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Substitution of beef with pea protein reduces the environmental footprint of meat balls whilst supporting health and climate stabilisation goals

Sophie Saget [a, *], Marcela Costa [b], Carla Sancho Santos [c], Marta Wilton Vasconcelos [c], James Gibbons [b], David Styles [d], Michael Williams [a]

[a] Department of Botany, School of Natural Sciences, Trinity College Dublin, Dublin, 2, Ireland
[b] School of Environment, Natural Resources and Geography, Bangor University, Bangor, Wales, UK
[c] Catholic University of Portugal, Porto, Portugal
[d] School of Engineering, University of Limerick, Limerick, Ireland

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ABSTRACT

Recent environmental footprint comparisons between meat and plant-based meat analogues do not consider nutritional density holistically, nor the high carbon opportunity costs (COC) of land requirements, which are critical in terms of climate stabilisation targets. We performed an attributional life cycle assessment (LCA) of a 100 g serving of cooked protein balls (PPBs) made from peas (*Pisum sativum*), and Swedish-style beef meatballs (MBs) made from Irish or Brazilian beef. Per serving, PPB production and consumption was associated with lower environmental burdens across all 16 categories assessed. Global warming, acidification, and land use burdens of PPBs were at least 85%, 81%, and 89% smaller, respectively, than MBs. The scale of environmental advantage was sensitive to the allocation method, with biophysical allocation across cattle co-products decreasing MB burdens by at least 35%, 38%, and 46% in the acidification, climate change, and land use categories, respectively. Furthermore, PPBs have a higher nutritional density than MBs, and hence their environmental footprint per unit of nutrition was considerably lower across all 16 impact categories. Per Nutrient Density Unit, global warming, acidification, and land use burdens of PPBs were at least 89%, 87%, and 93% smaller, respectively, than MBs. Results were tested with Monte Carlo simulations and a modified null hypothesis significance test, which supported the main findings. Finally, when COC of land was factored in, the climate advantage of PPBs extended greatly. Assuming MBs equivalent to just 5% of German beef consumption are replaced by PPBs, total carbon savings including COC could amount to 8 million tonnes CO_2e annually, an amount equal to 1% of Germany's annual GHG emissions. Therefore, this study highlights the potential of PPBs to meet health and climate neutrality objectives.

1. Introduction

The European Union set a target in September 2020 to become the first climate-neutral continent by 2050, and achieve a 55% reduction of net GHG emissions by 2030 from 1990 levels (European Commission, 2020a). The food sector is currently responsible for 26% of total GHG emissions worldwide (Crippa et al., 2021), and is therefore a key area in which finding sustainable alternatives is crucial to mitigate the associated environmental footprint. Furthermore, food production dominates global land use, in competition with alternative land uses such as forestry that are increasingly being promoted to address biodiversity and climate crises (Arneth et al., 2019). At the same time, European diets differ from national dietary recommendations, resulting in more than 50% of individuals being overweight and more than 20% obese (WHO, n.d.). The Farm to Fork strategy is at the centre of the European Green deal, and aims to build “fair, healthy and environmentally-friendly food systems” (European Union, 2020). Delivering nutrition with a minimal environmental impact on the environment is therefore key.

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* Corresponding author.
E-mail address: sagets@tcd.ie (S. Saget).

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Nomenclature

NDU	Nutrient Density Unit
EFA	Amount of essential fatty acids in 100 g of product (grams)
EoL	End of Life
Prot	Amount of protein in 100 g of product (grams)
Fib	Amount of fibre in 100 g of product (grams)
DV_{EFA}	Recommended daily value intake of essential fatty acids (grams)
DV_{prot}	Recommended daily value intake of protein (grams)
DV_{fib}	Recommended daily value intake of fibre (grams)
S_i	Amount of kilocalories in 100 g of product (kcal)
PPB	Pea protein ball
MB (BR)	Meatball (Brazilian beef)
MB (IE)	Meatball (Irish beef)
FU	Functional unit
HH	Human health
RU	Resource use

The excessive production and consumption of meat, especially beef, is of significant concern globally, driving major environment damage (Eshel et al., 2014; Poore and Nemecek, 2018) and, in industrialised countries, negative health outcomes through overconsumption (Godfray et al., 2018; Rust et al., 2020). The EAT-Lancet Commission 'planetary healthy' diet recommends an intake of red meat not exceeding 28 g a day, representing at most around 10 kg of red meat per person per year (Willett et al., 2019). Current red meat consumption is nearly four times higher than this in developed countries, at more than 39 kg retail weight per capita annually (FAO, 2019a). Furthermore, intake of processed meat is 90% higher than recommended globally (Afshin et al., 2019). High red meat consumption has been linked with increased risk of several chronic diseases (type 2 diabetes, gestational diabetes, coronary heart disease, heart failure, stroke, and cancer) and an increased death rate (Larsson and Wolk, 2006; Norat et al., 2005; Pan et al., 2012; van Dooren et al., 2014; Wolk, 2017). Some types of meat processing and cooking result in the formation of carcinogenic chemicals, and red meat consumption has been categorised as "probably carcinogenic to humans" (Bouvard et al., 2015). Other issues related to meat include the global antimicrobial resistance crisis catalysed by the improper use of antibiotics in the meat industry (Spellberg et al., 2016) and meat adulteration (Ali et al., 2015; Rahman et al., 2014). Limiting the consumption of processed and unprocessed red meat is now advised by several authoritative bodies (Richi et al., 2015; Willett et al., 2019).

From an environmental perspective, pasture-based beef production can enhance carbon sequestration in soils and improve nitrogen availability for plants (Henderson et al., 2015). However, these benefits are at best counterbalanced by the substantial greenhouse gas (GHG) emissions and losses of reactive nitrogen (N) to air and water from beef production. Beef production is an important source of methane emission globally, through the processes of enteric fermentation during feed digestion and manure management (Godfray et al., 2018). It is also an important source of ammonia and nitrous oxide from manure management and fertilisation, and carbon dioxide from manufacture of fertilisers, combustion of fuels, and feed production (Beauchemin et al., 2009; Chadwick, 2005; Nguyen et al., 2010). In addition to GHG emissions, extensive grazing and feed demand in particular drive deforestation, biodiversity loss, water pollution, nutrient leakage and land degradation (Godfray et al., 2018; Steinfeld et al., 2006). Cattle rearing is an inefficient way to provide calories and protein nutrition to humans (Shepon et al., 2016).

Substituting meat protein with plant protein in the human diet, in particular legumes, has the potential to significantly improve the sustainability of food systems (Jensen et al., 2012; McCrory et al., 2010; Peoples et al., 2019; Wagner, 2011). Legumes, including peas, fix atmospheric N through their symbiotic relationship with rhizobia in their roots, therefore do not necessitate the addition of synthetic N fertiliser (Stagnari et al., 2017; Wagner, 2011; Westhoek H. et al., 2016). A study by Harwatt et al. (2017) showed that replacing beef calories and protein intake by grain legume consumption in the United States would accomplish between half to three quarters of the 2020 GHG emissions reduction target and free nearly half of US cropland. However, consumers are reluctant to reduce meat consumption (Macdiarmid et al., 2016). Indeed, global diets have changed considerably since the 1960s. More calories are being consumed per person, and the proportion of fat and animal protein consumed has increased significantly with wealth. In contrast, the consumption of plant protein has remained static with increasing GDP. This has led to a marked decline in the healthiness of diets as personal wealth increases (Williams et al., 2020).

Current legume consumption in Europe represents just 1% of daily energy intake (FAO, 2019b; Williams et al., 2020). However, the growth of innovative legume-based food products that emulate meat products in terms of flavour and texture offers a potential sustainable diet transition that requires little consumer effort while meeting protein demand. The popularity of these products is increasing worldwide, and the meat substitute market is expected to reach USD 140 billion by 2029, ten times higher than IGV, 2019 (Statista, 2019). One such substitute product is the plant-based 'meatball.' Meatballs are a popular dish globally, and countries have their own variations in terms of key ingredients that typically include beef, veal, pork, spices, and breadcrumbs. In 2015, IKEA sold 2.9 million Swedish-style meatballs every day (IKEA, 2015). Our study is the first LCA of vegetarian protein balls, a meat alternative that has fewer processed ingredients than meatless burger patties, and are hence potentially healthier. Further, this study evaluates environmental impacts in terms of nutrition provided, and carbon opportunity costs.

