 2019)	○ Address the impacts of a meal or specific diet, which is a composition of food items and more complex study ○ Often includes healthy and nutritional aspects	○ Often calculated with average secondary information ○ Often ignores rotational effects and land use change implications of diet transitions	○ Hotspots and opportunities for community level ○ Design of sustainable and nutritional diets; ○ Basis for policy making such as school meal decisions
	Transitional aLCAs	(Lienhardt et al., 2019; Saget et al., 2021a, 2021c)	○ Include a wider view such as boundaries expansion and scenarios simulation ○ Maintains calculation simplicity whilst capturing land use pressures ○ Enables generic footprints to be calculated with carbon cost of land included	○ CoC are hypothetical; ○ It can be misleading as it is an aLCA and just include partial consequences modelling	○ It provides a product footprint and also the link land-related environmental impact perspective for policy makers
Consequential LCA	Consequential LCA (agricultural, food items and diets and meals	(Knudsen et al., 2014; Schmidt et al., 2021)	○ Captures wider view of efficiency, including indirectly affected systems	○ High uncertainty related to indirect and future consequences ○ Complex to model, requiring extensive economic assumptions ○ Often neglects nutritional aspects	○ Provides more holistic evidence on environmental sustainability and consequences of introducing a new demand on the market ○ Connects with land displacement and avoids allocation ○ It can provide the consequential footprint for agricultural phase, industry, or meal/diets ○ It offers more evidence for policy makers
Consequential LCA in food transitional scenarios	Consequential LCA in food transitional scenarios	(Costa et al 2022 *submitted;* Goldstein et al., 2016)	○ Captures wider view of efficiency, including indirectly affected systems ○ Consider options on a diet transition scenario	○ High uncertainty related to indirect and future consequences ○ Complex to model, requiring extensive economic assumptions ○ Often neglects nutritional aspects	○ Provides more holistic evidence on environmental sustainability of potential agri-food transitions to support public policies ○ Connects with land displacement and avoids allocation ○ It offers more evidence for policy makers

5.3.1 Agricultural phase (cradle-to-gate) LCA

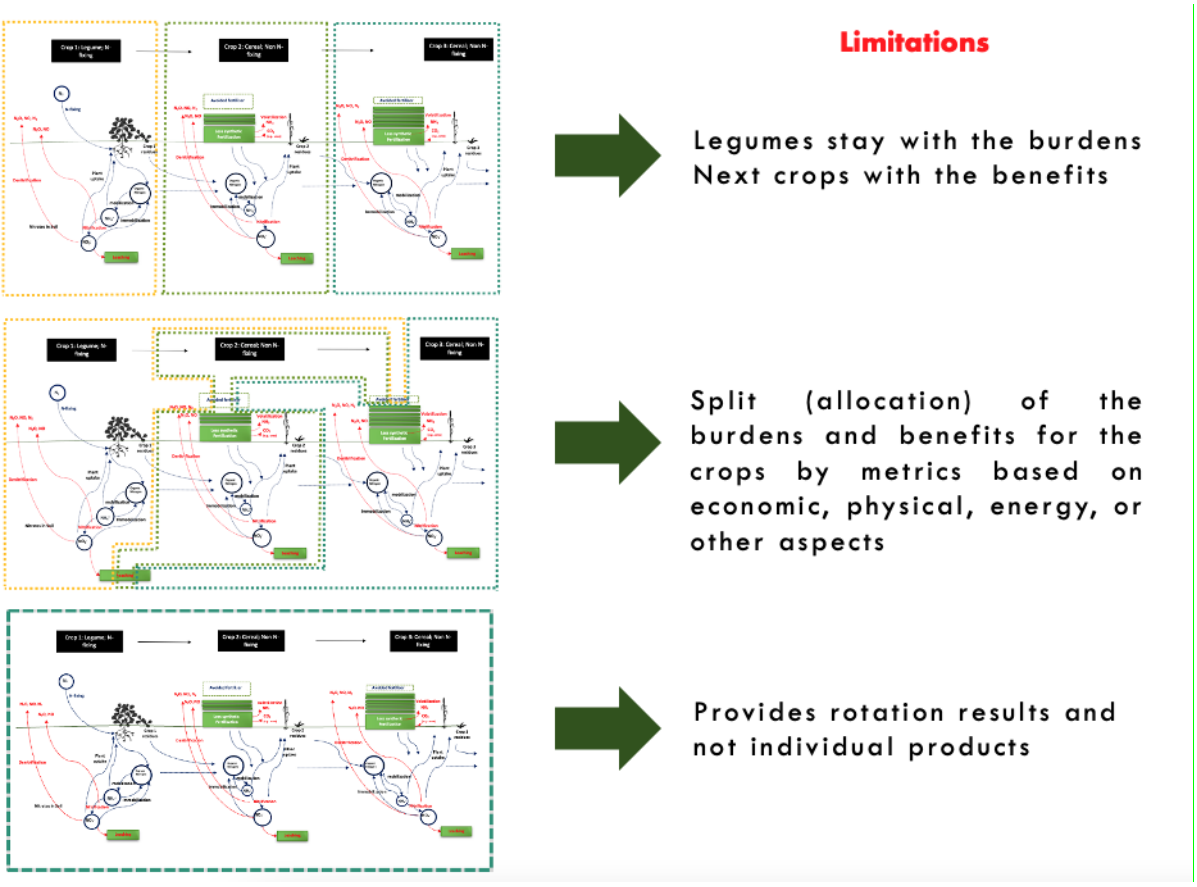
5.3.1.1 Attributional LCA of single crops

Attributional LCA of individual crops can generate a range of footprint results, depending on allocation choices and boundary delimitations. To better understand how these choices are made in LCA studies of cropping systems, Costa et al. (2020) performed a systematic review about LCA for legumes in rotations. They found many different approaches for splitting the benefits and burdens of introducing legumes across rotations (Figure 22, first and second situation). Typically, crop LCA studies set their boundaries around one cropping season, evaluating an individual crop, from soil preparation, planting, crop management, to harvesting. This delineation is intended typically to avoid allocation by subdivision of the systems following the ISO 14044 (2006). However, this does not consider the presence of other crops in the rotation, and consequently ignores any pre-crop and post-crop effects (Figure 22 1, first situation). Costa et al., (2020) highlighted how legume effects on rotations are rarely captured in aLCA, despite the fact that 80% of legume producers also produce cereals, probably in rotation (Eurostat, 2016). Yet, basic aLCA of crop production within a simplified single crop cycle boundary underpins most international LCI databases, such as agrifootprint and Ecoinvent (Durlinger et al., 2017; Moreno-Ruiz et al., 2018). Nevertheless, these databases typically contain the highest level of inventory completeness for specific cropping systems, including e.g. emissions of trace elements and losses of crop protection agents (Nemecek and Schnetzer, 2011). This approach has the aim of providing standardised datasets for LCA practitioners to undertake wider LCA modelling. Thus, despite ignoring rotational effects (discussed in the topic below), this approach is simple and standardised, allowing comparisons across crops and crop-derived foods – including rapid identification of potential environmental burdens and hotspots for each crop. Crop LCAs underpin LCAs of downstream food products, e.g. pasta made from wheat or chickpeas (Saget et al., 2020).

