Journal of Cleaner Production 424 (2023) 138826

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

# Environmental and land use consequences of replacing milk and beef with plant-based alternatives

Marcela Porto Costa [a,*], Sophie Saget [b], Beate Zimmermann [c], Eckart Petig [c], Elisabeth Angenendt [c], Robert M. Rees [d], David Chadwick [a], James Gibbons [a], Shailesh Shrestha [d], Michael Williams [b], David Styles [a,e]

[a] Bangor University, School of Natural Sciences, Bangor, United Kingdom
[b] Trinity College Dublin, Dublin, Ireland
[c] University of Hohenheim, Department of Farm Management, Stuttgart, Germany
[d] Scotland's Rural College (SRUC), Edinburgh, Scotland, United Kingdom
[e] School of Biological & Chemical Sciences and Ryan Institute, University of Galway, Galway, Ireland

ARTICLE INFO

Handling Editor: Zhifu Mi

*Keywords:*
Legumes
Life cycle analysis
Carbon opportunity cost
Carbon footprint
Plant-based

ABSTRACT

The consumption of meat and dairy products raise enormous environmental concerns. Circa 80% of global 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 (LCA). In this study, we investigated the environmental consequences of two independent yet 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 meatballs with pea-derived protein balls can result in GHG savings of 2.4 kg $CO_2$e per 100 g serving, and up to 7.3 kg $CO_2$e per 100 g serving if spared land is afforested. Environmental problems related to nutrient leakage such as acidification and eutrophication are also mitigated. Meanwhile, 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.

## 1. Introduction

Demand for animal-products, such as meat and milk, continues to increase. According to FAO (2018), the global dairy herd increased by 11%, and milk yields by 17%, in the preceding 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 gas emissions (GHG) from the livestock industry (Weiss and Leip, 2012). According to Godfray et al. (2018), a considerable part of these emissions is related to bovine enteric fermentation

* Corresponding author.
*E-mail address:* cmarcelaporto@gmail.com (M. Porto Costa).

https://doi.org/10.1016/j.jclepro.2023.138826
Received 17 April 2022; Received in revised form 19 August 2023; Accepted 11 September 2023
Available online 13 September 2023

(Beauchemin et al., 2009; Nguyen et al., 2010a,b). Chadwick (2005a,b) also highlights the significance of ammonia and nitrous oxide emissions from manure management and fertilisation, and GHG emissions 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 production and consumption of meat is seen as an important strategy to achieve ambitious emission reductions, and to free up land for 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 to produce this crop in Latin America (Lienhardt et al., 2019; Zander et al., 2016). The use of legume plant alternatives in human diets could lead to a reduction of 62% in meat consumption across Europe, as suggested by (Hallström and Börjesson, 2012; Zander et al., 2016). Western diets are known to contain foods that are energy-rich and nutrient-poor, leading to health problems such as obesity (Saarinen et al., 2017). Additionally, Dyer et a.l (2020) showed that reducing red meat can lead to reduced GHG emissions alongside health benefits, such as a lower incidence of cardio-related diseases and cancers. 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 just a few exceptions (e.g. 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 production system 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 can vary. For example, they can be based on physical ratios (e.g. respective masses of co-products), energy flows (respective energy contents of co-products), economic characteristics (respective monetary values of co-products), 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 co-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, at the end of their life via slaughter, and via surplus calf production. The shortfall in beef production would have to be compensated by dedicated beef systems (even if overall beef consumption in Europe is falling, because dairy-beef accounts for less than half of total beef in Europe), with considerably higher emission intensity per kg of beef produced (Baldini et al., 2017; Mazzetto et al., 2020). 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), and the sensitivity of GHG simulations for country level diet change (Dyer et al., 2020).

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 cLCA to simultaneously account for dairy-beef displacement, crop rotation changes and land carbon opportunity costs.

## 2. Methods

### *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 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 L 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. Despite possible differences in nutrition arising from these substiutions, functionality was considered on a mass basis assuming that consumers would replace a single serving of milk or beef, measured on a mass basis in meals, with a single serving of the plant-based alternative. In other words, a meal with rice and meat balls would be replaced by a meal of the same size (mass) of rice and pea-protein balls; and a glass of milk, or milk used in coffee or tea, would be replaced by an equal volume of soymilk. The pea protein balls evaluated in this study contain more protein per 100 g serving than meat balls (22.33 g against 17.5g respectively) (Saget et al., 2021c), while soymilk contains considerably less protein per litre than cow's milk. Nevertheless, across Europe and other industrialised regions, the population consumes on average 70% more protein than recommended by nutritional guidelines (Westhoek et al., 2015). Correcting for protein content was not deemed relevant in this context, where most food intake is clearly determined by factors other than basic nutrition. Such substitutions are also justified when following the EAT Lancet recommended diet for more healthy and environmentally respectful intakes, pointing to a reduction in beef and dairy products and an increase in legume products when compared to the European average diet (Willett et al., 2019).

Modelling was undertaken in Open LCA v1.9 (GreenDelta, 2006), using the Ecoinvent v.3.7 consequential database for background data (Moreno-Ruiz et al., 2018). Life Cycle Impact Assessment (LCIA) used the method recommended by the European Commission Product Environmental Footprint (PEF) guidelines (European Environmental Bureau et al., 2018). This 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, Freshwater Eutrophication, Resource use - fossil, and Water Scarcity. Land occupation was calculated in the respective life cycle inventories, and carbon opportunity costs expressed in terms of possible Climate Change effects (described later).

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 Hohenheim University (Petig et al., 2018, 2019), described in detail in Section 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. Modelling was 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, 2019). Dairy and beef system modelling was based on typical farms from the Baden-Württemberg region in Southern Germany (Petig et al., 2019). Farm level data are further described in sections 2.2 and 2.3. Milk (soybean and dairy) processing data assumptions are described in Section 2.4 and beef/protein ball processing assumptions are described in section 2.5.

Fertiliser application rates were based on agronomic practices embedded in the EFEM model, and partitioned across specific compounds using German consumption data for different fertiliser types from the International Fertilizer Association (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 ($NH_3$), nitrous oxide ($N_2O$), and carbon dioxide ($CO_2$) 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).

### 2.2. *Economic farm emission model (EFEM)*

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, 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 (Fig. 1). 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., 2020a,b; Nemecek et al., 2008; Reckling et al., 2016a,b). 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 diversification-related yield enhancement of about 10% in the following crop are assumed in model scenarios.

The input data derived from FADN include a wide range of structural data such as farm operational 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

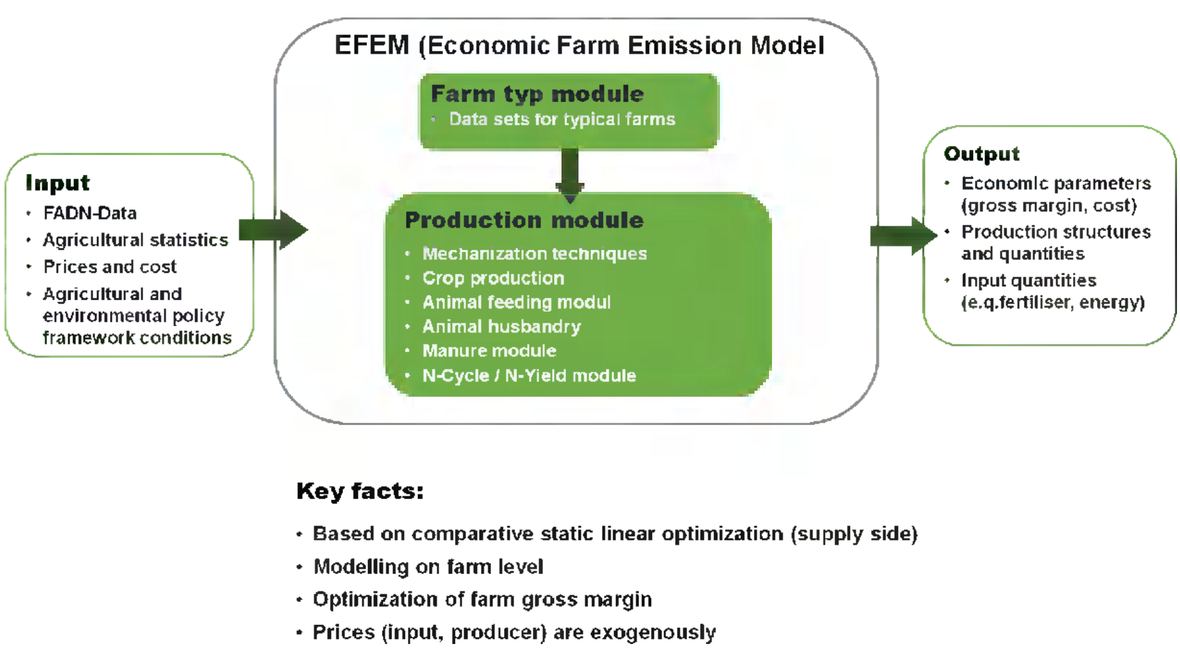


**Fig. 1.** Structure, data sources and output of the *Economic Farm Emission Model* (EFEM).

performance related feed costs based on Petig et al. (2019).

The main results of the optimisation 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.

### 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 1). The regions were characterized by different agro-climatic conditions and farm structures. Under a scenario where legume precrop effects, such as nitrogen provision and yield enhancement in following crops, the introduction of soybean and peas was considered, accounting for the (cereal) grains those legumes would replace (Table 1). Net grain displacement depends on the changed demand for dairy and beef feed, 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.

## 2.3. Beef and dairy systems data

The typical dairy farm is based on FADN data from Oberland/Donau, an intensive livestock region in Southern Germany (Baden-Württemberg), with a typical grass and maize feed regime (Table 2). The dairy farm comprises 139 milking cows, 35 calves and 35 heifers for rearing, and exports 8000 L 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.