Existing literature has evaluated the comparative environmental footprints of some legume and beef products. Smetana et al. (2015) compared the environmental footprints of common meat substitutes, using mass, energy, and protein functional units (FU), while Zhu and Van Ierland (2003) used a protein FU only. Davis et al. (2010) compared the environmental impacts of different protein sources using a meal as a FU. Mejia et al. (2020) compared the environmental impact of producing 57 different meat analogues, looking at GHG emissions only and using weight was a FU. However, the use of FUs that take into account more complete aspects of nutrition has not been used in LCA studies of meat analogues. Considering the prevalence of current Western diets that are nutrient-poor and energy-rich, with a high consumption of meat products, the surge in popularity of meat analogues, and the lack of correlation between nutrient content and environmental impact of foods (Saarinen et al., 2017), using a FU that integrates several nutrients is key to assess the sustainability of meat analogues versus meat. Sustainable nutrition is evaluated in this study through the use of the Nutrient Density Unit as a FU, as first proposed by Van Dooren (2016) and used in Saget et al. (2020). This FU allows the comparison of different types of protein balls on a basis of what modern diet formulations focus on: environmental sustainability and nutrition (Donati et al., 2016; Lawrence et al., 2015; Willett et al., 2019).

Beef from contrasting global export regions is considered to represent trade in these food commodities. However, the recent free trade agreement with the Mercosur is likely to compromise the achievement of carbon reduction targets, due to illegal deforestation that may contaminate the increased EU imports of Brazilian beef (Rajão et al., 2020). At present, Brazilian beef already represents up to 40% of European beef imports (Askew, 2020), with 200,000 tonnes of beef imported from the Mercosur every year (European Commission, 2020b). Germany is a major importer of Brazilian beef. IGV, 2019, the country imported 12.9 thousand tonnes of boneless meat of Brazilian bovine animals, fresh, chilled, or frozen, for a value of 89.1 million dollars (United Nations, 2020). The production of animal-based food also represents a substantial carbon opportunity cost (COC), due to the potential of carbon sequestration by land restoration (Hayek et al., 2020).

This study goes beyond the scope of previous food footprint comparisons to explore the consequences of different land requirements in the context of targets for Net Zero GHG emissions in the second half of this century (Masson-Delmotte et al., 2019), using the carbon opportunity cost method recently proposed by Searchinger et al. (2018).

2. Materials and methods

2.1. Goal, scope, and boundary definition

This study is a comparative assertion of the overall environmental impacts arising from consumption of Pea Protein Balls (PPBs) produced in Germany with conventional beef meatballs (MBs) produced in Germany using Brazilian (BR) or Irish (IE) beef, accounting for their respective nutritional values. The aim was to assess the relative advantages and disadvantages of the three products by performing an attributional LCA. The open source software OpenLCA v1.10.2 (GreenDelta, 2020) was used to calculate the environmental footprint of the three products from cradle to fork, using Agri-footprint v3.0 (Durlinger et al., 2017) and Ecoinvent v3.6 (Wernet et al., 2016) international databases. Agri-footprint (Durlinger et al., 2017) is a life cycle inventory database specialised in the food and agricultural sector, and Ecoinvent v3.6 (Wernet et al., 2016) is a life cycle inventory database covering extensively numerous fields (electricity generation, chemicals production, recycling, agricultural processes, etc.). In accordance with the ILCD handbook (JRC, 2010), identical product use and patterns were analysed, and the same life cycle stages were included. Packaging recycling was excluded from the system boundaries, as it was assumed to be similar in both cases. Primary data on the German PPBs were collected from IGV GmbH, a company specialising in food and feed processing located in the Potsdam-Mittelmark district (IGV, accessed 12/2019). Data on processing of beef and other ingredients to produce the MBs were adapted from Biswas and Naude (2016) and modelled as though the beef meatballs were produced in Germany, to align with the PPB geographical production.

As nutritional delivery is a key function of food, two FUs were used: a serving-based FU, 100 g cooked protein balls, and a nutritional FU, the Nutrient Density Unit (NDU) (Van Dooren, 2016) of cooked protein balls. Both economic and physical allocation was performed for beef co-products and pea co-products. Biophysical allocation, which allocates burdens to co-products based on their metabolic energy requirements, was also performed for MBs (BR and IE) as a sensitivity analysis. The aim of biophysical allocation is to allocate based on physical and causal relationships between co-products, to offer an alternative to economic allocation, since the latter can be subject to market fluctuations (Sandin et al., 2015). Physical allocation based on mass was performed for the pea dehulling and fractionation co-products in PPBs as a comparison.

Fig. 1 illustrates the system boundaries and manufacturing steps for the cradle to fork assessment of PPBs and MBs (BR and IE). The LCA methodology followed the Product Environmental Footprint (PEF) guidelines (European Commission, 2018) for the agricultural, distribution (40% distributed in Germany, 40% in Europe, and 20% outside Europe), storage and cooking stages. End of Life (EoL) was excluded from the boundaries, as it was considered to be the same across all products. Environmental impacts of the three alternatives were compared across sixteen environmental impact categories recommended in PEF guidelines (European Commission, 2018). Results were then normalised using global per person environmental loadings recommended in the PEF guide. This was done to facilitate interpretation of impact scores.

A Monte Carlo analysis with 1000 runs was performed in OpenLCA v1.10.2 (GreenDelta, 2020) for each of the three products across all sixteen categories for all scenarios: baseline, NDU FU, no beef transport, and biophysical allocation. The majority of parameters used an underlying lognormal distribution but in some places the default normal distribution was used. The negative Monte Carlo results were set to zero, as advised by Muller et al. (2016). A modified Null Hypothesis Significance Test (NHST), as presented in Mendoza Beltran et al. (2018) was implemented, after being identified as the most appropriate uncertainty statistics method for interpreting our propagated uncertainty LCA outcomes. The hypothesis “the different production systems delivering protein balls are associated with different environmental impacts” was tested statistically. The null hypothesis tested assumed that the environmental impacts of the inventory of the different production systems were equal. We applied the Bonferroni correction of the significance level to exclude false positives, as $\alpha_b = 0.05/48 = 0.001042$. The 48 factor stands for the sixteen environmental impact categories and for the three pairs of alternatives. All threshold values were tested with an effect size (δ_0) of 0.2. The results that were consistent across all scenarios were recorded.

2.2. Nutrient density unit functional unit

The Nutrient Density Unit (NDU) FU was applied following Van Dooren (2016) formula (1).

$$\mathrm{NDU} = \frac{\left(\frac{EFA}{\mathrm{DV_{EFA}}}\right) + \left(\frac{Prot}{\mathrm{DV_{prot}}}\right) + \left(\frac{Fib}{\mathrm{DV_{fib}}}\right)}{3 \times \left(\frac{S_i}{2000\ \mathrm{kcal}}\right)} \tag{1}$$

where:

EFA is the amount of essential fatty acids in 100 g of product, expressed in grams.

Protein is the amount of protein in 100 g of product, expressed in grams.

Fibre is the amount of fibre in 100 g of product, expressed in grams.

DV_{EFA} is the recommended daily value intake of essential fatty acids, 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 amount of kilocalories in 100 g of product, expressed in kilocalories.