Allocation procedures may be necessary to derive a more accurate result for a single crop LCA, and could improve attribution of some rotation effects (Figure 22, second situation). One example of this situation is the crop rotation effect that can be provided when legume is included in a crop rotation or as a cover crop, when crop residues are left to decompose and benefit the next crops. In both cases, there is the provision of nitrogen (N) to the following crops, and a credit arises when there is a reduction in the fertiliser dose required for the subsequent crop (Brankatschk, 2018; Costa et al., 2020). This situation is captured in the review of Costa et al., (2020), the fertiliser substitution credits are often accounted for in the LCA of the next crop while the burdens such as leaching remain with the previous crop (Figure 22, first situation). This is a result of setting the boundaries around one cropping season. A similar issue can arise when accounting the burdens and benefits of a pre-treatment of soil that will support a long-term rotation, as for example recovering degraded pastures with heavy machine operation and lime application to install no-till integrated crop-livestock-forest systems (Costa et al., 2018). Costa et al., (2018) apply area-time allocation regarding the impact of recovering of soils to establishment of no-till integrated systems. Martínez-Blanco et al., (2014) suggest N mineralization rates and N uptake rates as the most useful flows to biophysically allocate fertiliser rotation interactions. Meanwhile, Grant et al. (2019) recommend attributing full credit for avoided fertilisation requirements to the legume crop in the rotation, as the burden from the legume leaching is also often fully attributed to the legume crop.

5.3.1.2 Aggregated aLCA of rotation systems

Some LCA practitioners studying agricultural systems up to the farm gate have previously discussed the limitations of modelling individual crop cycles in isolation, proposing instead the evaluation of entire cropping cycles (rotations). This modelling technique can capture important inter-crop effects on yield, nutrient cycling and ecosystem services delivery that can often be missed in single-year crop LCAs (Brankatschk and Finkbeiner, 2014a; Costa et al., 2021, 2020, 2018; Goglio et al., 2018). In order to include the rotational effects in LCA, some studies have used simplified FU that transform all outputs of the rotational system into a common basis (Figure 22, third situation), avoiding the need for allocation. One example of such a FU commonly applied in LCA studies is the area over time (ha.yr-1), in which the impact is calculated for all crops under the system per hectare, and the results is displayed and interpreted per year (Nemecek et al., 2008). Other common FUs that evaluate the entire rotation are the dry matter (DM) output of all harvested crops in the rotation (kg DM), or similar to the financial perspective, the revenue minus the direct production costs (€ gross margin) (Nemecek et al., 2008). The rotational LCA approach is often applied with the purpose of advising landowners on the environmental sustainability of different rotation systems and rotation system modifications. However, this can be criticised in terms of results being highly sensitive to the FU adopted, and the lack of connection to final downstream products and/or services functionality in the value chain (Brankatschk, 2018). These functionalities can include energy generation, nutrition for animals and humans, delivery of various cultural or regulating ecosystem services, etc, or combination of all of them. A particular limitation of the analysis of a rotational LCA with a simplified FU is that it provides footprint results per rotation, and not per product under the rotation (third situation, Figure 22).



Limitations

Legumes stay with the burdens
Next crops with the benefits

Split (allocation) of the burdens and benefits for the crops by metrics based on economic, physical, energy, or other aspects

Provides rotation results and not individual products

Figure 22: Main Limitation on attributional LCA for crops under rotations mapped by (Costa et al., 2021, 2020).

In order to enhance interpretation from LCA of cropping systems, some approaches have been developed to represent the aggregate potential delivered nutrition as a functional unit (nFU) for animals and humans. Nutritional FUs for animals often convert the output grains from a rotation into an animal nutritional metric, such as digestible energy (MJ of DE) or digestible protein (kg of DP), instead of using the pure physical quantity (kg DM). (Brankatschk and Finkbeiner, 2014) created a metric called the Cereal Unit (CU), that can be used as a nFU (Costa et al., 2021) or as a basis for allocation within rotations (Brankatschk and Finkbeiner, 2014). The CU is calculated by the conversion all output grains from a rotation into barley equivalent. The calculation is based on a weighted metric of the feed energy provided from macronutrients of the grains (crude protein, crude lipids, crude fibre, and nitrogen-free extracts containing hydrocarbons) to a mix of livestock. The metric proposes a complementary conversion for non-feed crops such as fruits, vegetables, herbs, tobacco, hops, and flowers. For these crops, a yield comparison is conducted related one of the three yield intensity levels of reference crops, based on the agronomic and economic similarities of the crop growth (Brankatschk and Finkbeiner, 2014). Although there is a suggested calculation for these non-feed crops, the authors suggest that other allocation approaches should be investigated. The CU is proposed based on the argument that “The majority of agricultural goods are suitable for feeding animals”, and that “almost 80 percent of all agricultural land is used to produce livestock feed” (Brankatschk and Finkbeiner, 2014). However, despite the convenience and high level of applicability, the CU approach has an important limitation when tackling food transition scenarios involving a trend away from animal protein towards other vegetable-based diets.

Few authors have explored a nFU for (potential) direct human consumption at farm rotational level (Costa et al., 2021; Li et al., 2018). Costa et al., 2021 evaluated the environmental performance of ten different crop rotations (with and without legumes) through a novel approach involving the potential nutrition functional unit for humans within attributional LCA. The nFU used for potential human nutrition was the nutrient density unit (NDU) from Van Dooren (2016), which integrates the evaluation of protein, fibre, essential fatty acids, and energy delivery by the grains. Costa et al., 2021 adapted the NDU removing the essential fatty acids variable due to data availability limitation. They called the adapted nFU as NDUP-F, and according to them, the analysis provided a more systemic view of production systems reflecting nutritional and agronomic differences across cropping systems concomitantly.

Nevertheless, human nutritional functional units are rarely applied in rotation LCA. Based on Costa et al. (2021), we ran additional analyses to compare how the nFU and different FU applied in the literature, such as matter (DM, kg) and area (ha.yr^{-1}), influenced the apparent efficiency of different rotations across agro-ecological zones, and of legume-modification of baseline rotations. Environmental intensity rankings across rotations, using different FU, are presented in the SI. With our correlation analysis (Figure 24, SI), the dry matter FU (DM FU) showed to be a moderately proxy to evaluate human nutrition output, however, the study only considered changing one crop (legume) in a crop rotation sequence. There is a high probability of a weaker correlation between those FUs when more crops changes are simulated.

The nutrition aggregation approach can result in many insightful interpretations for modified rotation as shown in (Costa et al., 2021). Nonetheless it is still a challenge to apply a human nutrition potential for crops at a farm level, as the crops can be transformed into different final food items with various processing and cooking steps. Additionally, farm techniques can alter the bioavailability of nutrients by plants (Spadoni et al., 2007).