The beef system represents a typical suckler beef farm in Baden-Württemberg (Table 3), 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 1**
Crop rotations without and with legumes on typical arable farms located in Eastern Germany (Brandenburg) and Southern Germany (Bavaria). In the third column, the negative values show the crops subistituted by legume and catch crops (positive values) in the rotations.

| | Eastern Germany (Brandenburg) | | | Southern Germany (Bavaria) | | |
|---|---|---|---|---|---|---|
| | Crop rotation without legumes | Yield (FM) | Legume-modified rotation | Crop rotation without legumes | Yield (FM) | Legume-modified rotation |
| | ha | t/ha | ha | ha | t/ha | 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 |

**Table 2**
Key characteristics of a typical German grass and maize based dairy farm located in Baden-Württemberg.

| Arable land (total) | Cultivated area | N input | Use as feed (%) | yield | | |
|---|---|---|---|---|---|---|
| | ha | kg N/ha | | t FM/ha | % Dry mass | t DM/ha |
| | 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 |

**Table 3**
Key characteristics of a typical German suckler-beef farm located in Baden-Württemberg.

| Arable land (total) | Cultivated | N input | Use as feed (%) | yield | | |
|---|---|---|---|---|---|---|
| | ha | kg N/ha | | t FM/ha | % Dry mass | t DM/ha |
| | 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 using a modified version of the cattle system LCA tool developed by Styles et al. (2015), largely based on an IPCC Tier 2 methodology (IPCC, 2006, 2019a) and activity-specific $NH_3$ excretion-related emissions (Misselbrook et al., 2015). 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 h 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 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 by the soy milk substitution, 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 the ecoinvent v3.7 consequential database (Wernet et al., 2016) were 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 displacement possibilities for the wheat crop: (i) some wheat cultivation displacement occurs on the farm's spare arable land, while the rest is compensated by the German market; (ii) some wheat displacement occurs on the farm's spare arable land, while the rest occurs on spared dairy grassland (avoided land on the Cattle Farm (Table 1)). 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 (a fraction of) spared land – whether directly, or on more marginal land potentially freed up because of a migration of agricultural production on to the better quality spared land (Styles et al., 2018). 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 – based on the "carbon opportunity cost" approach proposed by Searchinger et al. (2018). This approach was intended to indicate the biophysical potential for net GHG emission fluxes associated with diet transitions, in response to possible future climate action, and is therefore not constrained by current economics or laws around land management. It is not a "prediction"; rather an indication of total climate mitigation potential if (spared) land is used for carbon doxide removal (CDR) in the future.

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 v3.7.1 consequential database, and therefore fully accounted for in calculations. Associated land balances (relevant to LUC) are reflected in the final results.

### 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 (Lienhardt 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 trends in FAO statistics, milk fat is most likely to be replaced by vegetable oil i.e., palm oil from Malaysia, a determining product (Schmidt, 2008b).

### 2.5. Beef meatballs and pea proteins balls processing data

Life cycle activities associated with processing of pea protein balls and beef meatballs 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 in ecoinvent v3.7.1 consequential database (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).

### 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.

## 3. Results

### 3.1. Soymilk replacing dairy milk

#### 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 displaces 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 (Fig. 2), 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 category results, accounting for any emissions related to that land. The spared dairy grassland available was considered for afforestation, varying from 0 to 100% of the area spared – as mentioned, such afforestation may ultimately arise on land spared elsewhere after production has migrated from less favourable areas on to the newly spared land.

In the second scenario (Fig. 3), on the foreground land balance, the additional wheat displaced was not compensated by the average German market; instead part of the spared dairy grassland was considered to be converted into wheat cultivation (considering emissions from LUC) and the remainder modelled for afforestation, of which 0–100% is afforested. There remains the necessity to compensate LW and calves with market alternatives from the ecoinvent consequential database, v3.7.1 (Wernet et al., 2016).

#### 3.1.2. Consequential life cycle assessment results

The results of five impact categories for both scenarios, expressed per 1 L of dairy milk replaced, are presented below in Table 4. Under

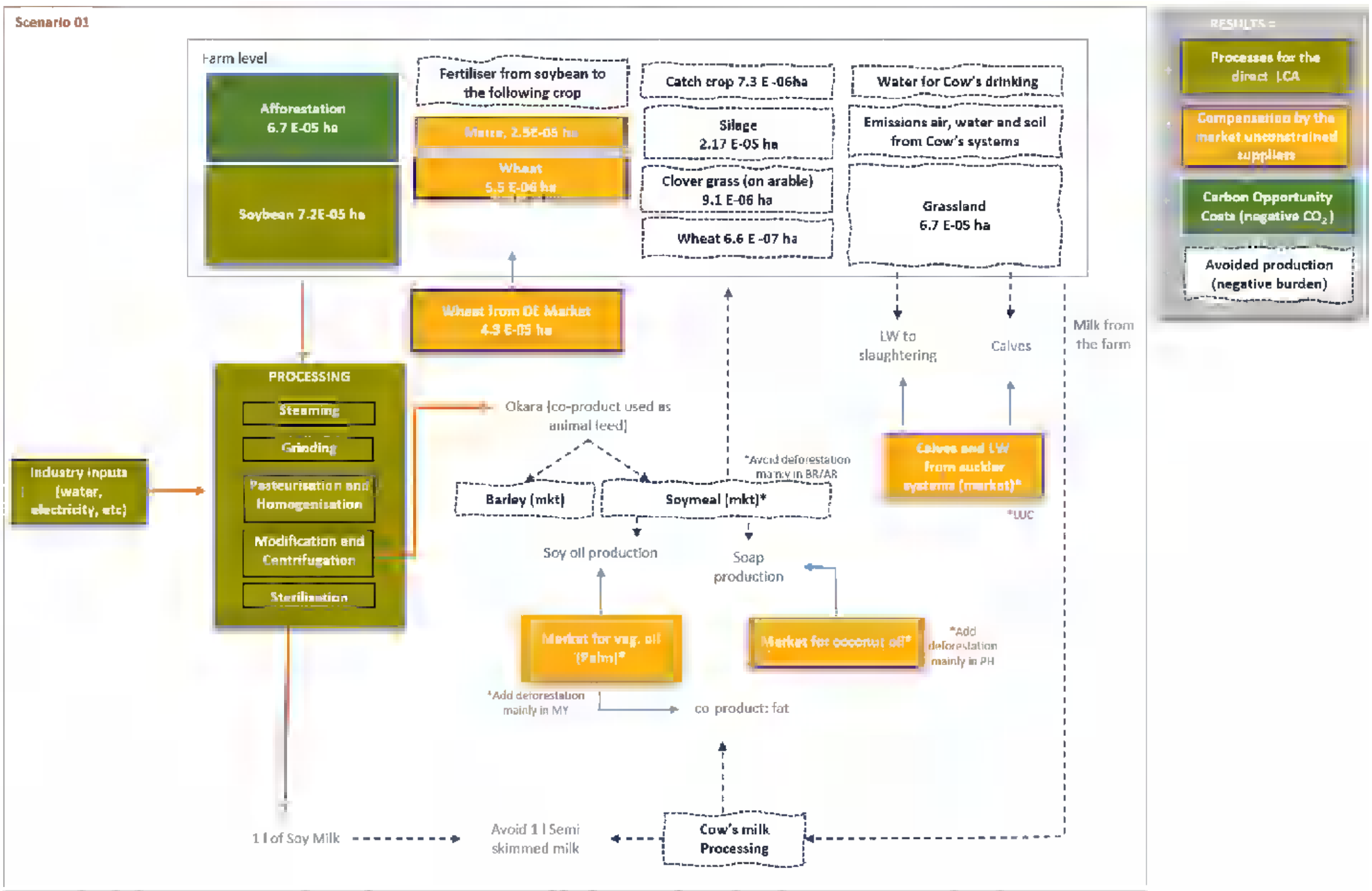


**Fig. 2.** Scenario 1. Soybean cultivation displaces grain cultivation on the arable farms and on the spared dairy farmland. Some of the wheat, culled cattle live weight and calves need to be compensated by market alternatives.

Scenario 02, three categories displayed an environmental improvement when dairy milk is replaced by soymilk, while two categories displayed an environmental deterioration. For Scenario 01, environmental improvements were 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).

Details about the processes in Scenarios 01 and 02 that contribute most to the climate change category, either positively or negatively, were recorded (Fig. 4). 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 0.89 kg $CO_2$e (Scenario 01) and 0.23 kg $CO_2$e (Scenario 02) per litre of milk replaced. The second most important process was the avoidance of cows (saving 0.82 kg $CO_2$e per litre of milk replaced), largely reversed by the compensation of weaned calves, which adds emissions of 0.69 kg $CO_2$e per litre of dairy milk replaced in Scenarios 01 and 02.

For both Scenarios, afforestation of the spared grassland area can lead to significant net GWP savings overall (Table 5). We highlight that displacement of surplus calf production from dairy systems means that a larger suckler herd is needed than would otherwise be the case (even with slowly declining beef consumption), generating substantial additional emissions (than would otherwise be the case). Thus, excluding potential afforestation of spared grassland, displacing cow milk with soymilk results in almost no overall change in GHG emissions (Table 5). This emission "leakage" effect, of dairy-calf displacement reducing dairy system emissions but increasing beef system emissions, has previously been shown for dairy intensification transitions (Styles et al., 2018), but not, as far as we are aware, for diet transitions. This effect also explains increases in eutrophication, resource depletion and water use burdens that are influenced by compensatory beef-calf production in dedicated beef breeding systems. Such leakage could be avoided if beef demand was dramatically (>50%) reduced to a level that could be satisfied exclusively by dairy-beef production.

There were no benefits from afforestation across other impact categories assessed in this paper. For freshwater eutrophication and acidification, wheat displacement was the main visible difference when the scenarios were compared, despite the wheat related values being considerably smaller than weaned calves compensation or avoided cows in the farm. Even when wheat is displaced in the same country (Germany) (Scenario 01, Fig. 2), 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 2.2. The wheat yield from the dairy farm was 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, 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 (imported) soybean meal due to the co-production of Okara feed from soymilk (Fig. 5).