Nutritional data for PPBs and MBs (BR and IE) were obtained from analyses undertaken by the Catholic University of Porto (Portugal). Details of the nutritional analysis method are recorded in Section 1 of the Appendix. The nutritional composition for MBs and PPBs and calculated NDUs of cooked PPBs and MBs (IE and BR)

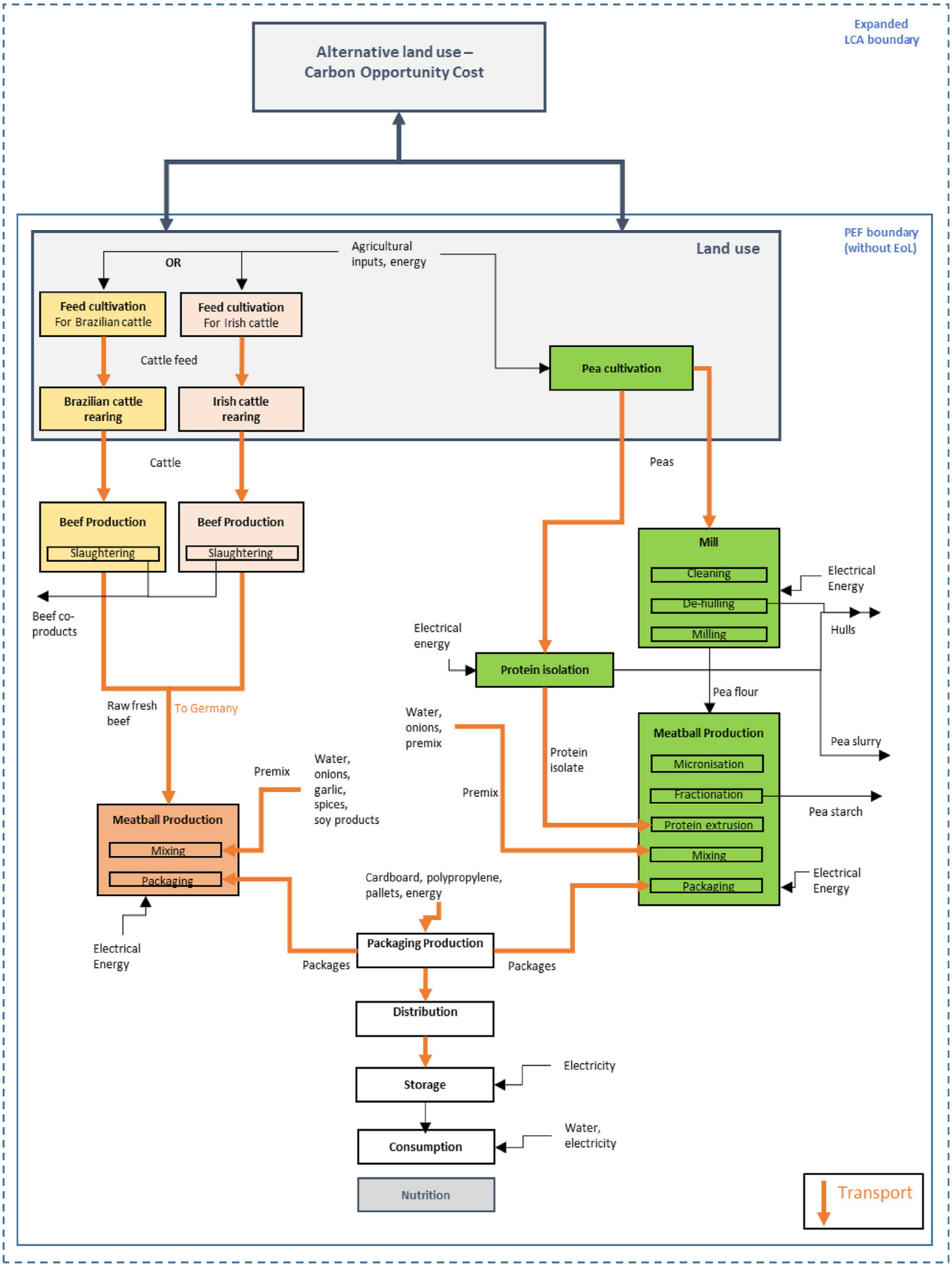

Fig. 1. System boundary of pea protein balls and Swedish-style beef meatballs (from Irish or Brazilian beef) production, from cradle to fork. Expanded boundary includes carbon opportunity cost of land that could be used for alternative purposes such as forestry to meet Net Zero GHG targets.

are recorded in Table 1. The simplicity of the NDU is a major advantage, requiring few nutritional analyses when compared with more extensive FUs, such as the Nutrient Rich Foods index 11.3 (Fulgoni et al., 2009), while still correlating with them (Saget et al., 2020).

Even though net protein assimilation is similar amongst adults regardless of whether the protein comes from plants or animals (WHO, 2007), and PPBs and MBs are present in countries in which protein is not a limiting nutrient, we calculated the NDU of PPB with adjusted protein digestibility, assuming all protein in the PPBs come from peas for simplicity. The protein digestibility of pea protein concentrate is 92% (Gilani and Lee, 2003), which makes the

Table 1
Summary of nutritional composition and Nutrient Density Units of pea protein balls and Swedish-style beef meatballs (from Irish or Brazilian beef) cooked, per 100 g.

Content per 100 g cooked	PPBs	MBs (BR and IE)
Energy (kcal)	209	240
Protein (g)	22.33	17.5
Dietary fibre (g)	1	2
EFAs (g)	1.6	0.6
NDU	1.96	1.33
NDU (adjusted)	1.85	NA

amount of protein available in the PPB 20.5 g per 100 g cooked PPBs, versus 22.33 g when not adjusted. The resulting NDU of adjusted protein digestibility for PPBs is 1.85, versus 1.96 for PPBs when protein digestibility was not accounted for, as shown in Table 1.

2.3. Pea protein balls and meatballs inventory

The three products assessed in this study are shown in Fig. 2: Pea Protein Balls (PPB) made in Germany with German peas, Swedish-style meatballs made in Germany with Brazilian beef (MB (BR)), and Swedish-style meatballs made in Germany with Irish beef (MB (IE)). These products reflect globally important and contrasting beef systems that supply export markets, to Germany and beyond. Brazil is the largest global exporter of beef, and Brazilian beef systems are diverse but dominated by low-input, low-output production across vast areas of degraded pastures. Meanwhile, Irish beef systems based on productive pastures with grazing through most of the year are considered to be amongst the most sustainable beef systems in Europe, with comparatively low carbon footprints (Leip et al., 2010). Irish beef cattle can be completed on grass with minimum concentrate feed inputs (Teagasc, 2020), and may be awarded a protected geographical indication status in Europe as “Irish grass-fed beef” (The Irish Times, 2020). Over 90% of Irish beef produced is exported, largely into the rest of Europe.

To assess water scarcity, Ecoinvent v3.5 electricity mixes (Wernet et al., 2016) were used instead of those of v3.6, due to an identified issue with the latter. Unrealistic water scarcity burdens were otherwise associated to the electricity use, as AWARE from EF method (adapted) was associating global water scarcity factors to the input water flows, and regional water scarcity factors to the output water flows. Instead, X and -X factors would normally to be attributed to input and output water flows for electricity (hydropower), respectively, as in Ecoinvent v3.5 (Wernet et al., 2016). Full recipes of the PPBs and MBs were recorded in Section 2 of the Appendix. Inputs and outputs for all processes involved in the life cycle of 100 g of cooked MBs and PPBs, from cradle to fork, were recorded and are included in full in Section 3 of the Appendix. MBs were made of beef, onions, garlic, vegetable oil, salt, soy protein, and water. Further details on the MBs inventory were recorded in Section 4 of the Appendix. PPBs were made of peas, potato starch, sugar, chives, onions, paprika, cornflakes, salt, and water. Production of PPBs included dehulling, milling, micronisation, fractionation, and extrusion. All details on the PPBs inventory were recorded in Section 5 of the Appendix. Geographical locations for all steps from cattle rearing to sale of final products are recorded in Fig. 2. Transport distances were modelled following PEF guidelines, include sea-transport distance calculations (Searates, accessed 01/2020). As mentioned above, the scenario MB (BR) is likely to take place in reality, due to Brazil being a major beef exporter to Germany, and the probability of this scenario happening will increase with the recent trade agreement between the Mercosur and the EU. Nevertheless, a sensitivity analysis was performed to assess the importance of transport of beef in the life cycle of MB (IE and BR).

2.4. Carbon opportunity cost calculations

The COC factors of crops and livestock used in this study were extracted from the carbon loss method presented in Searchinger et al. (2018), and were applied to the recipe ingredients for the PPBs and MBs recorded in Tables A1 and A2 of the Appendix. The carbon loss method calculates the COC with the global carbon loss from native vegetation and soils caused by producing a certain crop and divides it by the global annual production of this crop. The ingredients’ COC were then summed proportionally to match the recipes. The COC for a 100 g serving and for one NDU of MBs and PPBs was multiplied by the corresponding factors to match the economic or physical allocation approaches. These were added to the production GHG emissions, and reported as a separated COC-inclusive GWP footprint.