Costa et al., (2021) also evaluated the performance of the crop rotations for animal nutrition, using the CU and digestible protein (DP) content. The correlations of the FUs for animal feed purposes (Figure 25, SI) showed that area FU is an ineffective proxy for nutritional output, possibly leading to misleading conclusions on rotation efficiency – e.g. a fallow system would appear environmentally advantageous with an area FU, but not offer any potential nutrition. Brankatschk, (2018) states that the use of area as a FU can be misleading by suggesting that less agricultural activity generates fewer environmental burdens and therefore reduced agricultural production is always favourable. Nonetheless, the area FU is applied by some authors (Nemecek et al., 2008) as an important approach for assessing and comparing, for example, soil quality or biodiversity. However, the area FU approach can lack useful interpretation in the context of food system transitions discussed in this paper. From an animal feed perspective, the DM FU has been applied in numerous LCAs evaluating agricultural rotations, to avoid allocation of burdens across (co-)products (e.g. different grains and straws). Results presented in the Figure 2, SI indicate that this FU (DM) is a reasonable proxy for the CU FU, when one crop is changed in the sequence. However, when the protein aspect is the focus of animal nutrition, DM does not provide a useful proxy. Most of the animal feed FUs found in the literature refer to only one isolated aspect of animal nutrition. A complete nutritional functional unit for animal feed production is still absent in the literature (Costa et al., 2021). Furthermore, there remains a considerable challenge to link nutritional flows from crops to feed animals through to final nutrition delivered to humans.

With the FU correlation in SI, it is clear that aggregated results and interpretations vary considerably depending on the FU. Therefore, the FU must be carefully selected to align with the specific goal of the study, as per (ISO 14040, 2006; ISO 14044, 2006). Lastly, the consolidated approach with nFU can be useful to understand trade-offs arising from modification of typical rotations, and for incentivising land policies linked with food security and diet change transitions. This allows the LCA to capture important rotation-level effects and efficiencies. As shown by Costa et al. (2021), and the supplementary FU correlations undertaken here, further development of nFUs for rotational systems is needed. Meanwhile, more sophisticated (biophysical) allocation procedures should also be developed to improve the accuracy of food footprints derived from LCA of particular crops (within rotations).

5.3.2 Food aLCA (farm-to-fork or cradle-to-grave)

5.3.2.1 aLCA for Food Products

There are many LCA studies for food products available, and there is no one single main goal or end user for these studies. For instance, an LCA can be conducted to understand the impacts of packaging optimization for a certain company (Camps-Posino et al., 2021), or for ecolabeling and environmental product declarations for companies, policy makers or consumers (del Borghi et al., 2020), choice of ingredient base for a certain food for companies or consumers (Saget et al., 2020), policy information such as ranking product groups or benchmarking of products (Konstantas et al., 2020). Additionally, food products span a spectrum of complexity(McLaren et al., 2021), from a simple single-ingredient food that is ready for consumption and does not require cooking (e.g. a banana); a food ingredient in which further processing or mixing is required before consumption (e.g. wheat flour); or a complex food available on the market that is composed of multiple ingredients (e.g. hamburger, pizza, fermented beverages, etc). Certain food items could be classified differently according to the goal of LCA, for instance, a banana could be an ingredient for a banana bread and not a simple food (McLaren et al., 2021).

LCA models that includes processing and production of foods often add an extra layer of complexity due to the potential co-product generation and allocation decisions. This could include animal supply chains, in which, for instance, livestock provides many co-products to many different food value chains, fishery products also generate fish oil and fish meal, among others. This issue also arises for non-animal products, such as the milling of wheat that generates flour and wheat bran for feed purposes (Brankatschk, 2018). Similarly to the agricultural phase, many LCA practitioners trend to simplify the studies and adopt functional units and allocation factors based on mass or volume-based quantities of foods. The simplification, by adopting a physical quantity FU, is valuable when the goal of LCA is not the final consumption, but, for example, identifying the best packaging for that food item, considering e.g. related transportation and shelf-life (wastage) effects.

The LCA community has been actively discussing FU and allocation problems, and some relevant sector specific metrics have already been proposed. For livestock products, biophysical allocation is proposed as the recommended approach, in which the allocation is conducted based on the nutritional requirements of animals' metabolic processes (FAO, 2014). For milk, the mass of Fat and Protein Corrected Milk (FPCM) is proposed as a nutrition-adjusted FU (IDF, 2015). Beyond livestock and milk, there are many other LCAs of food items that measure the environmental impact per unit of nutrition achieved (Chaudhary et al., 2018; Saget et al., 2021c, 2021a, 2020; Sonesson et al., 2017). However, this is not yet the mainstream for food LCAs, and even when the study is intended to assess final consumption or to sustainable diets, the nutrition aspect is commonly neglected (McLaren et al., 2021). This neglect is for two main reasons: (i) the complexity and lack of standardisation for inclusion of nutrition in LCA; (ii) debate over whether nutrition is regarded as the main driver of food consumption. These two points are discussed below.

Regarding the complexity issue (i), nFU metrics can vary in terms of which nutritional elements are evaluated. This can include just one aspect of nutrition, such as the amount of calories or protein provided, possibly adapted by quality or digestibility (Sonesson et al., 2017). Recently, more complex nFUs in LCAs have been applied, taking into consideration more nutrients in their metrics. Saget et al., (2020) suggests the use of van Dooren (2016) nFU, that considers protein, fibre, essential fatty acids, and energy of foods compared to daily intake recommendations. They choose this path as this nFU is relatively easy to apply in terms of nutrient data requirements. Moreover, Williams et al. (2020) demonstrated a good correlation of this nFU with the Nutrient Rich Food Index (NRF12:3), that includes 12 nutrients to encourage and three to limit (Williams et al. 2020). Other authors apply similar multi-dimensional metrics as nFU, representing a balance of nutrients to encourage and to limit compared to their recommended daily intake (Chaudhary et al., 2018). These metrics are more complex to apply due to the data intake needs. A recent study from Food and Agriculture Organisation (FAO) (McLaren et al., 2021) proposes guidance on different nFU for food items or meals with a range of complexity, and applications. The document contains reference to different national nutritional databases, hence LCA practitioners can find reliable data on nutrients present in certain foods within particular diets. Similarly, Agribalyse is a French Life Cycle Inventory (LCI) database which contain many types of food (Colomb et al., 2015).

The discussion of nutrition being a central goal of food item consumption is raised by Weidema and Stylianou (2020) who argue that nutrition should not be framed as a FU. They state that food is often chosen by consumers because of a combination of features including flavour, pleasure, or cultural aspects, and therefore nutrition is not the main driver of choice. This certainly seems very reasonable for products such as mayonnaise (Saget et al., 2021b) and alcoholic drinks (Lienhardt et al., 2019). However, McLaren et al. (2021) contest this perspective, stating that nutrition is important and should not be ignored in LCA given the context that millions of people are currently suffering from diseases related to poor nutritional foods, such as chronic hunger in many developing countries, or obesity in developed nations. Saget et al. (2021a, 2021c, 2020) apply LCA to many novel food items in a European context, and strongly advocate the application of nFU to compare foods given that Europeans have easy access to energy-rich foods and consume three times more protein than needed whilst lacking essential nutrients such as fibre and essential fatty acids. Therefore, nutrition can play a central role on food LCA, especially when novel products are proposed, given that we live in a world of widespread malnutrition of one form or another, and where a food transition is urgently required to align with Sustainable Development Goals (SDGs) proposed by the United Nations

(UN, 2016), to deliver food security (McLaren et al., 2021) and emission reduction targets established by Paris Agreement (UNFCCC, 2015).