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 dairy cattle emissions,

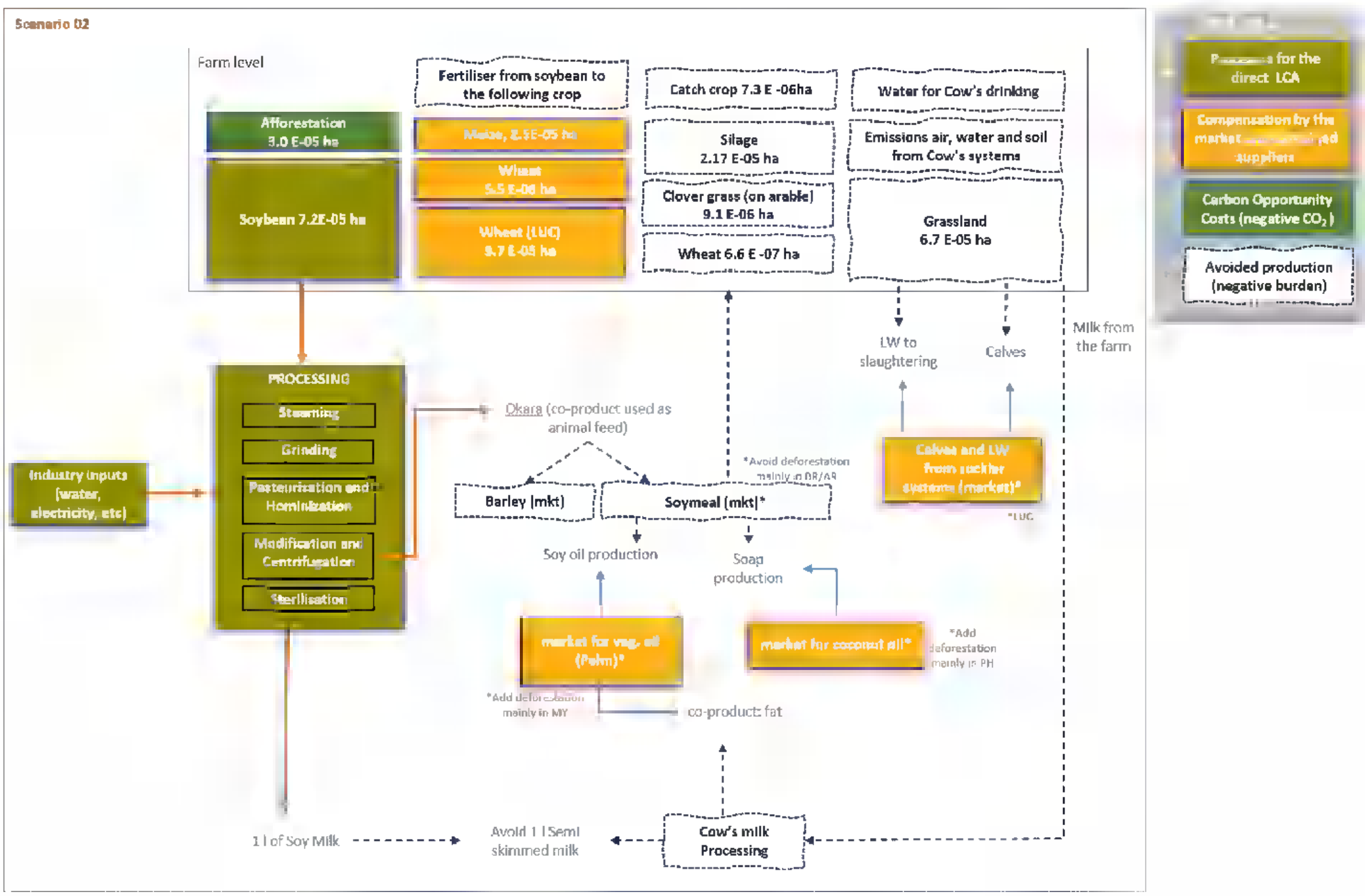


**Fig. 3.** Scenario 2. Soybean cultivation displaces grain cultivation on the arable farms and on the spared dairy farmland. Some of the wheat production is displaced onto spared dairy grassland, whilst culled cattle live weight and calves need to be compensated by market alternatives.

**Table 4**
Net environmental balance and associated uncertainty ranges across five environmental categories for the replacement of 1 L of dairy milk with soymilk under two land balance scenarios analysed. Red shaded cells (positive values) represent environmental deterioration while the green shaded cells (negative values) represent environmental improvement.

| 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 scarcity | 3.9E-03 ± 3.21E-02 | -2.4E-03 ± 3.22E-02 | $m^3$ deprived. |

somewhat offset by a burden from compensatory weaned beef calves (Fig. 6).

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 Fig. 7.

Water scarcity potential, measured in $m^3$ $H_2O$ deprived eq., demonstrated an environmental disadvantage for Scenario 1 and an improvement for Scenario 2 (Fig. 8). 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.

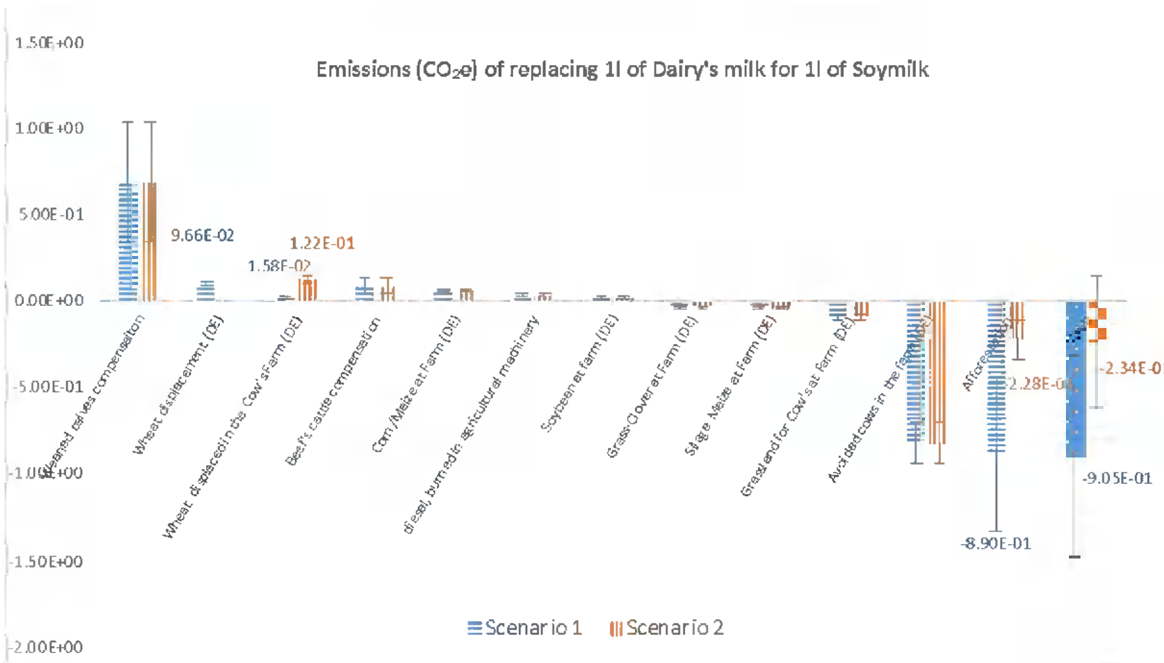


**Fig. 4.** Milk Scenario 1 and 2 results, expressed as net GWP balance (kg $CO_2e$) per litre of soymilk produced, per main incurred or displaced process that accounts for more than 1% of the total emissions (positively or negatively). Indicative maximum 100% afforestation of spared farmland is illustrated.

**Table 5**
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 |

### 3.2. *Pea protein balls replacing meatballs*

#### 3.2.1. *Land balance*

According to the EFEM model, the introduction of peas in the rotation displaces 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 (Fig. 9). 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).

#### 3.2.2. *Consequential life cycle assessment results*

Results are more clear-cut for pea proteinballs substituting beef meatballs than for the substation of dairy milk for soymilk, across most of the categories, and uncertainties do not interfere in the final interpretation (Table 6). There was an environmental disadvantage across one of the five categories analysed (resource use, fossil fuels, in MJ).

Details about the processes that contributed the most to GWP mitigation can be observed in Fig. 10. The process that contributed the most 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 contributed to the results was the avoidance of cattle production (−2.1 kg $CO_2e$ per 100g of pea protein balls). The highest additional burden arose from the production of other ingredients in the pea protein balls, which added emissions burdens of 0.2 kg $CO_2e$ per 100 g of meatballs replaced.

Table 7 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 ration. Thus, up to 3.7 $m^2$ yr is spared per 100 g serving of pea protein balls, resulting in a potential GWP saving of up to 7.3 kg $CO_2e$ per portion (Table 6).

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 released to freshwater) when the meatballs were replaced (Fig. 10). This was mainly due to the avoided nutrient 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, as soybean protein is an 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, which includes potatoes, sugar, onions, among others (Saget et al., 2021c).

Acidification potential, measured in mol $H^+$ eq., demonstrated an environmental improvement from replacing meatballs (Fig. 10). The process that mostly contributed to this result was the avoidance of cattle rearing ammonia emissions. There was an environmental deterioration for resource depletion, fossil, from replacing meatballs (Fig. 10). The processes that most contributed positively to this result (burden) were other ingredients for the pea protein ball manufacturing followed by