Following the extrapolation scenario in which it is assumed that 5% of the beef consumed in Germany is processed into MBs, the COC involved with the consumption of MBs was determined using the COC calculation described above. This COC was multiplied by the average beef consumption per capita in Germany and the German population. To this was added the COC of the corresponding amounts of other ingredients to make the MBs. The COC was also calculated for an equal weight of PPBs using the same approach in order to calculate the potential COC saving associated with a simple 5% substitution of beef, in the form of MBs, with PPBs.

3. Results

3.1. General results

Across all scenarios, the burdens of PPBs were statistically significantly lower than those of MBs (IE and BR) across the

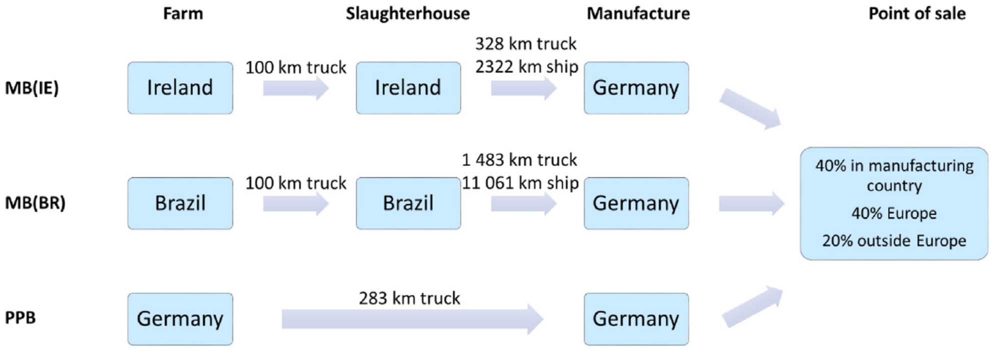

Fig. 2. Geographical locations where steps across the life cycle of pea protein balls and Swedish-style meatballs (with Brazilian or Irish beef) take place. The percentages in the point of sale step represent the portion of total products sold around the world.

acidification, climate change, marine and terrestrial eutrophication, land use, photochemical ozone formation, resource use energy carriers and minerals and metals, and respiratory inorganics categories. The modified NHST results with the Bonferroni correction common to all scenarios were recorded in Table A8 of the Appendix. All Monte Carlo simulations and modified NHST results were recorded in the Microsoft Excel workbooks in the Supplementary Data.

The economically-allocated environmental impact results for the sixteen categories are recorded in Table 2. The results per 100 g cooked MBs (BR and IE) and PPBs, and per NDU are shown. In terms of 100 g cooked balls, the PPBs have the lowest environmental burdens across all impact categories, irrespective of whether the beef comes from Ireland or from Brazil. The environmental burdens of PPBs were statistically significantly lower than those of MBs across 11 categories out of 16 when comparing PPBs to MBs (IE), and across 12 categories out of 16 when comparing PPBs to MBs (BR) (Supplementary Data). In terms of climate change, land use, and eutrophication, the impact of MBs (IE) is between 4 and 34 times that of PPBs, and for MBs (BR), it is between 3 and 31 times that of PPBs (Table 2). Brazilian beef meatballs were shown to perform better than those from Irish beef across 11 out of 15 categories, including resource use energy carriers, and the three eutrophication categories. However, MB (BR) was associated with 40% more GHG emissions than MB (IE).

Relative results normalised per person equivalents per NDU are recorded in Fig. 3. Besides the commonly highlighted higher climate change and land use burdens involved with beef production, this study provided a larger overview of the other relative impacts on the environment. Notably, the comparatively higher marine (53% higher than a serving of MB with Brazilian beef) and terrestrial (3.4 times higher than a serving of MB with Brazilian beef) eutrophication involved with beef production in Ireland, as well as acidification (2.9 times higher than a serving of MB with Brazilian beef) and respiratory inorganics (3.1 times higher than a serving of MB with Brazilian beef). These four categories were the ones with the higher person equivalent burdens, with 100 g of MB (IE) corresponding to 0.1%, 0.2%, 0.1%, and 0.1% of an average person's annual marine eutrophication, terrestrial eutrophication, acidification, and respiratory inorganics impacts, respectively. The main reasons for this marine eutrophication burden lie in the nitrate emissions from grass cultivation and grazing (75% of total impact). The terrestrial eutrophication burden is mainly due to ammonia emission from cattle (43% of total impact) and from grass cultivation and grazing (45% of total impact). The acidification burden is due to ammonia emission from cattle (41% of total impact) and from grass cultivation and grazing (43% of total impact). Finally, the respiratory inorganics burdens are due to ammonia emissions from cattle (40% of total impact) and from grass cultivation and grazing (42% of total impact).

The results of the sensitivity scenario in which transport of beef was excluded was recorded in Table A9 of the Appendix. The environmental burdens associated with beef transport were not large enough to substantially reduce their difference from PPBs, excepted for in the water scarcity category (Supplementary Data). Ignoring the transport burdens reduced the climate change burden of MB (IE) by 1% and of MB (BR) by 2%. There was also a reduction between 1 and 8% across other impact categories, and an ozone depletion burden reduction of 18% for the MB (BR).

Per NDU, the differences between the PPBs and the MBs increased, as the NDU of PPBs was 19% higher than the NDU of MBs

Table 2
Summary of economically-allocated environmental burdens for pea protein balls, meatballs (Brazil), and meatballs (Ireland), expressed per 100 g cooked product and per Nutrient Density Unit.

From smallest (1) to largest (3) environmental burden: 1 □ 2 ▒ 3 ▓

Impact category	Unit	Impact per serving			Impact per NDU			
		PPB	MB(IE)	MB(BR)	PPB	MB(IE)	MB(BR)	PPB (adj)
Acidification ter. & freshwater	mol H^+ eq	0.0034	0.070	0.018	0.0017	0.052	0.013	0.0018
Cancer human health	CTUh	1.1E-08	5.0E-08	7.9E-07	5.4E-09	3.7E-08	5.9E-07	5.75E-09
Climate change (w/o COC)	kg CO_2 eq	0.5	3.3	4.6	0.27	2.5	3.4	0.29
Climate change + COC	kg CO_2 eq	1.1	13.4	14.7	0.5	10.1	11.1	0.6
Ecotoxicity freshwater	CTUe	1.1	5.7	271	0.55	4.3	203.4	0.58
Eutrophication freshwater	kg P eq	0.0003	0.0012	0.0008	0.0002	0.0009	0.0006	0.0002
Eutrophication marine	kg N eq	0.0013	0.029	0.019	0.0007	0.021	0.014	0.0007
Eutrophication terrestrial	mol N eq	0.0088	0.30	0.067	0.004	0.22	0.05	0.005
Ionising radiation, HH	kBq U^{235} eq	0.17	0.30	0.30	0.08	0.23	0.23	0.090
Land use	Points	38	354	1186	19.6	266.3	891.4	20.8
Non-cancer human health	CTUh	6.6E-07	2.3E-06	4.2E-04	3.4E-07	1.8E-06	3.2E-04	3.58E-07
Ozone depletion	kg CFC-11 eq	6.5E-08	9.1E-08	1.1E-07	3.3E-08	6.8E-08	8.5E-08	3.50E-08
Photochem. ozone form.	kg NMVOC eq	0.0014	0.0076	0.0055	0.00072	0.0057	0.0041	0.0008
Resource use, energy carriers	MJ	8.6	19.8	15.4	4.4	14.9	11.6	4.6
Resource use mins. & metals	kg Sb eq	3.4E-09	2.9E-07	4.4E-09	1.7E-09	2.2E-07	3.3E-09	1.82E-09
Respiratory inorganics	disease inc.	2.2E-08	5.0E-07	1.2E-07	1.1E-08	3.7E-07	9.1E-08	1.18E-08
Water scarcity	m^3 depriv.	0.27	1.03	0.43	0.14	0.78	0.32	0.14