A main limitation of food item LCAs, especially for more complex items made from different ingredients such as a veggie patty, is the challenge of connecting them to rotation-level effects noted above. Many food item LCAs rely on secondary databases, and this is a barrier for providing feedback to farmers on potential improvements related to specific products (McAuliffe et al., 2020). Additionally, most secondary data comes with pre-defined assumptions and allocation metrics, and the final environmental impact can vary according to this.

Hence, effort should be made in order to better connect food item LCAs with different agricultural systems and practises. More widespread application and development of nFUs in the context of food item LCA is necessary to analyse trade-offs and synergies among nutritional-health-environmental dimensions (Green et al., 2020), in order to inform better decisions by companies developing foods, consumers, and agri-food and health policy makers.

5.3.2.2 aLCA for Meals and Diets

Meal LCAs often analyse the combination of many possibilities of food item combinations consumed in a serving. These types of study are often designed for public policy level evidence, such as for example understanding the impact of school meals on the environment (Saarinen et al., 2017). In such scenarios, the nutritional aspect becomes very important as the LCAs trend to have their goal established toward the synergistic or antagonistic effects that can occur across different diets (assortments of food items) at a societal level (McLaren et al., 2021). The majority of LCA studies that currently apply nFUs are undertaken on a datary level (McAuliffe et al., 2020).

Meal combinations include complexes choices that affect the environmental impact but also nutrition, flavour, texture, and cultural behaviours. The challenge for meal and diet LCA studies is often to represent realistic consumption patterns at the society level, and to obtain all the necessary environmental and nutritional information for all food items or ingredients, and for the combination of them. Jones et al., (2016) argues that methodological frameworks should include not only the nutrition variable, but also dynamics of consumer behaviour, to elaborate realistic meals options based on the acceptance from society. Saget (2021) remarks the potential of including more legume products in meals to achieve a more sustainable diet, because unprocessed legume grains can be unpopular among consumers.

McAuliffe et al. (2020) highlight that the line between diet-level LCA and commodity-level LCA sometimes can be blurred. They note that is important to further link diet LCA with agricultural LCA thorough an enhanced focus on human nutrition throughout the value chain. Green et al. (2020) state the necessity of combining LCA with other metrics to better model diet changes. Willett et al. (2019) applied aLCA and ecosystem services analyses to evaluate the impact of different diets, recommending a food system transformation based on a healthy diet and efficient and diverse agricultural production. They emphasised the need to reduce intake of red meat and increase intake of legumes (Willett et al., 2019). Similar recommendations were made by Röös et al. (2020). As an alternative approach to integrate nutrition and environmental impact, some authors, such as Stylianou et al. (2016), assessed the impact of nutrition on human health within life cycle impact assessment, based on the endpoint disability-adjusted life years (DALY) indicator.

5.3.2.3 1.5.3. Food system transition aLCA

As already mentioned, most food LCA studies rely on secondary agricultural data, and farm rotation effects are often ignored or highly simplified in those databases (Costa et al., 2020). Some attributional LCA studies acknowledge this limitation, and in other to capture links to land management, adopt techniques such as boundary expansion – without taking the full consequential LCA (cLCA) approach discussed below. Lienhardt et al. (2019), for instance, expanded system boundaries to capture the impact of use of pea co-products, generated by the pea-gin distillery process, as fish and cattle feed – thereby avoiding the import of soybean from North and South America, and related impacts such as deforestation. Saget et al. (2021c, 2021a) evaluated meat and legume products via aLCA, and incorporated Carbon Opportunity Costs (CoC) (Searchinger et al, 2028) into the footprints. They calculated the CoC savings if land was spared by choosing vegetarian foods instead of meat-based options, finding a potential reduction of 89% in CO2e emissions when pea protein balls are chosen instead of meatballs (Saget et al., 2021a,), and 81% when a vegetarian burger replaces a beef burger (Saget et al., 2021c). If accounting further reduction due to the potential afforestation of spared land, the veggie burger would represent a reduction of 96% of GHG when compared to the beef option (Saget et al., 2021c). For the pea protein ball analysis, they showed that substituting 5% of Germany's beef consumption with pea protein balls could spare enough land to offset 1% of national GHG emissions, annually (Saget et al., 2021a).

These analyses can bring some insight into important land use implications of food choices for consumers and policy makers. However, expanding LCA boundaries in this way is highly simplified and may be biased by value judgements. For instance, in full consequential LCA modelling, soybean meal avoidance has indirect consequences that can include increased palm oil production in Malaysia, which is also linked with deforestation (Schmidt and Weidema, 2008). Therefore, the results of Lienhardt et al. (2019) could change if a full cLCA was applied. Nevertheless, these types of expanded boundary aLCA studies can be valuable, and do not require uncertain economic modelling based on volatile commodity prices. Brander et al. (2019) propose an approach to consider aLCA coupled with the check of system wide consequences effects in other value chains. Ultimately, expanded-boundary aLCA can provide insights into diet-land use linkages, and it is imperative that LCA practitioners provide transparency on methodology, limitations and modelling choices when communicating the results of LCA studies.

5.3.3 Consequential LCA

Consequential life cycle assessment (cLCA) has recently been applied to assess food ingredients, ready-to-consume food items (Schmidt et al., 2021; Schmidt and Dalgaard, 2012, Costa et al submitted 2022) and diets (Goldstein et al., 2016). Consequential LCA consists of a modelling framework that considers cause-effect changes across systems following a particular intervention, typically based on economic responses (marginal effects), e.g. as a consequence of a change in demand for (a) certain product(s) (Dalgaard et al., 2014). This approach aims to overcome allocation problems, and at the same time consider wider effects across multiple value chains, forecasting the effects of introducing a certain product into the market, for example. Therefore, the modelling is more complex and requires a broader knowledge of economics and other supply chains that may be affected in the study (McLaren et al., 2021). Some authors (Plevin et al., 2014; Weidema et al., 2018) propose that cLCA is better suited to supporting policy decisions than aLCA, because it considers likely effects that arise indirectly, outside of narrow product system boundaries and can identify hidden risks of ‘leakage’. Brander et al., (2019) proposes a mixed approach (aLCA and cLCA), while Brandão et al. (2014) propose cLCA for designing new policies and aLCA for implementing policies.

Consequential LCA studies for food systems are not as common as aLCA, as they require more knowledge of other interlinked supply chains and economic effects, and they are less standardised by international guidelines. It is also common to find cLCA studies limited to the impact assessment of only the climate change impact category (Knudsen et al., 2014). Additionally, this type of modelling is particularly vulnerable to uncertainty and bias if not conducted properly, especially when anticipating future counterfactual systems. On an agricultural level, Knudsen et al. (2014) conducted a cLCA study on the inclusion of legumes in rotations, though that study was not connected with the consumption phase of legumes, nor with diet transitions. On a product level, Schmidt and Dalgaard, (2012) conducted some studies for Arla Foods, to calculate greenhouse gas (GHG) emissions per kg raw milk. On a dietary level, Goldstein et al., (2016) conducted a cLCA study comparing meat-based (average Danish diet), vegetarian and vegan diets. They used a nFU, i.e provision of 2000 kcal/day. However, they did not consider indirect land use change effects, due to the methodologies still being discussed in the literature, and modelled the impact of foods based on secondary databases. Examples of consequential databases available are Ecoinvent (Wernet et al., 2016) and the Big Climate change database (Schmidt et al., 2021).