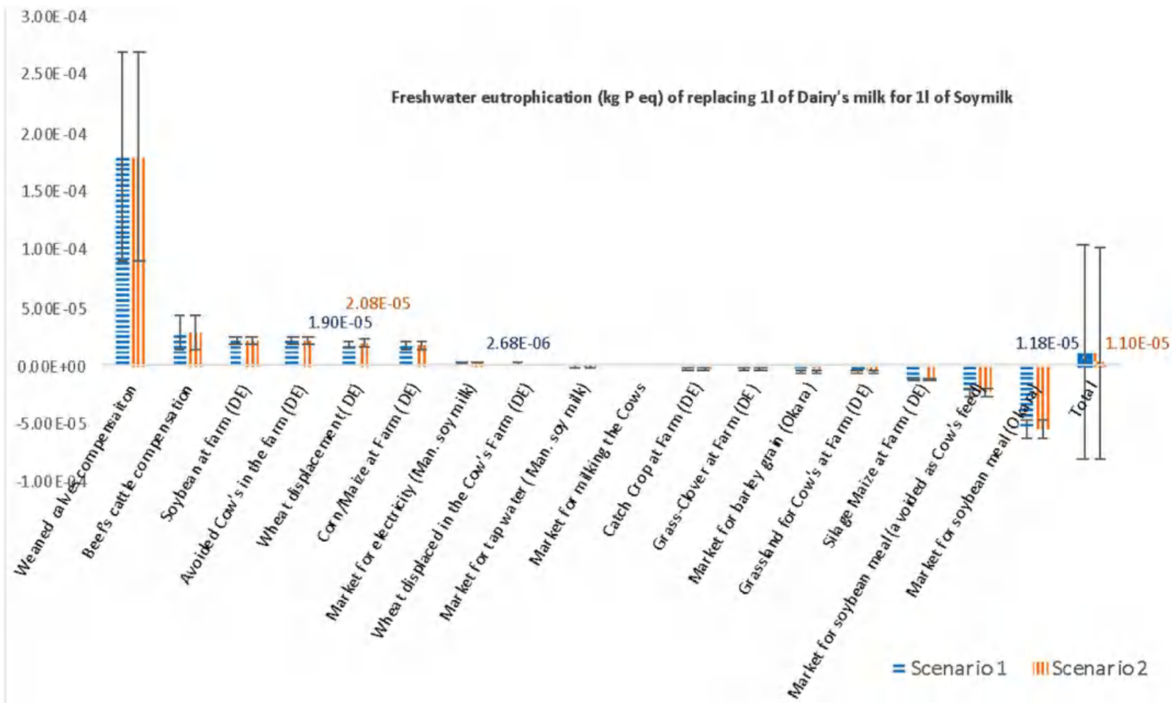


**Fig. 5.** Results for Scenario 01 and Scenario 02 for freshwater eutrophication, expressed in kg P eq. per litre of soymilk produced, per main incurred or displaced process that accounts for more than 1% of the total emissions (positively or negatively). Scenario results are shown in blue for Scenario 01 and in orange for Scenario 02.

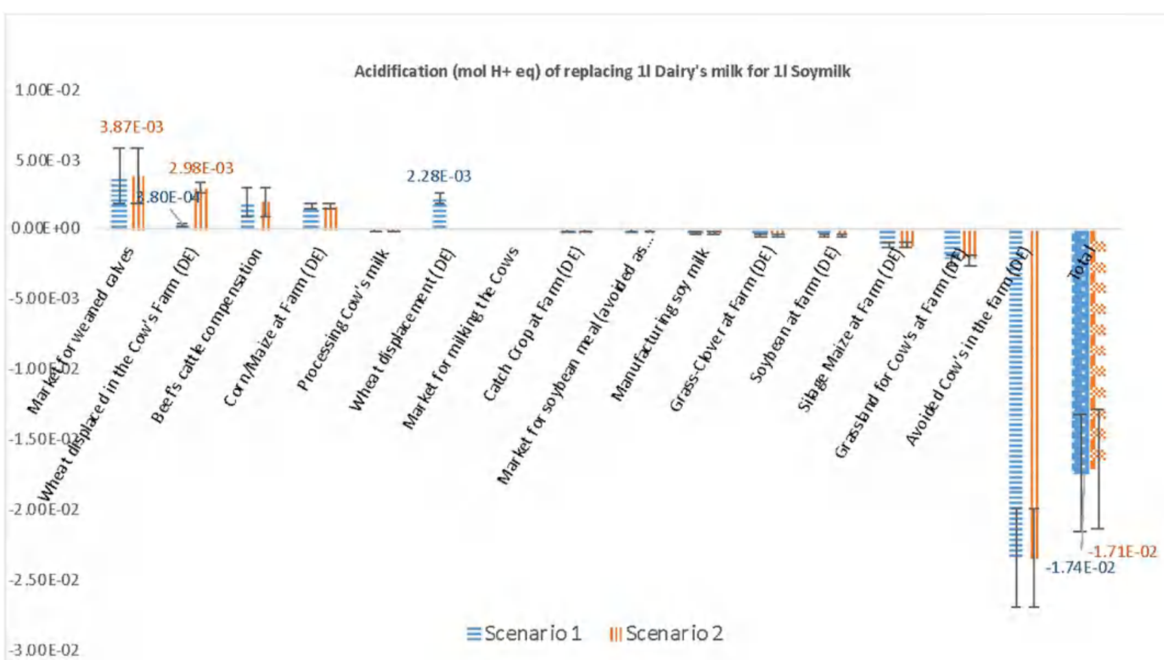


**Fig. 6.** Results for Scenario 01 and Scenario 02 for the acidification potential, measured in mol $H^+$ eq. per litre of soymilk produced, per main incurred or displaced process that accounts for more than 1% of the total emissions (positively or negatively). Scenario results are presented in blue for Scenario 01 and in orange for Scenario 02.

processing. The aspect that was responsible for this burden in other ingredients was 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 were the main contributors to the environmental impact. Looking at the environmental improvements, the main processes were the avoided grassland production (avoiding need for diesel burned in agriculture machines for fertilisation and cutting, etc), 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 100 g of meatballs (Fig. 10). The process

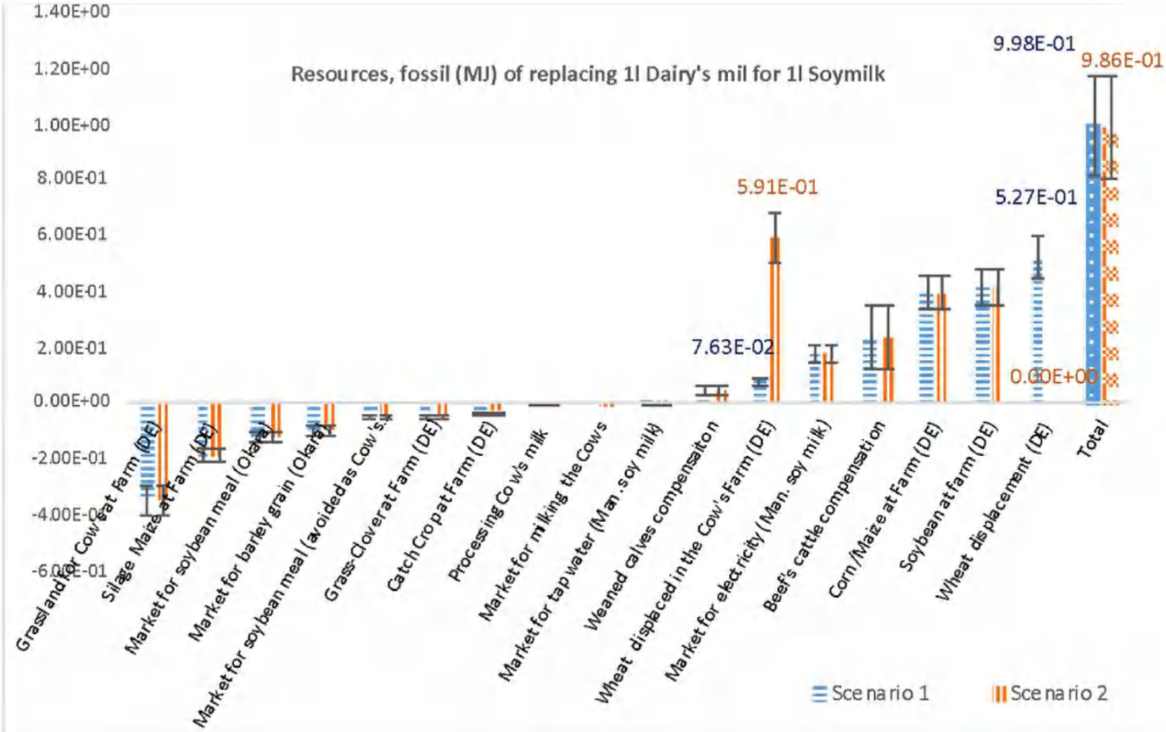


**Fig. 7.** Results for Scenario 01 and Scenario 02 for the resources, fossil fuels depletion potential, measured in MJ eq. per litre of soymilk produced, per main incurred or displaced process that accounts more than 1% of the total emissions (positively or negatively). Scenario results are presented in blue for Scenario 01 and in orange for Scenario 02.

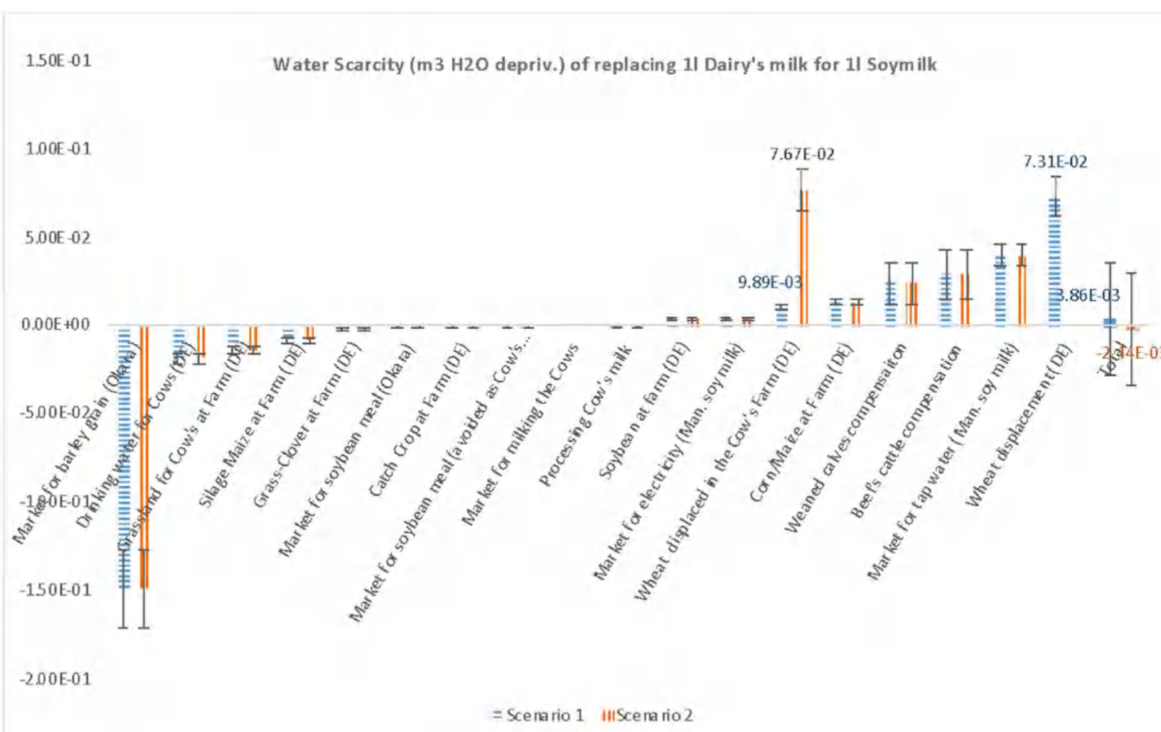


**Fig. 8.** Results for both scenarios for the water scarcity potential, measured in $m^3$ $H_2O$ deprived eq. per litre of soymilk produced, per main incurred or displaced process that accounts for more than 1% of the total emissions (positively or negatively). In red and green there are the values 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.