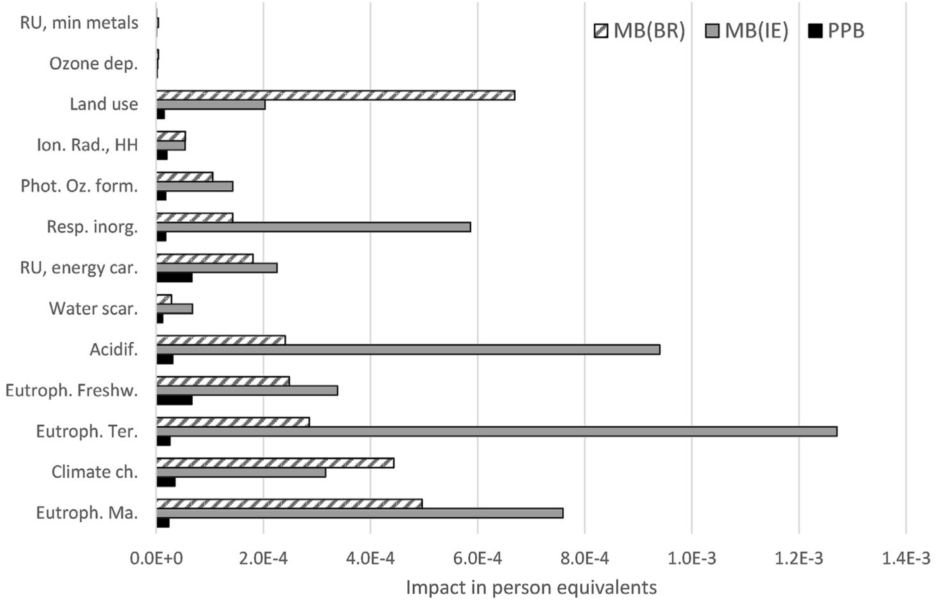

Fig. 3. Environmental burden of cooked pea protein balls and meatballs from Irish and Brazilian beef across 13 impact categories, using as a FU the Nutrient Density Unit. Results are normalised per person equivalents.

(IE and BR). Per NDU, in terms climate change, land use, and eutrophication, the impact of MBs (IE) was between 4.5 and 55 times that of PPBs. The Monte Carlo simulation and modified NHST supported these findings of the differences between the results per serving and per NDU (Supplementary Data). The environmental impact of PPBs per NDU with adjusted protein digestibility remained lower across all impact categories than per NDU of either MBs.

With economically allocated burdens, adding the COC to the GHG emissions of producing and consuming the three products resulted in the MBs having a climate change burden 11 and 12 times greater than that of PPBs, for MBs (IE) and MBs (BR), respectively (Table 2). When using one NDU as the FU, these differences increased to 19 and 21 times greater, for MBs (IE) and MBs (BR), respectively (Table 2). With (bio)physically allocated burdens, per serving, the differences were 5 and 7 times greater, for MBs (IE) and MBs (BR), respectively (Table A10).

To evaluate the sensitivity of results to the allocation choice for partitioning of flows between co-products, a physical and biophysical approach was tested and compared with the aforementioned impact assessment results based on economic allocation (Table 2). The environmental burdens of PPBs with physical allocation between kernels and starch co-products, starch-rich and protein-rich co-products, and MBs with biophysical allocation between beef and other cattle co-products are available in Table A10. With a biophysical allocation factor for beef of 26.8% of total cattle production burdens, the environmental burdens associated with production of MBs (BR and IE) were significantly reduced across most categories when compared to the same system economically-allocated. For example, the burdens of MBs (IE) when biophysical allocation was performed were between 55 and 71% smaller in the climate change, acidification, and land use categories, than when economic allocation was performed. Biophysical allocation reduced these burdens for MBs (BR) by between 36 and 46%. The environmental burdens of PPBs only decreased between 2 and 37% across all categories when economic allocation was replaced with biophysical allocation. Nonetheless, the environmental burdens of PPBs remained smaller than those of MBs (BR and IE), regardless of the allocation method.

3.2. Process contributions

Burden contributions across each stage of the value chain for PPBs and MBs (BR and IE) are recorded in Fig. 4 for all sixteen environmental impact categories. For MBs (IE and BR), production of the main ingredient (beef) is responsible for most of the impacts across all categories, except for freshwater eutrophication and ionising radiation (cooking contributed 41–57% and 85% of these burdens, respectively, along with 50–60% of total energy use). Beef production was responsible for 77–95% of total acidification, 76–82% of total climate change, 90–98% of total marine and terrestrial eutrophication, and 96–99% of total land use burdens. Acidification and terrestrial eutrophication were in part due to ammonia emission to air from cattle raising and grass production. Non-fossil methane emitted to the air from cattle was responsible for more than one third of the climate change impact. Nitrate emission to water was responsible for most of the marine eutrophication burden. Land use was mostly due to grassland occupation for pasture. The high differences in land use burdens were due to Brazilian beef cattle grazing at much lower stocking density than Irish beef cattle, often on degraded pastures, hence requiring more area. Animals are also slaughtered later, therefore generating less beef per animal (and grazed area) per year.

Large differences were revealed between cattle rearing in Brazil and Ireland across the cancer and non-cancer human health categories. The high non-cancer burden associated with Brazilian beef was due to zinc and lead emitted to the soil, while those of the cancer burden were due to emissions of chromium, nickel, lead, and cadmium to the soil. These emissions of heavy metals stem from mineral fertilisation and liming, and were regionalised to Brazil (Milà i Canals, 2003; Wernet et al., 2016).

The majority (75%) of water scarcity burdens of MBs (IE) were due to compound feed production, with oat production responsible for more than half of the burdens, and maize production for 16%. For MBs (BR), water scarcity burdens were much more spread across beef production and other ingredients' production, with no specific process responsible for a majority of the impact. Water scarcity burdens of PPBs were mainly due to irrigation required for onion and bell pepper production. Aside from the agricultural

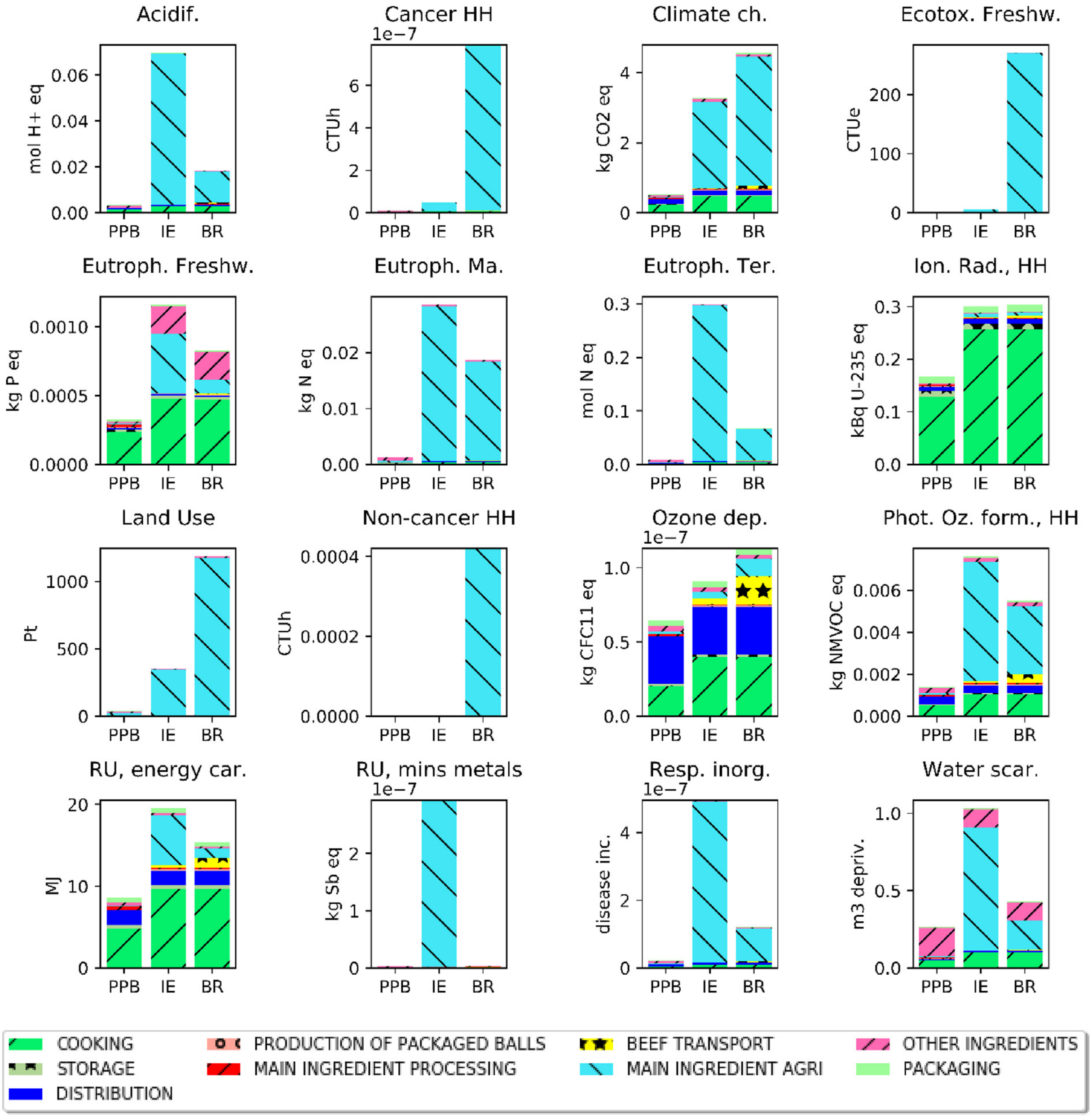

Fig. 4. Process contributions of pea protein balls and meatballs (Irish and Brazilian) across the 16 impact categories.

stage, cooking of each product was responsible for 10–24% of the total water scarcity burdens.