Costa et al submitted (2022) applied cLCA to evaluate the replacement of dairy milk with soymilk (Figure 23) and the replacement of meatballs with pea protein balls. The authors connected economic modelling of legume-modified rotations in Germany with the replacement of animal products by plant (legume) based options. Avoidance of dairy milk was linked with avoidance of other constrained co-products such as meat and calves, which are substituted by meat and calves from suckler-beef systems. This compensation demonstrated that cow milk substitution with soy milk may not in itself lead to climate mitigation, if there is no reduction of meat on the market. However, including land CoC can change the result so that a shift towards soy milk becomes environmentally beneficial (Costa et al submitted, 2022). This study highlights how cLCA of food system transitions must develop beyond simple aggregation of cLCA inventory data from new databases, to consider detailed consequential scenarios within foreground systems, in order to generate meaningful results. Considering the role of diet transitions within the context of ambitious projections for decarbonisation and expansion of the circular bioeconomy requires future-oriented scenario modelling, potentially limiting the use of economic models parameterised within the confines of past macro-economic linkages.

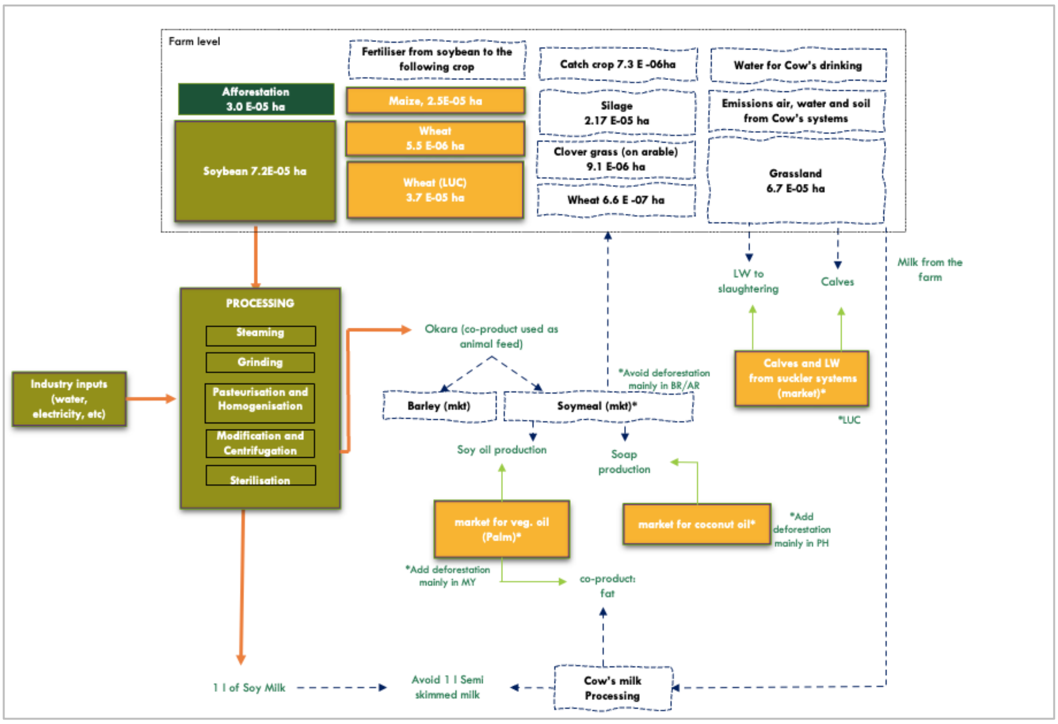


Figure 23: System boundaries of a cLCA comparing the replacement of Dairy Milk by Soybean milk by Costa et al *submitted* (2022).

5.4 Conclusion - LCA applied to food transitions

LCA is applied to understand the impact of different foods, diets, and food systems, but involves many value judgements and controversies. Diet transitions involve product substitutions, implying land use transitions and crop rotation modifications. These topics are strongly linked but have typically been addressed separately by LCA academics so far. The goal of a sustainable food system transition is to provide nutritious food with lower environmental harm in an economically viable and socially fair manner. Current state-of-the-art LCA studies for food systems do not yet simultaneously capture rotational effects, human nutritional aspects, product substitution and land use change in a coherent way. However, parts of the food value chain can be meaningfully studied via LCA and still result in insightful interpretation related to specific goals. To align with international challenges, in particular the Paris Agreement (UNFCCC, 2015)and SDGs (UN, 2016), nutrition should be intrinsic to the main goal of the LCA, and this can be reflected in the functional unit chosen or the scenarios (foreground systems) developed.

Databases should be developed to incorporate important rotational effects into single crop/product inventories, e.g. based on specific farm contexts and management practises, to improve the quality of harmonised attributional LCA data widely used by the LCA community.

Databases, such as Agrifootprint and Agrybalyse (ADEME, 2020; Durlinger et al., 2017) should include consequential versions. Additionally, databases such as the Climate Database (Schmidt et al., 2021) should include wider information on other environmental problems, beyond just GHG emissions. In terms of farm management and landscape assessment, the use of nutritional FUs to aggregate rotation outputs could address rotation interactions among crops, and connect downstream value chains to better link food items and diet choices with land management effects. Our FU correlations highlight the importance of careful choice of FU at rotation level, and the need to develop more sophisticated FUs that can be applied throughout food value chains. Meanwhile, wider adoption of consequential modelling could provide a strong evidence base for policymakers on sustainable food system transition pathways. Further research is urgently needed to refine holistic application of LCA to food system transitions, especially considering future-oriented “what-if” scenarios of coupled shifts in diet and land use – in line with food security, health, climate and biodiversity goals that will demand system transformations.

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5.7 Supplementary Information

5.7.1 Different Functional Units modelling for Rotational Systems

On this in this study, we compare the performance of the selected nutritional FUs by Costa et al. (2021) with two FUs commonly applied in an LCA agriculture rotation studies – i.e. dry matter (DM, kg) and area (ha.yr)$^{-1}$. An attributional LCA for the ten crop rotations (cereal-cereal [C-C], cereal-oilseed [C-O], and cereal-oilseed-legume [C-O-L]) for three regions in Europe (Scotland (SC), Italy (IT) and Romania (RO)) was conducted for Dry Matter (DM) and Area Funcional Units. The environmental performance for the DM and Area FUs were generated following exactly the same data, method and assumptions of the performance calculated for the nutritional FUs by Costa et al. (2021). To understand the consequences of the choice of those FUs, we correlated the results for climate change potential (CC) evaluated under the nutritional FUs (Feed and Food) by Costa et al. (2021) against the results obtained for Dry Matter (DM) and Area FUs. The same correlations were also undertaken for the total environmental impact (TI) – the sum of normalized scores of each LCA impact category in the unit of person.year^{-1} (how much one person emit, use resources, etc in one year), an optional step in PEF guidelines (European Environmental Bureau et al., 2018) to facilitate the interpretation of a multi category LCA. The correlation was performed between the following FUs:

- FU_{Food}: Functional Units for Human Nutrition:
  - Correlation between NDUP-F[1] and DM (EA)[2]
  - Correlation between NDUP-F and Area

- FU_{Feed}: Functional Units for Animal Nutrition:
  - Correlation between Cereal Unit (CU)[3] and DM(g+s)[4]
  - Correlation between CU and Area
  - Correlation between digistbale protein for ruminants (DP) and DM(g+s)
  - Correlation between DP and Area

[1] The NDUP-F refers to the potential human nutrition of the grains. It takes into account the protein, fibre and callories values of the grain compared with the daily values recommendation (Costa et al., 2021)

[2] We only considered DM appropriate for human consumption, and therefore applied economic allocation to separate the environmental burdens attributable to non-human-edible straw co-products from wheat and barley cultivation. We called this functional unit DM (EA)

[3] The Cereal Uniti (CU) (Brankatschk and Finkbeiner, 2014b) represents the sum of metabolisable energy in all macronutrients (crude protein, crude lipids, crude fibre, and nitrogen-free extracts containing hydrocarbons) – calculated as weighted average energy across the German livestock profile (pigs, poultry, cattle, and horses). The final value is converted into 1 kg of barley feed energy equivalent.

[4] When designated to feed, all outputs of dry matter from grain and straw were summed up together, composing the final output of the rotations and avoiding the need for any allocation. We called this functional unit DM (g+s). The area FU in ha.yr-1 also avoided any need for allocation

5.7.2 Results

The nutritional FUs proposed by Costa et al 2021 for animal and human display a wide range of correlations with common FUs adopted in previous rotation LCA studies. The regression coefficients (r^2) ranged from <0.01 to > 0.9 as can be observed in Figure 24 for FU_{Food} and in Figure 25 for FUFeed. Footprints expressed per FU_{Food} and FU_{Feed} correlate very poorly with footprints calculated per Area (ha.yr-1) FU in all situations, with the highest regression coefficient (r^2) of 21% for the total impact between CU and area. FU_{Food} footprints were moderately correlated with DM (EA) FU footprints (56% for TI) (Figure 24). Meanwhile, FU_{Feed} footprints based on DP were moderately correlated with footprints based on a DM (g+s) FU (r^2 23% for TI), and FU_{Feed} footprints based on CU were stronger correlated with DM (g+s) FU footprints (r^2 89% for CC, and r2 73% for TI)(Figure 25).

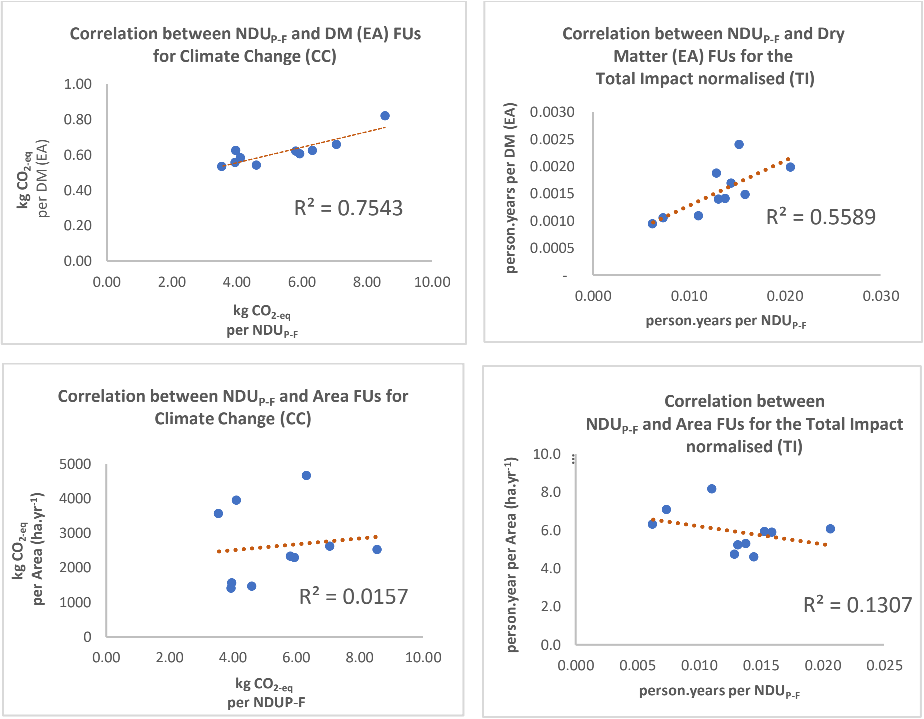

Figure 24: Correlations of human nutrition functional units. The rotation footprints are expressed per NDU$_{P-F}$ against footprints expressed per dry matter economic allocated (DM EA) and area functional units. The correlations were performed for climate change (CC) and total normalised impact (TI).

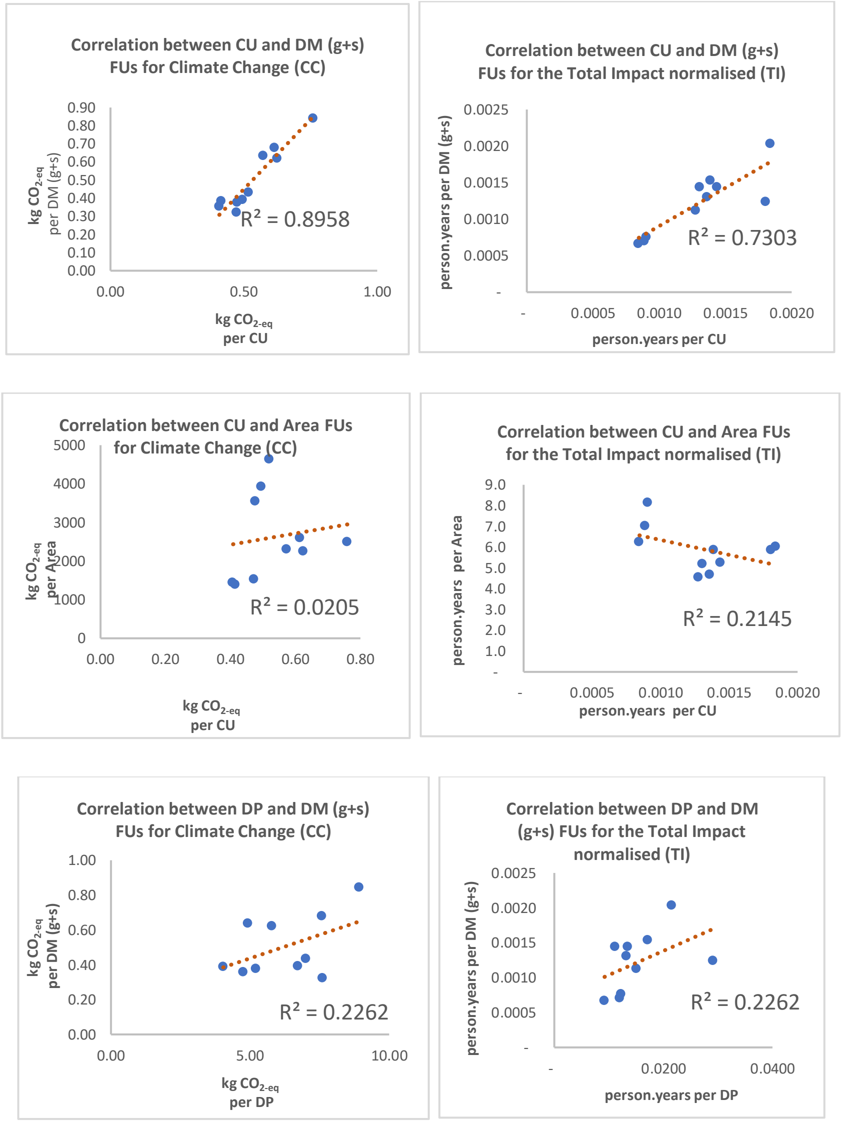

Figure 25: Correlations of functional units for animal feed. The rotation footprints are expressed per Cereal Unit (CU) and Digestible Protein (DP) against footprints expressed per dry matter (DM (g+s)) and Area FU. The correlations were performed for climate change (CC) and total normalised impact (TI).