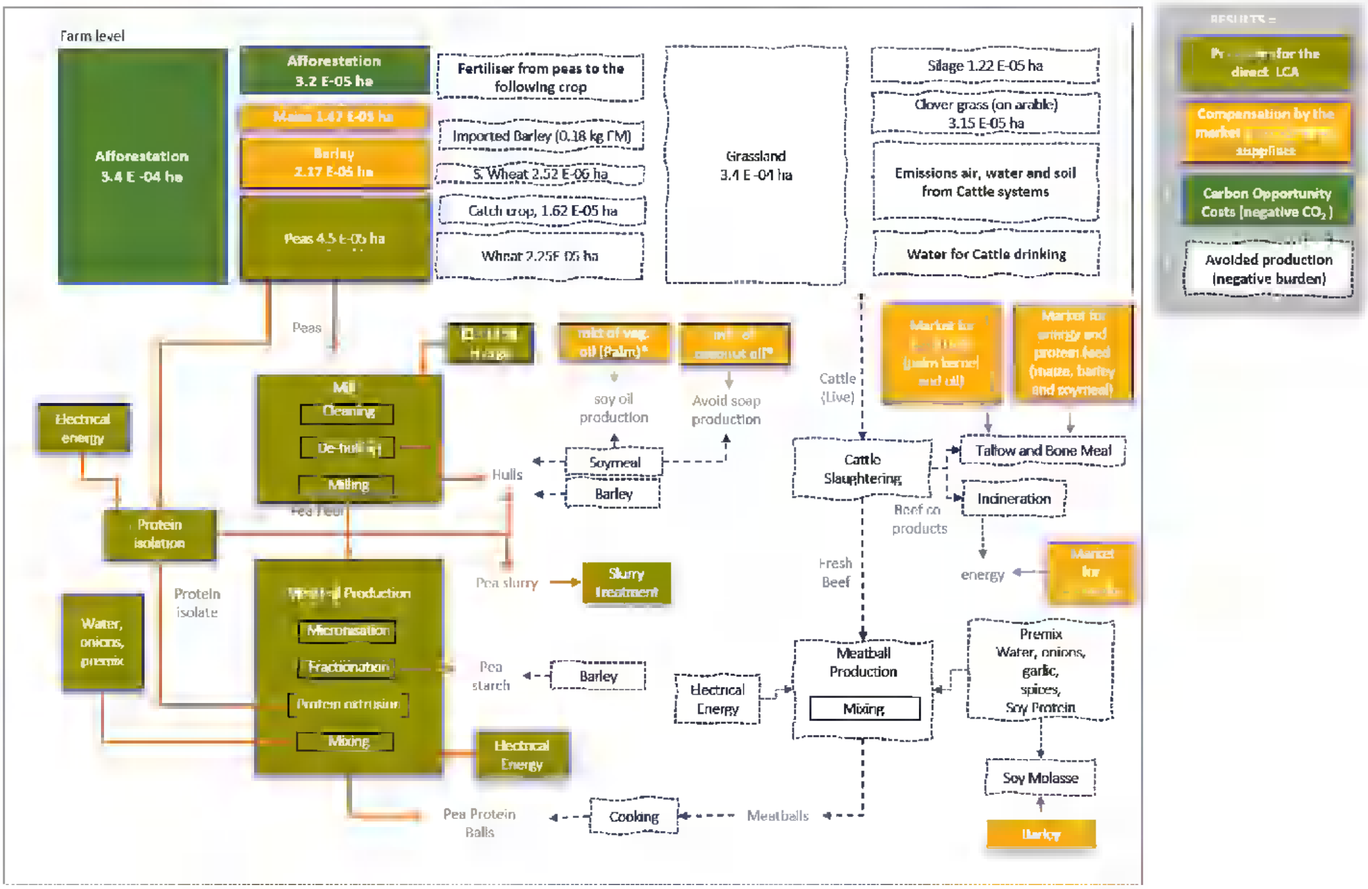


**Fig. 9.** Flow diagram showing process changes when beef meatballs are substituted with pea protein balls, where pea cultivation replaces cultivation of cereals used for beef cattle feed, sparing large areas of arable and grassland for afforestation.

**Table 6**
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. |

that most contributed towards this saving was the avoidance of cattle rearing, avoiding 13 $m^3$ of water scarcity per portion of 100 g of meatballs. This is mainly related to the dataset for the market for wastewater in Europe (ecoinvent 3.7.1 consequential database) avoided during the slaughtering process: in other words, the effluent is avoided. Regarding the cattle drinking water, only 15% is considered consumptive, meaning that it is not returned to the farm system, as it is incorporated in the cattle products or lost through evapo-respiration 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. 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 peppers, onions, etc.

## 4. Discussion

### 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 balls, 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., 2020a,b). 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 calorie 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 larger 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.,

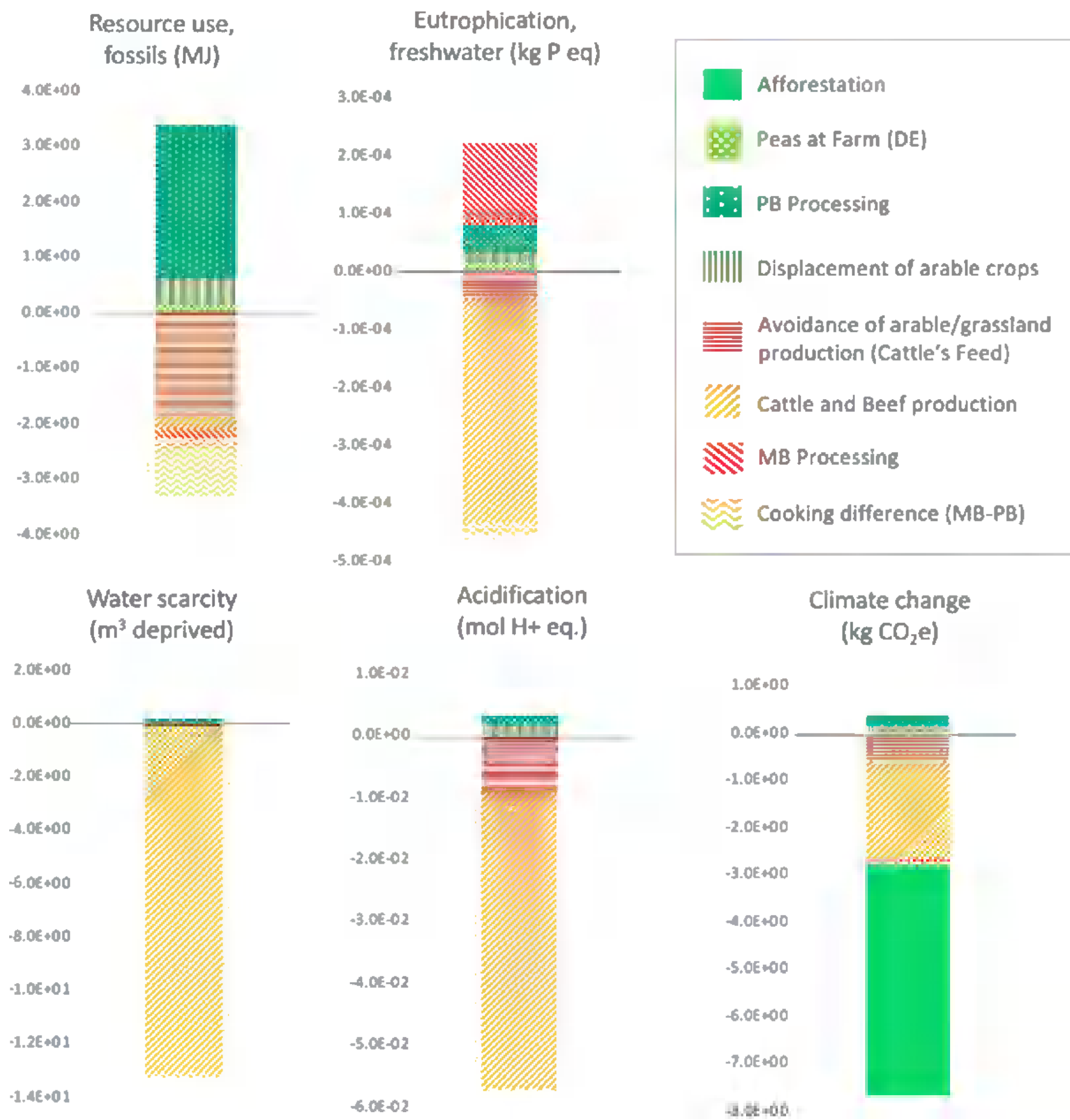


**Fig. 10.** Results for the substitution of 100g of meatball (MB) by 100 g of pea protein ball (PB), across five environmental categories, broken down into main incurred or displaced processes accounting for more than 1% of positive or avoided emissions. Indicative maximum 100% afforestation of spared farmland is illustrated.

**Table 7**
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 $CO_2$e 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 |

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 slaughter 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 $CO_2$e for 1 kg soymilk; (ii) 0.61 kg $CO_2$e per kg of milk, semi-skimmed (1.5%); (iii) 0.61 kg $CO_2$e per kg of vegan mince (0.061 kg per 100g of vegan/mince), pea-based; and (iv) 11.08 kg $CO_2$e per kg of meatball (1.1 kg $CO_2$e 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, mainly across Latin America and the US, as a marginal market composite.

### 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, increasing opportunities for 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., 2010a,b). 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 (by over 50%) – 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 °C 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 (SBTi, 2021), meaning huge reductions in emissions and scale up of CDR (Stark et al., 2019).

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 and Murray, 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.