Cooking was the stage contributing the most towards the environmental impacts of PPBs, with a percentage contribution of at least 20% across 10 out of 16 impact categories. It contributed to 47% of the total climate change burden and 56% of total resource use energy carriers. The second stage that contributed the most to the environmental burdens was the cultivation and processing of the other ingredients. This stage was responsible for 53% of the total marine eutrophication, and 29% of total land use. Pea cultivation had a low share of burdens across all categories, except marine eutrophication for which it was responsible for 22% of the total, and land use for 57%. Across the other categories, its contribution was less than 7%. The burdens associated with cooking were higher for MBs due to a longer cooking time and different cooking instructions.

3.3. Extrapolated scenario impacts

With a consumption of 10 kg of beef on average per capita (Statista, 2020) and a population of more than 83 million inhabitants in 2018 (FAOSTAT, 2020), 5% of beef consumed in Germany represents an amount of around 42 thousand tons. Extrapolating this as the amount of MBs (IE) produced and consumed amounts to a climate change burden of 2.0 million tons CO_2 equivalent, and for MBs (BR) 2.7 million tons CO_2 equivalent. For a same weight of protein balls, the corresponding climate change impact of PPBs was of 216 thousand tons CO_2 equivalent, 90% smaller than the climate change burden of the corresponding amount of MBs (IE) and 93% smaller than that of MBs (BR).

With a COC of 144 kg CO_2 equivalent per kg of beef (Searchinger et al., 2018), the COC of just 5% of German beef consumption (in meatballs) would be 5.6 million tonnes CO_2 equivalent a year. A COC of 10.5 kg CO_2 equivalent per kg fresh weight of pulses (Searchinger et al., 2018) would translate into an aggregate COC of 0.3 million tonnes CO_2 equivalent a year for a weight of PPBs equivalent to 5% of German beef consumption in the form of MBs. Therefore, the COC saving of substituting 5% of beef consumption in Germany (as MB) with an equivalent weight of PPBs is approximately 5.3 million tonnes CO_2 equivalent a year. Including the lower emissions from PPB production, the total emission saving of such a substitution would amount to around 7 million tonnes of CO_2 equivalent a year (MB IE), or 8 million tonnes CO_2 equivalent a year (MBs BR). Besides this, considerable savings in this scenario include a positive difference of 195–688 billion land use points, 370 to 540 quadrillion global person equivalents in resource use, energy carriers, and 6.4 to 31 quadrillion global person equivalent in terrestrial eutrophication, among others.

4. Discussion

4.1. A meatball alternative at a lower environmental cost

The working hypothesis that “a serving of PPB has a significantly overall lower environmental impact than a serving of MB (IE or BR) per unit of nutrition” was validated. The results showing that the environmental burdens of a serving of a vegetarian alternative are lower than those of a meat product are coherent with those from other studies. For example, soybean versus chicken (Smetana et al., 2015), peas versus pork (Zhu and Van Ierland, 2003), soy burger versus beef (Khan et al., 2019), pea burger versus beef (Heller and Keoleian, 2018) and versus pork (Davis et al., 2010). However, Davis et al. (2010) found that the pea burger required around the same amount of energy than other meat products, due to high energy requirements for processing. We present an example of how a vegetarian meat analogue can also require less energy using few ingredients and little processing. Moreover, PPBs are a pilot product from IGV GmbH and are not commercialised yet, thus energy efficiency may improve when produced at a larger scale.

Growing peas in Germany appears to be associated with a low environmental impact when compared with other processes in the value chains assessed here, as shown by the contribution analysis. Cooking at the consumer’s house was the main contributor of the overall environmental impact of PPBs, while cattle rearing was the main contributor to the overall environmental impact of MBs. For all three products, cooking was found to be a major contributor across the freshwater eutrophication (between 41% and 72% of total impact), ionising radiation human health (between 77% and 85% of total impact), ozone depletion (between 31% and 44% of total impact), and resource use energy carriers (between 50% and 63% of total impact). Water scarcity burdens were high for onion irrigation, which represent 12% of the PPBs in weight. However secondary data was used, and irrigation may not be required in northern countries like Germany as it would in Mediterranean countries (Abdelkhalik et al., 2019).

In their study comparing the climate change impact of beef with cultured meat, Lynch and Pierrehumbert (2019) questioned the relevance of standard GWP_{100} values used in most environmental foot-printing studies. They claimed that because beef production emits more methane, a short-lived climate forcing gas, whilst cultured meat that emits more CO_2, a long-lived climate forcing gas, cultured meat could cause a greater warming effect over the very long term (1000 year scenarios) - if meat consumption and associated methane emissions decrease over time. However, the CO_2 emitted from processing the veggie options could potentially be compensated hundreds of times over by the alternative use of the land spared from meat production for carbon sequestration activities – as indicated by the COC method (Searchinger et al., 2018). Climate change burdens of processing 100 g of PPBs are 99.7% smaller than the COC of 100 g of MBs. The large land footprint of beef production reduces opportunity for land-based GHG offset necessary to achieve climate stabilisation (Arneth et al., 2019). Moreover, besides GHG emissions, beef production is associated with multiple environmental burdens pertinent to exceedance of planetary boundaries (Steffen et al., 2015), such as water use.

Beef production was by far the most impactful process across most impact categories, reflecting the environmental challenges posed by ruminant livestock rearing in relation to climate change, land use and reactive N losses in particular, as well documented in the literature (Eshel et al., 2014). The large environmental variation of different beef production systems was captured in this study with the use of the Irish beef on one hand, and the Brazilian beef on the other hand. Beef production burdens taken from Ecoinvent v3.6 represent a market average for widely differing Brazilian cattle systems. This is representative of beef originating from Brazil, a major global exporter of beef, but masks large differences in environmental efficiency of beef production across Brazil. When compared to Irish beef, Brazilian beef has a higher land and GHG footprint, while Irish beef has higher acidification, eutrophication, and energy use. Irish beef requires more inputs, such as fertilisers, but less land, and emits less enteric methane, as shown by the FAO (2019b)**.** These results highlight that the environmental impact of beef is very sensitive where and how it is produced, as previously indicated by Poore and Nemecek (2018), but these differences are not enough to achieve better environmental sustainability than a vegetarian alternative like PPBs.

Biophysical allocation for beef co-products greatly decreased the calculated environmental footprints of beef meatballs, though they remained considerably larger than for PPBs. For example, the burdens of MBs (IE) when biophysical allocation was performed were between 55 and 71% smaller in the climate change, acidification, and land use categories, than when economic allocation was performed. Biophysical allocation reduced these burdens for MBs (BR) by between 36 and 46%. The aim of biophysical allocation is to allocate based on physical and causal relationships between co-products, to offer an alternative to economic allocation, since the latter is subject to market fluctuations and uncertainties. However, despite biophysical allocation of beef co-products being recommended by the FAO (2016), Mackenzie et al. (2017) showed that the approach still relies on economic values of co-products. Nguyen, Van der Werf and Doreau (2012) compared economic, mass, and protein allocation in beef systems and found that results from economic allocation yielded the smallest differences with the other allocation methods, suggesting that economic allocation was a suitable allocation reference. In any case, results demonstrate the particular sensitivity of beef product footprints to choice of allocation method, which should be explored making comparisons with plant-based alternatives. The environmental burdens of PPBs only decreased between 2 and 37% across all categories when economic allocation was replaced with mass allocation. Therefore in this study, a physical allocation approach instead of an economic one decreased the environmental burdens of all three types of protein balls and had a greater reduction impact on the beef products than the pea product.