5.7.3 References

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6 **Chapter Six:** General Conclusions

6.1 Life Cycle Assessment Applied to Food Systems

Life Cycle Assessment methodology is crucial to analyse the environmental impact of food systems. Chapter two highlighted that important crop system level effects arising from the incorporation of legumes in crop rotations are still neglected by many attributional LCA studies and farmers. The establishment of system boundaries around a single cropping season can ignore the interaction between crops within a rotation, although this practice remains common and comprises many international databases. With these aspects potentially being a significant factor in product footprints, it would be highly beneficial for the LCA community to begin demonstrating rotational interactions within their aLCA (Brankatschk, 2018; Brankatschk and Finkbeiner, 2014; Goglio et al., 2018a, 2018b; Nemecek et al., 2008)

This can be achieved by the wider evaluation of entire cropping systems, considering those crops which are succeed the legume cultivation within the rotation, capturing the N cycle and ideally the impact on the carbon cycle alongside additional factors where possible. Studies should consider at least two functional units (Goglio et al., 2018a), where one encompasses the multifunctional outputs of entire rotation sequence (e.g. by assessing human or animal nutrition potential) and the other enabling product footprints to be calculated. For the latter, proper allocation should be considered, and sensitivity analyses are important to test the effect of the allocation choices, enabling the reader to have a broader view of the trade-offs intrinsic to the analysis. Additionally, LCA practitioners should make the effort to collect data that support calculation of other environmental categories beyond that of global warming potential (carbon footprints).

From the analysis within chapter three, and the correlation of functional units performed in chapter five, it was shown that a nutritional FU could be used to assess rotation-level efficiency, bringing valuable interpretation of rotation changes to drive sustainable food system transitions. Nevertheless, such a FU remains a highly simplified and somewhat crude proxy for human nutrition potential, and could be developed further. Considering the real nutritional content of grains according to farm practices (AHDB, 2019), the nutritional effects of grain processing and preparation (Saget et al., 2020), and a broader focus on elements beyond protein, fibre, and energy, would be key issues to consider. Protein quality, represented by amino acid profile (Leinonen et al., 2019), or micronutrient bioavailability, may also be particularly important. Building on the cereal unit proposed for crop system allocation (Brankatschk and Finkbeiner, 2014), a more sophisticated FU to aggregate rotation outputs for the purpose of animal feed would be useful. Chapter three showed how animal feed values differ significantly depending on whether an energy or protein basis is applied. Ideally, a FU could be developed to represent ultimate human nutrition delivered by rotations directly from crops, and indirectly from animal products derived from those crops. Ultimately, such environmental assessment of nutritional outputs from cropping systems could strengthen the evidence base for driving change in the current food system, thus improving overall sustainability.

Consequential LCA applied in chapter four, and discussed further in chapter five, provides a framework whereby allocation can be mostly avoided by boundary expansion. On the one hand, this approach provides a wider systemic view of the value chains studied and their potential impact on other, connected, value chains. In a diet transition scenario, important conclusions can be derived from this approach. For example, as mentioned in chapter four, the replacement of 1 litre of dairy milk for 1 litre of soymilk may only be beneficial to the environment if demand for beef declines. Dairy system displacement can displace co-production of meat and calves, a change which would need to be compensated for by unconstrained value chains in the market, such as suckler beef systems. However, cow milk substitution can still spare land, which could lead to indirect climate benefits. The calculation of carbon opportunity costs can provide valuable insight to policy makers, i.e. if there is no increase demand for new arable land due to diet change transitions, the areas avoided due to avoided animal systems (feed and grazing) can instead be designated to afforestation, and carbon thus carbon dioxide removals, compensating for the environmental impact of food production.

However, on the other hand, many assumptions need to be made to conduct a cLCA, especially regarding the market responses and co-product substitutions. Despite relying on consequential databases that contain pre-modelled market responses, the consequential framework is highly complex, and requires deep economic knowledge of multiple value chains (Dalgaard et al., 2014; Schmidt, 2008). This is especially necessary in order to make assumptions about foreground system changes (plausible scenarios) across interlinked agri-food value chains. Consideration of human nutritional or behavioural effects may require a more sophisticated approach that simply assuming pea protein balls replace meatballs and soymilk replaces cow milk on a 1:1 mass basis. Legume alternative foods as pea protein balls have more fibre, but potentially less digestible protein, than meat (Saget et al., 2021a). The protein deficit may not be significant from a nutritional perspective, as Western European diets are generally associated with the overconsumption of protein (Nijdam et al., 2012), but the fibre could contribute to satiety and avoid the consumption of other foods. Nutritional analysis would be important to infer potential secondary diet change effects, and this topic should be developed in further research.

From the application of LCA to legumes in the context of this thesis and other studies, it is clear that food system transitions, including product innovation and product substitutions, often imply land use changes and crop rotation modifications that are critical to the sustainable development. The nutritional aspect is intrinsic in the goal of food transitions, and therefore it is essential that studies should consider it. Moreover, it is clear that cLCA has an important role to play in supporting public policies (Brandão et al., 2014; Plevin et al., 2014; Weidema et al., 2018; Brander et al., 2019). Therefore, database deverlopers should support LCA practitioners to apply cLCA by developing consequential versions of their databases – e.g. for Agrifootprint and Agrybalyse (ADEME, 2020; Durlinger et al., 2017). It is also important that cLCA databases include wider environmental impact results than just GHG emissions, which is currently the case for the Climate Database (Schmidt et al., 2021).

As discussed in chapter five, LCA can be applied to specific parts of the value chain, with a narrower scope, and still be valuable and insightful, generating data for databases or providing a deeper analysis with details and answering specific questions, as analysed within chapters three and four of this study. Also, transitional LCA analyses (aLCA with boundary expansion and carbon ppportunity cost estimations) can provide insight into land use repercussions of food choices for consumers and policy makers. However, boundary expansion and carbon opportunity costs should be calculated and reported in a transparent way, to avoid bias. Brander et al. (2019) propose an approach to consider aLCA coupled with a check for major consequences in other value chains. There remains a challenge to refine a coherent and consistent application of LCA in the food system transition context, considering future-oriented "what-if" scenarios of coupled shifts in diet and land use – in line with food security, health, climate and biodiversity goals. To support permanent changes and to align with international objectives, in particular the Paris Agreement (UNFCCC, 2015) and the Sustainable Development Goals (SDGs) (UN, 2016), it is desirable that all aforementioned aspects should be included within LCA assessments for food transitions, to accurately inform policymakers seeking more sustainable food systems (McLaren et al., 2021).