### 4.3. 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 across systems and economic sectors such as agricultural production, processing, health, energy generation and others. The consequential framework is complex, and requires a deep knowledge of the economy and biophysical linkages across systems (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 background data and interlinkages, and should be interpreted carefully. This study is associated with significant uncertainty as it uses a mix of data sources to represent the manufacturing of pea protein balls and avoided meatballs (Saget et al., 2021b), the manufacturing of soy milk (Birgersson et al., 2009), weaned calf production from the ecoinvent cLCA database (Moreno-Ruiz et al., 2018), and German farm operations from the EFEM model, among others. Considering the interlinkages, the substitution of cow milk with soymilk 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 (which may mean calves are slaughtered earlier, rather than being fattened for beef, thus resulting is less compensatory beef calf production, and therefore a larger GHG mitigation effect from soy milk). 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, but German-specific data were lacking. Future studies could undertake wider sensitivity analyses around these effects.

Another limitation of this study was the simplified assumption that milk and beef products would be substituted on a simple mass (portion) basis, disregarding possible consequences for human nutrition and wider dietary choices. On the one hand, vegetarian and vegan diets could necessitate a 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). Legume alternatives such as pea protein balls are known to have more fibre, but potentially less digestible protein, than the meat products they may replace (Saget et al., 2021a). Those authors compared a 100 g cooked portion of meatballs (17.5 g of protein) with pea protein balls (22.3g of protein), adjusting pea protein down to 20.5 g of protein to account for 8% lower digestability (Gilani and Lee, 2003). The nutritional value of the two products was then compared using a nutrient density unit (NDU) that integrates fibre, protein, fatty acids and calories, resulting in higher calculated nutritional delivery for a portion of pea protein balls compared with meatballs (Saget et al., 2021a). Increasing emphasis is also being placed on the quality of protein, in terms of amino acid profile, alongside much longer lists of important constituents relevant to human nutririon (Sonesson et al., 2017; Leinonen et al., 2019; Notarnicola et al., 2017). Nevertheless, those same authors highlight that some products are consumed more for social objectives than nutrition, which supports the 1:1 mass (simple portion) substitution, as the assumption in this paper. In reality, would someone drink more plant based milk than cow's milk to ensure the same protein/nutritional intake, despite average protein and fat consumption in excess of recommendations (in Germany or other industrialised countries)? Or would someone eat less pea protein balls than meatballs owing to a high nutrient density in pea balls? Our analysis is predicated on the assumption that one portion of milk or beef can be simply substituted by one portion of plant-based alternative, based on product switching. Possibly there could be secondary effects via degree of saiety, influencing consumption of other products. However, attempting to model such affects would require considerable survey and/or behaivoural data inputs. Attempting to correct for nutritional delivery in the absence of more sophicated diet change analysis is likely to introduce error, as hypothetical substitution ratios could deviate from the most direct (likely) consumption shifts. Nevertheless, nutrition is an important aspect of diet transitions, and its consequences should be analysed further.

## 5. Conclusion

The substitution of beef by pea-derived protein can result in large direct 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 GHG mitigation via afforestation (as an effective climate action), 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 direct 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 – and mitigation could be considerably increased if beef consumption is dramatically reduced (by over 50%) so that compensatory beef production is no longer displaced to dedicated beef systems.

This study confirms that legumes can play an important role in the 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, due to potential GHG gains and to avoid emissions "leakage" via displacement of (dairy) beef calf production to less efficient, dedicated beef systems. 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.

## CRediT authorship contribution statement

**Marcela Porto Costa:** Conceptualization, Investigation, Methodology, Data curation, Formal analysis, Writing – original draft. **Sophie Saget:** Data support, Writing – review & editing. **Beate Zimmermann:** Data curation, Formal analysis, Writing – review & editing. **Eckart Petig:** Data curation, Formal analysis, Writing – review & editing. **Elisabeth Angenendt:** Data curation, Formal analysis. **Robert M. Rees:** Writing – review & editing, Supervision. **David Chadwick:** Writing – review & editing, Supervision. **James Gibbons:** Writing – review & editing, Supervision. **Shailesh Shrestha:** Writing – review & editing. **Michael Williams:** Writing – review & editing, Funding acquisition. **David Styles:** Conceptualization, Writing – review & editing, and, Supervision.

## 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.

## Data availability

Data will be made available on request.

## Acknowledgements

This research was supported by the TRUE and RADIANT projects, funded by the EU Framework Programme for Research and Innovation H2020, Grant Agreement numbers 727973 and 101000622, respectively. The research related to the Dairy and Beef Farms in Baden-Wuerttemberg was supported by grants from the Ministry of Science, Research, and the Arts of Baden-Wuerttemberg Az 7533-10-5-189A.

## References

ADEME, 2020. Agribalyse: l'évaluation environnementale au service de l'alimentation durable - La librairie [WWW Document]. URL. https://librairie.ademe.fr/produire-autrement/573-agribalyse-l-evaluation-environnementale-au-service-de-l-alimentation-durable-9791029714511.html, 1.31.22.

Afshin, A., Murray, C.J.L., 2019. Uncertainties in the GBD 2017 estimates on diet and health – authors' reply. Lancet 394, 1802–1803. https://doi.org/10.1016/S0140-6736(19)32629-7.

AHDB, 2021. EU medium-term outlook for agriculture – 2020 to 2030 | AHDB [WWW Document]. URL. https://ahdb.org.uk/news/eu-medium-term-outlook-for-agriculture-2020-to-2030, 1.30.22.

Baldini, C., Gardoni, D., Guarino, M., 2017. A critical review of the recent evolution of Life Cycle Assessment applied to milk production. J. Clean. Prod. 140, 421–435. https://doi.org/10.1016/J.JCLEPRO.2016.06.078.

Beauchemin, K.A., McAllister, T.A., McGinn, S.M., 2009. Dietary mitigation of enteric methane from cattle. CAB Reviews: Perspectives in Agriculture, Veterinary Science, Nutrition and Natural Resources 4, 1–18.

Birgersson, S., Moberg, Å., Björklund, A., Söderlund, L., 2009. Soy Milk- an Attributional Life Cycle Assessment Examining the Potential Environmental Impact of Soy Milk. Project report.

Carbon Offset Guide, 2021. Permanence - carbon offset Guide [WWW Document]. URL. https://www.offsetguide.org/high-quality-offsets/permanence/, 2.1.22.

Chadwick, D.R., 2005a. Emissions of ammonia, nitrous oxide and methane from cattle manure heaps: effect of compaction and covering. Atmos. Environ. 39, 787–799. https://doi.org/10.1016/j.atmosenv.2004.10.012.

Chadwick, D.R., 2005b. Emissions of ammonia, nitrous oxide and methane from cattle manure heaps: effect of compaction and covering. Atmos. Environ. 39, 787–799. https://doi.org/10.1016/J.ATMOSENV.2004.10.012.

Chai, B.C., van der Voort, J.R., Grofelnik, K., Eliasdottir, H.G., Klöss, I., Perez-Cueto, F.J. A., 2019. Which diet has the least environmental impact on our planet? A systematic review of vegan, vegetarian and omnivorous diets. Sustainability 11, 4110. https://doi.org/10.3390/su11154110.

Chaudhary, A., Marinangeli, C.P.F., Tremorin, D., Mathys, A., 2018. Nutritional combined greenhouse gas life cycle analysis for incorporating Canadian yellow pea into cereal-based food products, 2018 Nutrients 10. https://doi.org/10.3390/NU10040490, 490 10, 490.

Choudhary, A.K., Kumar, N., 2017. ENVIRONMENTAL IMPACT OF NON-VEGETARIAN DIET: AN OVERVIEW. International Journal of Engineering Sciences & Research Technology. https://doi.org/10.5281/zenodo.843908.

Clark, M.A., Domingo, N.G.G., Colgan, K., Thakrar, S.K., Tilman, D., Lynch, J., Azevedo, I.L., Hill, J.D., 2020. Global food system emissions could preclude achieving the 1.5 and 2 C climate change targets. Science 370 (6517), 705–708.

Costa, M.P., Chadwick, D., Saget, S., Rees, R.M., Williams, M., Styles, D., 2020a. Representing crop rotations in life cycle assessment: a review of legume LCA studies. Int. J. Life Cycle Assess. 25, 1942–1956. https://doi.org/10.1007/s11367-020-01812-x.

Costa, M.P., Chadwick, D., Saget, S., Rees, R.M., Williams, M., Styles, D., 2020b. Representing crop rotations in life cycle assessment: a review of legume LCA studies. Int. J. Life Cycle Assess. 1–15. https://doi.org/10.1007/s11367-020-01812-x.

Costa, M.P., Reckling, M., Chadwick, D., Rees, R.M., Saget, S., Williams, M., Styles, D., 2021. Legume-modified rotations deliver nutrition with lower environmental impact. Front. Sustain. Food Syst. 5, 656005 https://doi.org/10.3389/fsufs.2021.656005.

Dalgaard, R., Schmidt, J., Flysjö, A., 2014. Generic model for calculating carbon footprint of milk using four different life cycle assessment modelling approaches. J. Clean. Prod. 73, 146–153. https://doi.org/10.1016/j.jclepro.2014.01.025.

Davis, J., Sonesson, U., Baumgartner, D.U., Nemecek, T., 2010. Environmental impact of four meals with different protein sources: case studies in Spain and Sweden. Food Res. Int. 43, 1874–1884. https://doi.org/10.1016/J.FOODRES.2009.08.017.

Duffy, C., Prudhomme, R., Duffy, B., Gibbons, J., O'Donoghue, C., Ryan, M., Styles, D., 2022. GOBLIN version 1.0: a land balance model to identify national agriculture and land use pathways to climate neutrality via backcasting. Geosci. Model Dev. (GMD) 15, 2239–2264. https://doi.org/10.5194/GMD-15-2239-2022.

Durlinger, B., Koukouna, E., Broekema, R., van Paassen, M., Scholten, J., 2017. Agri-footprint 4.0.

Dyer, J.A., Worth, D.E., Vergé, X.P.C., Desjardins, R.L., 2020. Impact of recommended red meat consumption in Canada on the carbon footprint of Canadian livestock production. J. Clean. Prod. v266 https://doi.org/10.1016/j.jclepro.2020.121785.