Besides the commonly highlighted higher climate change and land use burdens involved with beef production, this study provides a comprehensive overview of other important impacts on the environment, underlining the significantly higher marine, terrestrial eutrophication, acidification, and respiratory inorganics burdens involved with production of Irish beef due to ammonia emissions from cattle and grass cultivation and grazing. The high respiratory inorganics burden for the MBs (IE) adds on to the negative impacts on human health from overconsumption of red meat. Respiratory inorganics are one of the major environmental factors damaging human health, and are linked to respiratory and cardiovascular morbidity, mortality, lung cancer, and diabetes, amongst others (Fantke et al., 2015).

Restoring the land currently occupied by cattle holds great potential in storing atmospheric CO_2. Our model shows that there is a 5.3 million tons CO_2 equivalent a year difference between 5% of beef consumption in Germany and the same weight in PPBs for only COC. This amount is equal to 1% of Germany's annual GHG emissions (when including international aviation and excluding land use change and forestry) in 2018 (Eurostat, 2020a).

4.2. Delivering nutrition at a lower environmental cost

Besides the potential for mitigating the environmental burdens of food production and consumption, identifying healthier food options in developed countries is an urgent matter, with unhealthy diets representing a greater risk to morbidity and mortality than the sum of unsafe sex, alcohol, drug and tobacco use (Willett et al., 2019). Using a nutrient density unit as a functional unit provides a simple approach to compare the environmental efficiency of nutrition delivered by different foods, in this case protein balls made from primarily beef or peas. This is the first time in the literature that a more complete nutritional FU (as opposed to protein or calorie content individually) was used to compare meat alternatives. Existing LCA studies of meat alternatives have been so far limited by the use of a serving size or single aspect FU only, constraining their conclusiveness regarding the environmental efficiency of wider nutrition. The use of a nutrient density FU such as the NDU when evaluating different food alternatives, and for formulating diets in developed areas such as Europe, is a major advance when compared to using a simple serving size FU. Further research should be undertaken on consumer behaviour, specifically on whether an environmental sustainability label on unhealthy foods incites certain individuals to purchase these.

The choice of the NDU followed Saget et al. (2020), and is a practical approach based on analysis of a few crucial nutrients that correlate with the more extensive index of the Nutrient Rich Foods Index (NRF) 12.3, which includes all the nutrient of NRF 11.3, plus essential fatty acids: protein, fibre, vitamins A, C, E, B_{12}, calcium, iron, magnesium, potassium zinc, added sugars, saturated fats, and sodium (Fulgoni et al., 2009). Sonesson et al. (2017) claim that comparing plant and animal-based foods should be done on a protein digestibility basis. Adjusting for protein digestibility in the PPBs did not affect the NDU significantly, nor the comparative environmental performance between pea- and beef-derived protein balls.

Although the NDU correlates with the NRF 12.3 (Saget et al., 2020), which takes into account other nutrients such as added sugar, sodium, and saturated fats, the NDU does not itself consider nutrients to limit. These may be present in high amounts in processed meat alternatives. There is a general concern that these types of foods may be detrimental to health (Hu, 2011), and further study is needed to determine the comparative health disadvantages of "negative" nutrients in protein balls made from both beef and peas. The use of the NDU, however, was sufficient to show that PPBs are more nutrient-dense than MBs, thus extending their advantage over beef in terms of environmental efficiency per unit of nutrition delivered.

Despite the fact that being a healthier and more environmentally-friendly alternative to meat, consumption of PPBs and other innovative plant-based meat analogues is hindered by several factors, such as taste and texture (consumers are looking for satisfying mouthfeels), availability, and price, as they are not as easily accessible and often more expensive than industrially-produced meat (Gapper, 2018). However, plant protein products may have a further public health advantage over meat products insofar as they avoid the use of growth hormones and antibiotics used in some livestock systems.

4.3. Future context

Due to the energy decarbonisation strategy of the EU to achieve climate neutrality by 2050, the climate change burden of PPBs has a large potential to decrease considerably with the use of cleaner energy sources, whereas the substantial decrease in climate change burden of cattle remains limited in comparison. Between 2004 and 2018, the average share of electricity from renewable energy sources went from 14% to 32% (Eurostat, 2020b). Table A11 shows the environmental burdens of replacing the electricity mixes from Europe and Germany to the Swedish electricity mix. The Swedish electricity mix was chosen due to it having the highest share of "clean" energy, with 55% of its electricity coming from renewable sources (Eurostat, 2020c). Therefore, the mix represents a good example of how other European countries like Germany will evolve towards a cleaner electricity supply. The climate change footprint of a serving of PPBs went from 0.5 kg CO_2 equivalents with the current mix to 0.3 kg CO_2 equivalents with the Swedish mix, incurring a 45% reduction. The environmental burdens were also reduced across all other categories, excepted for the ionisation human health and land use ones, across which the Swedish mix had a 69% and 3% increase, respectively.

Current carbon footprint comparisons of foods may underestimate the critical importance of land requirements in the context of future climate objectives, as they do not include COCs. Land is increasingly required to offset residual emissions and achieve Net Zero Targets (Committee on Climate Change, 2019). Land use is a resource that can be potentially spared if beef production and consumption is substituted with legume products like the PPBs, with 5% of annual beef consumption in Germany used in protein balls representing a positive difference land use impact of 195 and 688 quadrillion global person equivalents. Water scarcity savings were also substantial, ranging between 1.7 and 5.8 trillion person equivalents in m^3 deprivation.

4.4. Limitations

Notwithstanding the fact that life cycle inventories for Irish and Brazilian beef could only be sourced from separate databases, the respective environmental profiles correspond with an increasing body of literature on the environmental footprints of European and Latin American beef systems (Nguyen et al., 2010; Willers et al., 2017). Several studies have identified large differences in the environmental impacts of beef systems (Capper, 2012; Costa et al., 2018; Pelletier et al., 2010; Picasso et al., 2014). Picasso et al. (2014) compared five different types of systems in Uruguay and found that cattle fed with a combination of improved pasture and feedlot had the largest environmental impacts across six of seven categories assessed, and the smallest impact in the seventh category, GWP. The other systems, native grasslands, improved pasture, or a combination of grassland and improved pasture or grassland and feedlot had lower environmental impacts across the same six impact categories and had a higher GWP. Capper (2012), on the other hand, found that in the United States grass-fed systems (cow-calf, pre-grass and grass finishing) required more inputs and produced more waste than typical American systems (cow-calf, stocker, feedlot, and dairy) with or without growth enhancing technologies. Costa et al. (2018) showed that an integrated livestock-crop system production could decrease land requirement six-fold and halve GHG emissions compared to traditional systems.

Most of these results were linked with a more efficient cattle system. In this study, we deliberately looked at beef from major beef-exporting countries previously shown to span the spectrum of carbon footprints (FAO, 2018; A. Leip et al., 2010), including Brazil, which is the largest exporter of beef (Willers et al., 2017), thus evaluating a representative range of beef meatball footprints.

Other limitations of this study include the lack of background LCA data available for seasoning ingredients present in the PPBs and MBs, which could have a significant impact due to energy requirements for processing. Biswas and Naude (2016) LCA on MB and the PPB inventory did not include trace elements in the study, such as food additives. However, because trace elements were excluded in both products, the relative burdens of products were not affected.

5. Conclusions

Our approach shows the potential of combining environmental and nutritional attributes into quantitative footprints that can be used to assess sustainable food options in the food sector. Our attributional life cycle assessment of 100 g of cooked pea protein balls versus beef meatballs made from Irish or Brazilian beef from cradle to fork showed that pea protein balls have a smaller environmental impact across most impact categories assessed, regardless of the origin of the beef or the allocation method employed. Using a biophysical instead of an economic allocation approach across cattle co-products lowered significantly the environmental footprint of the meatballs. Due to their higher nutrient density, the comparative environmental advantage of pea protein balls over beef meat balls was extended when footprints were expressed per unit of nutrition.