Hence, there is an immediate need for further research to develop relevant LCA methodological transparency and standardisation, building on existing general LCA guidelines, incorporating both attributional and consequential frameworks, for assessing entire crop rotations and the effects of introducing new crops, addressing system boundaries, priority impact categories, allocation methods, and appropriate functional units, assumptions of interlinked value chains, etc. It is desirable that an approach is considered that can be applied for the various value chains arising from agriculture, such as agroforestry and intercropping systems, livestock grazing on temporary leys, and also non-food-or-feed uses of crops (bioenergy, textiles, cosmetics, etc). With these results, we conclude on specific research objectives number one and four.

6.2 Sustainability of integrating legumes into European Food Systems

Overall, integrating legumes into both food production and consumption across Europe appears to be a sustainable strategy that would in fact hark back to past practises – before a high degree of specialisation became widespread. On the agricultural level, this research corroborates existing sustainability evaluations available in the literature (Nemecek et al., 2008; Reckling et al., 2016b; Watson et al., 2017). The analysis within chapter three showed that, compared to typical cereal systems, legume-modified rotations improve nitrogen cycling, reducing the requirement for external fertilization, increase yields of subsequent crops, and provide a better nutritional profile of outputs for both humans and livestock with a lower environmental burden - across three European agro-climatic zones and for most of the 16 impact categories studied. Despite other research indicating potential for increased leaching within legume rotations (Nemecek et al., 2008), this was not a concern when considered using the rotational and functional unit approach, as the cereals cultivated after legumes "mopped up" much of the N in legume residues, reducing fertiliser requirements (Reckling et al., 2016a). This research also showed that, overall, legume incorporation in rotations is a more effective strategy than the use of technical options to improve mineral nitrogen fertiliser use efficiency.

According to Watson et al., (2017), Europe would benefit from a fourfold increase in grain legume production based on 2014 levels, reaching 6% of the arable area used for legumes. In this context, legumes are only considered for local protein production and nitrogen efficiency. When diet transitions scenarios are accounted for, this number tends to increase. In this case, the consumption of more legumes would be needed to replace meat consumption in diets (Poore and Nemecek, 2018; Willett et al., 2019).

On the food product level, most aLCA studies point to an advantage in terms of both nutrition and environmental impact for legume-enriched products, compared to their typical alternatives, i.e chickpea pasta (Saget et al., 2020), pea protein balls (Saget et al., 2021a), vegetarian patties (Saget et al., 2021c) and pea flour (Chaudhary et al., 2018), among others. Also, gin made from peas demonstrated an environmental advantage compared with traditional gin (from wheat grain), as the residues of the gin made from peas can serve as a protein-enriched co-product for fish and cattle feed, thereby avoiding the import of soybean for this purpose (Lienhardt et al., 2019). On the other hand, the vegan mayonnaise (Saget et al., 2021b) made with chickpea cooking water showed disadvantages in its environmental impact compared with typical egg mayonnaise. This is because the chickpea water required further processing and transport. These two last products are not intended for nutrition and therefore were compared on a volume and mass basis.

When analysed via consequential LCA, pea protein balls were environmentally advantageous compared with meatballs, resulting in a saving of 2.4 kg CO_2e per 100 g serving. If the land spared by shifting from beet to pea-protein balls were to be afforested, the GHG savings could triple to 7.3 kg CO_2e per 100 g per serving. In contrast, it is not possible to confirm an environmental benefit by the substitution of cow milk with soymilk, if no offsetting from afforestation is considered. This is due the displacement of the dairy calves and culled meat production to less efficient suckler-beef herds. Nonetheless, these co-products would not need to be compensated if there were a substantial coincident reduction in beef demand within diet transitions.

It is important to state that the efficiency of livestock systems can vary considerably depending on the region and management practises. For instance, Costa et al (2018) found that integrating crop, livestock, and forest can reduce the land demand six-fold to produce the same amount of meat and grains. This integration can also reduce the slaughtering time of cattle by 38% and reduce overall emissions from the integrated systems to 55%. Poore and Nemececk (2018) mapped five environmental impacts from 38,700 farms and concluded that ‘impact can vary 50-fold among producers of the same product’. Nevertheless, they also state that the lowest impact from animal products is still higher than plant-based alternatives.

Therefore, this thesis confirms that legumes have a central role to play within diet transitions and food system transformation in Europe, towards the realisation of the sustainable EAT-Lancet diet proposed by Willett et al. (2019). Diet change and legume-based farming systems can support considerable land sparing, livestock emission avoidance and synthetic fertiliser efficiency, particularly lowering environmental burdens regarding climate change and acidification, among others. It is recommended that diet substitution with legume products prioritises replacement of meat products rather than dairy products, to avoid environmental “leakage” via the displacement of (surplus) calf production. Better environmental results can be achieved when there is coordination of food and land system management, i.e, legume protein should be an incentive to substitute animal protein, alongside a land use strategy that considers afforestation, in order to deliver climate neutrality.

6.3 Key messages for stakeholders

- **Academics:** This main message to academics is to understand the intercrop effects that should be represented within LCA of food products and system transitions, and to develop attributional and consequential LCA methodology in order to capture potential benefits from legumes in crop rotations and across interlinked value chains (including via product substitution). There is an urgent need for specific food system transition LCA guidelines to address the methodological challenges raised in this thesis.
- **Farmers**: Farmers should invest in crop rotation diversification, including legumes within typical cereal rotations, in order to increase yields, promote break-crop effects, reduce reliance on synthetic nitrogen fertilisation, and reduce overall environmental burden related to their production whilst increasing the nutrition potential of outputs from their rotations.
- **Food Industry**: The food industry should actively invest in innovation of legume-enriched foods, in particular as substitutes to meat products where possible, with grains from crop rotations delivering more nutrition with a lower environmental footprint compared with conventional cereal- and livestock- dominated value chains.
- **Consumers**: Consumers should consider sustainable behaviour change by opting to purchase food with lower environmental impact and better nutrition, towards significantly reducing or avoiding meat products, and considering sustainability impacts of consumed products. If still consuming (small amounts of) meat, consumers should seek products from livestock systems that play a positive role in landscape management, nutrient cycling, and rural livelihoods such as minimising or avoiding industrial farmed animals.
- **Policy makers**: Policy makers should look for evidence that connects different perspectives of food system sustainability, including economic environmental and social dimensions, and different (stages of) interconnected value chains. They should commission studies that holistically evaluate the environmental effects of particular changes, such as legume incorporation into European food systems. Legumes can play an important role not only in meat substitutes but also in improving livestock efficiency, more specifically in areas not suitable for arable cropping. Legumes intercropped with pasture (i.e grass-clover) can maintain productivity in livestock systems that could deliver ecosystem services benefits on land not suitable for cropping. Finally, policy makers should identify the types and scales of legume production that fit best within transformed food systems and design policies that favour growing and consuming legumes as a meat substitute in Europe.

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