Eshel, G., Shepon, A., Makov, T., Milo, R., 2014. Land, irrigation water, greenhouse gas, and reactive nitrogen burdens of meat, eggs, and dairy production in the United States. Proc. Natl. Acad. Sci. U.S.A. 111, 11996–12001. https://doi.org/10.1073/pnas.1402183111.

Eu-Fadn – Dg Agri, 2018. FADN Data - Set of Selected Farm Data Out of the Farm Accountancy Data. Network of the EU Commission (DG Agri).
European Commission (Directorate-General VI Agriculture), 1999. RICA2, ARACOST: A Program for Estimating Costs of Production of Arable Crops, 10 March 1999.
European Environmental Bureau, Pro, G.P., Commission, E., 2018. The EU product environmental footprint (PEF) methodology what can it deliver and what not. An NGO viewpoint 1–10.
Falcone, G., Iofrida, N., Stillitano, T., de Luca, A.I., 2020. Impacts of food and diets' life cycle: a brief review. In: Current Opinion in Environmental Science and Health. https://doi.org/10.1016/j.coesh.2019.12.002.
FAO, 2019. OECD-FAO Agricultural Outlook 2017-2026: MEATS - OECD-FAO Agricultural Outlook 2017-202.
FAO, 2018. Climate Change and the Global Dairy Cattle Sector – the Role of the Dairy Sector in a Low-Carbon Future. Rome. Rome.
Gerber, P.J., Steinfeld, H., Henderson, B., Mottet, A., Opio, C., Dijkman, J., Falcucci, A., Tempio, G., 2013. Tackling climate change through livestock: a global assessment of emissions and mitigation opportunities. In: Tackling Climate Change through Livestock: a Global Assessment of Emissions and Mitigation Opportunities.
Gilani, G.S., Lee, N., 2003. PROTEIN | sources of food-grade protein. In: Encyclopedia of Food Sciences and Nutrition. Elsevier, pp. 4873–4879. https://doi.org/10.1016/b0-12-227055-x/00834-8.
Godfray, H.C.J., Aveyard, P., Garnett, T., Hall, J.W., Key, T.J., Lorimer, J., Pierrehumbert, R.T., Scarborough, P., Springmann, M., Jebb, S.A., 2018. Meat Consumption, Health, and the Environment. Science, New York, N.Y.. https://doi.org/10.1126/science.aam5324
Goldstein, B., Hansen, S.F., Gjerris, M., Laurent, A., Birkved, M., 2016. Ethical aspects of life cycle assessments of diets. Food Pol. 59, 139–151. https://doi.org/10.1016/J.FOODPOL.2016.01.006.
GreenDelta, 2006. OpenLCA, Professional Life Cycle Assessment (LCA) and Footprint Software [WWW Document].
Hallström, E., Börjesson, P., 2012. Sustainable Meat Consumption to Meet Climate and Health Goals-Implications of Variations in Consumption Statistics. 8th International Conference on LCA in the Agri-Food Sector.
Heuzé, V., Tran, G., Kaushik, S., 2017. Feedpedia, A programme by inra, CIRAD, AFZ and FAO. Available at: https://feedipedia.org/.
Huppmann, D., Rogelj, J., Kriegler, E., Krey, V., Riahi, K., 2018. A new scenario resource for integrated 1.5 °C research. Nat. Clim. Change 8 (12 8), 1027–1030. https://doi.org/10.1038/s41558-018-0317-4, 2018.
IFASTAT, 2021. International fertilizer association [WWW Document]. URL. https://www.ifastat.org/, 1.30.22.
IPCC, 2019a. Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (Chapter 11).
IPCC, 2019b. Climate Change and Land. An IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems. Geneva.
IPCC, 2006. IPCC Guidelines for National Greenhouse Gas Inventories.
ISO14040, 2006. SO 14040:2006 - Environmental Management — Life Cycle Assessment — Principles and Framework.
Jensen, E.S., Peoples, M.B., Boddey, R.M., Gresshoff, P.M., Henrik, H.N., Alves, B.J.R., Morrison, M.J., 2011. Legumes for mitigation of climate change and the provision of feedstock for biofuels and biorefineries. A review. Agron. Sustain. Dev. 32 (2 32), 329–364. https://doi.org/10.1007/S13593-011-0056-7, 2011.
Joyce, A., Dixon, S., Comfort, J., Hallett, J., 2012. Reducing the environmental impact of dietary choice: perspectives from a behavioural and social change approach. Journal of Environmental and Public Health. https://doi.org/10.1155/2012/978672.
Knudsen, M.T., Hermansen, J.E., Olesen, J.E., Topp, C.F.E., Schelde, K., Angelopoulos, N., Reckling, M., 2014. Climate impact of producing more grain legumes in Europe. In: Proceedings of the 9th International Conference on Life Cycle Assessment in the Agri-Food Sector. Available at: https://www.opia.cl/601/articles-58891_archivo_01.pdf.
Krimly, T., Angenendt, E., Bahrs, E., Dabbert, S., 2016. Global warming potential and abatement costs of different peatland management options: a case study for the Pre-alpine Hill and Moorland in Germany. Agric. Syst. 145, 1–12. https://doi.org/10.1016/j.agsy.2016.02.00, 2016.
Leinonen, I., Iannetta, P.P.M., Rees, R.M., Russell, W., Watson, C., Barnes, A.P., 2019. Lysine supply is a critical factor in achieving sustainable global protein economy. Front. Sustain. Food Syst. 3, 1–11. https://doi.org/10.3389/fsufs.2019.00027.
Lienhardt, T., Black, K., Saget, S., Costa, M.P., Chadwick, D., Rees, R.M., Williams, M., Spillane, C., Iannetta, P.M., Walker, G., Styles, D., 2019. Just the tonic! Legume biorefining for alcohol has the potential to reduce Europe's protein deficit and mitigate climate change. Environ. Int. 130, 104870 https://doi.org/10.1016/j.envint.2019.05.064.
López, E.P., 2018. Improvement of the Functionality Soybean Okara by Simultaneous Treatment with High Hydrostatic Pressure and Food-Grade Enzymes. PhD thesis. Universidad Complutense de Madrid.
Lynch, H., Johnston, C., Wharton, C., 2018. Plant-based diets: considerations for environmental impact, protein quality, and exercise performance. Nutrients 10, 1841. https://doi.org/10.3390/nu10121841.
McLaren, S., Berardy, A., Henderson, A., Holden, N., Huppertz, T., Jolliet, O., de Camillis, C., Renouf, M., Rugani, B., 2021. Integration of Environment and Nutrition in Life Cycle Assessment of Food Items: Opportunities and Challenges. FAO. https://doi.org/10.4060/CB8054EN.
Mazzetto, A.M., Bishop, G., Styles, D., Arndt, C., Brook, R., Chadwick, D., 2020. Comparing the environmental efficiency of milk and beef production through life cycle assessment of interconnected cattle systems. J. Clean. Prod. 277, 124108 https://doi.org/10.1016/j.jclepro.2020.124108.
Misselbrook, T.H., Gilhespy, S.L., Cardenas, L.M., Williams, J., Dragosits, U., 2015. Inventory of Ammonia Emissions from UK Agriculture – 2014. Retrieved from. https://uk-air.defra.gov.uk/assets/documents/reports/cat07/1605231002_nh3inv2014_Final_20112015.pdf.
Moreno-Ruiz, E., Valsasina, L., Brunner, F., Symeonidis, A., FitzGerald, D., Treyer, K., Bourgault, G., Wernet, G., 2018. Documentation of Changes Implemented in Ecoinvent Data, 3.5. Zürich, Switzerland.
Nemecek, T., von Richthofen, J.S., Dubois, G., Casta, P., Charles, R., Pahl, H., 2008. Environmental impacts of introducing grain legumes into European crop rotations. Eur. J. Agron. 28, 380–393. https://doi.org/10.1016/J.EJA.2007.11.004.
Nguyen, T.L.T., Hermansen, J.E., Mogensen, L., 2010a. Environmental consequences of different beef production systems in the EU. J. Clean. Prod. 18, 756–766. https://doi.org/10.1016/j.jclepro.2009.12.023.
Nguyen, Thu Lan T., Hermansen, J.E., Mogensen, L., 2010b. Environmental consequences of different beef production systems in the EU. J. Clean. Prod. 18, 756–766. https://doi.org/10.1016/j.jclepro.2009.12.023.
Nijdam, D., Rood, T., Westhoek, H., 2012. The price of protein: review of land use and carbon footprints from life cycle assessments of animal food products and their substitutes. Food Pol. 37, 760–770. https://doi.org/10.1016/j.foodpol.2012.08.002.
Notarnicola, B., Sala, S., Anton, A., McLaren, S.J., Saouter, E., Sonesson, U., 2017. The role of life cycle assessment in supporting sustainable agri-food systems: a review of the challenges. J. Clean. Prod. 140, 399–409. https://doi.org/10.1016/j.jclepro.2016.06.071.
Peoples, M.B., Hauggaard-Nielsen, H., Huguenin-Elie, O., Jensen, E.S., Justes, E., Williams, M., 2019. The contributions of legumes to reducing the environmental risk of agricultural production. In: Agroecosystem Diversity: Reconciling Contemporary Agriculture and Environmental Quality, pp. 123–143. https://doi.org/10.1016/B978-0-12-811050-8.00008-X.
Poore, J., Nemecek, T., 2018. Reducing food's environmental impacts through producers and consumers. Science 360. https://doi.org/10.1126/science.aaq0216.
Petig, E., Rudi, A., Angenendt, E., Schultmann, F., Bahrs, E., 2018. Linking a farm model and a location optimization model for evaluating energetic and material straw valorization pathways - A case study in baden-wuerttemberg. GCB Bioenergy. https://doi.org/10.1111/gcbb.12580.
Petig, E., Choi, H.S., Angenendt, E., Kremer, P., Grethe, H., Bahrs, E., 2019. Downscaling of agricultural market impacts under bioeconomy development to the regional and the farm level - an example of Baden-Wuerttemberg. GCB Bioenergy 10 (8), 504. https://doi.org/10.1111/gcbb.12639.
Reckling, M., Hecker, J.M., Bergkvist, G., Watson, C.A., Zander, P., Schläfke, N., Stoddard, F.L., Eory, V., Topp, C.F.E., Maire, J., Bachinger, J., 2016a. A cropping system assessment framework—evaluating effects of introducing legumes into crop rotations. Eur. J. Agron. 76, 186–197. https://doi.org/10.1016/j.eja.2015.11.005.
Reckling, M., Bergkvist, G., Watson, C., Stoddard, F., Zander, P., Walker, R., Pristeri, A., Toncea, I., Bachinger, J., 2016b. Trade-offs between economic and environmental impacts of introducing legumes into cropping systems. Front. Plant Sci. 7 (669), 1–15.
Richi, E.B., Baumer, B., Conrad, B., Darioli, R., Schmid, A., Keller, U., 2016. Health Risks Associated with Meat Consumption: A Review of Epidemiological Studies, vol. 85, pp. 70–78. https://doi.org/10.1024/0300-9831/a000224.
Rosi, A., Mena, P., Pellegrini, N., Turroni, S., Neviani, E., Ferrocino, I., di Cagno, R., Ruini, L., Ciati, R., Angelino, D., Maddock, J., Gobbetti, M., Brighenti, F., del Rio, D., Scazzina, F., 2017. Environmental impact of omnivorous, ovo-lacto-vegetarian, and vegan diet. Sci. Rep. 7, 1–9. https://doi.org/10.1038/s41598-017-06466-8.
Saarinen, M., Fogelholm, M., Tahvonen, R., Kurppa, S., 2017. Taking nutrition into account within the life cycle assessment of food products. J. Clean. Prod. 149, 828–844. https://doi.org/10.1016/J.JCLEPRO.2017.02.062.
Saget, S., Costa, M., Barilli, E., Wilton de Vasconcelos, M., Santos, C.S., Styles, D., Williams, M., 2020. Substituting wheat with chickpea flour in pasta production delivers more nutrition at a lower environmental cost. Sustain. Prod. Consum. 24, 26–38. https://doi.org/10.1016/j.spc.2020.06.012.
Saget, S., Costa, M., Santos, C.S., Vasconcelos, M.W., Gibbons, J., Styles, D., Williams, M., 2021a. Substitution of beef with pea protein reduces the environmental footprint of meat balls whilst supporting health and climate stabilisation goals. J. Clean. Prod. 297, 126447 https://doi.org/10.1016/J.JCLEPRO.2021.126447.
Saget, S., Costa, M., Styles, D., Williams, M., 2021b. Does circular reuse of chickpea cooking water to produce vegan mayonnaise reduce environmental impact compared with egg mayonnaise?, 2021 Sustainability 13, 4726. https://doi.org/10.3390/SU13094726, 4726 13.
Saget, S., Porto Costa, M., Santos, C.S., Vasconcelos, M., Styles, D., Williams, M., 2021c. Comparative life cycle assessment of plant and beef-based patties, including carbon opportunity costs. Sustain. Prod. Consum. 28, 936–952. https://doi.org/10.1016/J.SPC.2021.07.017.
SBTi, 2021. SBTI corporate NET-zero standard [WWW Document]. URL. https://sciencebasedtargets.org/net-zero, 2.1.22.
Schaubroeck, T., Schaubroeck, S., Heijungs, R., Zamagni, A., Brandão, M., Benetto, E., 2021. Attributional & consequential life cycle assessment: definitions, conceptual characteristics and modelling restrictions, 2021 Sustainability 13, 7386. https://doi.org/10.3390/SU13137386, 7386 13.
Schmidt, J., Merciai, S., Muñoz, I., de Rosa, M., Astudillo, M.F., 2021. The Big Climate Database. V1 - Methodology Report. 2.-0 Consultants. Denmark.
Schmidt, J.H., 2008a. System delimitation in agricultural consequential LCA: outline of methodology and illustrative case study of wheat in Denmark. Int. J. Life Cycle Assess. 13, 350–364. https://doi.org/10.1007/s11367-008-0016-x.
Schmidt, J.H., 2008b. System delimitation in agricultural consequential LCA. Int. J. Life Cycle Assess. 13, 350–364. https://doi.org/10.1007/s11367-008-0016-x.

Schmidt, J.H., Weidema, B.P., 2008. Shift in the marginal supply of vegetable oil. Int. J. Life Cycle Assess. 13, 235–239. https://doi.org/10.1065/lca2007.07.351.

Searchinger, T.D., Wirsenius, S., Beringer, T., Dumas, P., 2018. Assessing the efficiency of changes in land use for mitigating climate change. Nature 564, 249–253. https://doi.org/10.1038/s41586-018-0757-z.

Springmann, M., Godfray, H.C.J., Rayner, M., Scarborough, P., 2016. Analysis and valuation of the health and climate change cobenefits of dietary change. Proc. Natl. Acad. Sci. U.S.A. 113, 4146–4151. https://doi.org/10.1073/pnas.1523119113.

Stark, C., Thompson, M., Andrew, T., Beasley, G., Bellamy, O., Budden, P., Cole, C., et al., 2019. Net Zero: The UK's contribution to stopping global warming.

Steffen, W., Richardson, K., Rockström, J., Cornell, S.E., Fetzer, I., Bennett, E.M., Biggs, R., Carpenter, S.R., de Vries, W., de Wit, C.A., Folke, C., Gerten, D., Heinke, J., Mace, G.M., Persson, L.M., Ramanathan, V., Reyers, B., Sörlin, S., 2015. Planetary boundaries: guiding human development on a changing planet. Science 347. https://doi.org/10.1126/SCIENCE.1259855/SUPPL_FILE/STEFFEN-SM.PDF.

Styles, D., Gibbons, J., Williams, A.P., Dauber, J., Stichnothe, H., Urban, B., Chadwick, D. R., Jones, D.L., 2015. Consequential life cycle assessment of biogas, biofuel and biomass energy options within an arable crop rotation. GCB Bioenergy 7, 1305–1320. https://doi.org/10.1111/gcbb.12246.

Styles, D., Gonzalez-Mejia, A., Moorby, J., Foskolos, A., Gibbons, J., 2018. Climate mitigation by dairy intensification depends on intensive use of spared grassland. Global Change Biol. 24, 681–693. https://doi.org/10.1111/gcb.13868.

Sonesson, U., Davis, J., Flysjö, A., Gustavsson, J., Witthöft, C., 2017. Protein quality as functional unit – a methodological framework for inclusion in life cycle assessment of food. J. Clean. Prod. 140, 470–478. https://doi.org/10.1016/j.jclepro.2016.06.115.

Soteriades, A.D., Gonzalez-Mejia, A.M., Styles, D., Foskolos, A., Moorby, J.M., Gibbons, J.M., 2018. Effects of high-sugar grasses and improved manure management on the environmental footprint of milk production at the farm level. J. Clean. Prod. 202, 1241–1252. https://doi.org/10.1016/J.JCLEPRO.2018.08.206.

The Health Council of the Netherlands, 2001. The health Council of The Netherlands, 2001. In: Voedingsnormen energie, eiwitten, vetten en verteerbare koolhydraten (in Dutch: Reference intakes for energy, protein, fat and digestible carbohydrates).

True legumes, 2021. WP6: an economic assessment of sustainable and profitable legume production and consumption - TRUE project [WWW Document]. D.6.3 Scenarios for upscaling production, including economic and trade indicators. URL. https://www.true-project.eu/work-packages/economics-of-sustainable-and-profitable-legume-production-and-consumption/, 3.23.22.

UNFCCC, 2015. In: The Conference of the Parties: Report of the Conference of the Parties on its Twenty-First Session Held in Paris from 30 November to 13 December 2015 [WWW Document]. https://unfccc.int/sites/default/files/resource/docs/2015/cop21/eng/10a01.pdf.

Weiss, F., Leip, A., 2012. Greenhouse gas emissions from the EU livestock sector: a life cycle assessment carried out with the CAPRI model. Agric. Ecosyst. Environ. 149, 124–134. https://doi.org/10.1016/j.agee.2011.12.015.

Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., Weidema, B., 2016. The ecoinvent database version 3 (part I): overview and methodology. Int. J. Life Cycle Assess. 21 (9), 1218–1230. https://doi.org/10.1007/S11367-016-1087-8, 2016.

Westhoek, H., Lesschen, J.P., Leip, A., Rood, T., Wagner, S., De Marco, A., Murphy-Bokern, D., Pallière, C., Howard, C.M., Oenema, O., Sutton, M.A., 2015. Nitrogen on the Table: the Influence of Food Choices on Nitrogen Emissions and the European Environment. (European Nitrogen Assessment Special Report on Nitrogen and Food.). Centre for Ecology & Hydrology, Edinburgh, UK.

Willett, W., Rockström, J., Loken, B., Springmann, M., Lang, T., Vermeulen, S., Garnett, T., Tilman, D., DeClerck, F., Wood, A., Jonell, M., Clark, M., Gordon, L.J., Fanzo, J., Hawkes, C., Zurayk, R., Rivera, J.A., de Vries, W., Majele Sibanda, L., Afshin, A., Chaudhary, A., Herrero, M., Agustina, R., Branca, F., Lartey, A., Fan, S., Crona, B., Fox, E., Bignet, V., Troell, M., Lindahl, T., Singh, S., Cornell, S.E., Srinath Reddy, K., Narain, S., Nishtar, S., Murray, C.J.L., 2019. Food in the Anthropocene: the EAT–Lancet Commission on healthy diets from sustainable food systems. Lancet 393, 447–492. https://doi.org/10.1016/S0140-6736(18)31788-4.

Zander, P., Amjath-Babu, T.S., Preissel, S., Reckling, M., Bues, A., Schläfke, N., Kuhlman, T., Bachinger, J., Uthes, S., Stoddard, F., Murphy-Bokern, D., Watson, C., 2016. Grain Legume Decline and Potential Recovery in European Agriculture: a Review. Agronomy for Sustainable Development. https://doi.org/10.1007/s13593-016-0365-y.

Zimmermann, B., Krimly, T., Barrios, Oré, Angenendt, E., Lippert, C., Gamer, W., Petig, E., Bahrs, E., Shresta, S., Toma, L., 2020. Definition of Sustainability Indicators for WP8. A Confidential (Consortium Only) Deliverable (D) 6.1 (D36) for the EU-H2020 Project, 'TRansition Paths to sUstainable Legume-Based Systems in Europe' (TRUE), Which Is Funded Grant Agreement Number 727973.