The carbon opportunity cost associated with land occupation is usually not represented within food footprints, yet has an enormous influence on the climate impact of foods. We show that substituting 5% of Germany's beef consumption with pea protein balls could spare enough land to offset 1% of total annual GHG emissions. Spared land could also be used to produce bio-based feedstocks supporting the transition to a bio-based circular economy. In addition to reducing GHG emissions, substitution of beef meatballs with pea protein balls could lead to large reductions in other forms of resource use and pollution, including energy demand, and reduced emission of health-impacting respiratory inorganics. Through holistic environmental foot-printing and accounting for carbon opportunity costs of land we demonstrate that substitution of beef meat balls with pea protein balls could play an important role on the path to climate neutrality and a more circular economy.

CRediT authorship contribution statement

Sophie Saget: Conceptualization, Methodology, Writing – original draft, Investigation. **Marcela Costa:** Writing – review & editing. **Carla Sancho Santos:** Investigation. **Marta Wilton Vasconcelos:** Resources. **James Gibbons:** Methodology, Writing – review & editing, Supervision. **David Styles:** Methodology, Writing – review & editing, Supervision. **Michael Williams:** Writing – review & editing, 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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2021.126447.

References

Abdelkhalik, A., Pascual, B., Nájera, I., Baixauli, C., Pascual-Seva, N., 2019. Regulated deficit irrigation as a water-saving strategy for onion cultivation in mediterranean conditions. Agronomy 9, 521. https://doi.org/10.3390/agronomy9090521.

Afshin, A., Sur, P.J., Fay, K.A., Cornaby, L., Ferrara, G., Salama, J.S., Mullany, E.C., Abate, K.H., Abbafati, C., Abebe, Z., Afarideh, M., Aggarwal, A., Agrawal, S., Akinyemiju, T., Alahdab, F., Bacha, U., Bachman, V.F., Badali, H., Badawi, A., Bensenor, I.M., Bernabe, E., Biadgilign, S.K.K., Biryukov, S.H., Cahill, L.E., Carrero, J.J., Cercy, K.M., Dandona, L., Dandona, R., Dang, A.K., Degefa, M.G., El Sayed Zaki, M., Esteghamati, A., Esteghamati, S., Fanzo, J., Farinha, C.S. e S., Farvid, M.S., Farzadfar, F., Feigin, V.L., Fernandes, J.C., Flor, L.S., Foigt, N.A., Forouzanfar, M.H., Ganji, M., Geleijnse, J.M., Gillum, R.F., Goulart, A.C., Grosso, G., Guessous, I., Hamidi, S., Hankey, G.J., Harikrishnan, S., Hassen, H.Y., Hay, S.I., Hoang, C.L., Horino, M., Islami, F., Jackson, M.D., James, S.L., Johansson, L., Jonas, J.B., Kasaeian, A., Khader, Y.S., Khalil, I.A., Khang, Y.-H., Kimokoti, R.W., Kokubo, Y., Kumar, G.A., Lallukka, T., Lopez, A.D., Lorkowski, S., Lotufo, P.A., Lozano, R., Malekzadeh, R., März, W., Meier, T., Melaku, Y.A., Mendoza, W., Mensink, G.B.M., Micha, R., Miller, T.R., Mirarefin, M., Mohan, V., Mokdad, A.H., Mozaffarian, D., Nagel, G., Naghavi, M., Nguyen, C.T., Nixon, M.R., Ong, K.L., Pereira, D.M., Poustchi, H., Qorbani, M., Rai, R.K., Razo-García, C., Rehm, C.D., Rivera, J.A., Rodríguez-Ramírez, S., Roshandel, G., Roth, G.A., Sanabria, J., Sánchez-Pimienta, T.G., Sartorius, B., Schmidhuber, J., Schutte, A.E., Sepanlou, S.G., Shin, M.-J., Sorensen, R.J.D., Springmann, M., Szponar, L., Thorne-Lyman, A.L., Thrift, A.G., Touvier, M., Tran, B.X., Tyrovolas, S., Ukwaja, K.N., Ullah, I., Uthman, O.A., Vaezghasemi, M., Vasankari, T.J., Vollset, S.E., Vos, T., Vu, G.T., Vu, L.G., Weiderpass, E., Werdecker, A., Wijeratne, T., Willett, W.C., Wu, J.H., Xu, G., Yonemoto, N., Yu, C., Murray, C.J.L., 2019. Health effects of dietary risks in 195 countries, 1990–2017: a systematic analysis for the Global Burden of Disease Study 2017. Lancet 393, 1958–1972. https://doi.org/10.1016/S0140-6736(19)30041-8.

Ali, M.E., Razzak, M.A., Hamid, S.B.A., Rahman, M.M., Amin, M. Al, Rashid, N.R.A., Asing, 2015. Multiplex PCR assay for the detection of five meat species forbidden in Islamic foods. Food Chem. 177, 214–224. https://doi.org/10.1016/J.FOODCHEM.2014.12.098.

Arneth, A., Barbosa, H., Benton, T., Calvin, K., Calvo, E., Cowie, A., et al., 2019. IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems. Summary for Policy Makers. Intergovernmental Panel on Climate Change (IPCC), Geneva.

Askew, K., 2020. EU-mercosur Deal Faces Mounting Opposition as Soy and Beef Exports Drive Deforestation in Brazil. Food Navigator [WWW Document].

Beauchemin, K.A., McAllister, T.A., McGinn, S.M., 2009. Dietary mitigation of enteric methane from cattle. CAB Rev. Perspect. Agric. Vet. Sci. Nutr. Nat. Resour. 4, 1–18.

Biswas, W.K., Naude, G., 2016. A life cycle assessment of processed meat products supplied to Barrow Island: a Western Australian case study. https://doi.org/10.1016/j.jfoodeng.2016.02.008.

Bouvard, R., Loomis, D., Guyton, K.Z., Grosse, Y., El Ghissassi, F., Benbrahim-Tallaa, L., Guha, N., Mattock, H., Straif, K., 2015. Agency for research on cancer monograph working group, I. carcinogenicity of consumption of red and processed meat. Lancet Oncol. 16, 1599–1600. https://doi.org/10.1016/S1470-2045(15)00444-1.

Capper, J.L., 2012. Is the grass always greener? Comparing the environmental impact of conventional, natural and grass-fed beef production systems. Animals 2, 127–143. https://doi.org/10.3390/ani2020127.

Chadwick, D.R., 2005. 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.

Committee on Climate Change, 2019. Net Zero: the UK's Contribution to Stopping Global Warming.

Costa, M.P., Schoeneboom, J.C., Oliveira, S.A., Viñas, R.S., de Medeiros, G.A., 2018. A socio-eco-efficiency analysis of integrated and non-integrated crop-livestock-forestry systems in the Brazilian Cerrado based on LCA. J. Clean. Prod. 171, 1460–1471. https://doi.org/10.1016/j.jclepro.2017.10.063.

Crippa, M., Solazzo, E., Guizzardi, D., Monforti-Ferrario, F., Tubiello, F.N., Leip, A., 2021. Food systems are responsible for a third of global anthropogenic GHG emissions. Nature Food. https://doi.org/10.1038/s43016-021-00225-9.

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.

Donati, M., Menozzi, D., Zighetti, C., Rosi, A., Zinetti, A., Scazzina, F., 2016. Towards a sustainable diet combining economic, environmental and nutritional objectives. Appetite 106, 48–57. https://doi.org/10.1016/j.appet.2016.02.151.

Durlinger, B., Koukouna, E., Broekema, R., van Paassen, M., Scholten, J., 2017. Agri-footprint 3.0. Blonk Consultants, Gouda [WWW Document].

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. Unit. States Am. 111.

European Commission, 2018. Product Environmental Footprint Category Rules Guidance.

European Commission, 2020a. EU Climate Action and the European Green Deal | Climate Action [WWW Document].

European Commission, 2020b. EU-mercosur Trade Agreement- Creating Opportunities while Respecting the Interests of European Farmers.

Eurostat, 2020a. Greenhouse Gas Emission Statistics-Emission Inventories- Statistics Explained.

Eurostat, 2020b. The Average Share of Electricity from Renewable Energy Sources in the EU.

Eurostat, 2020c. Renewable Energy Statistics [WWW Document].

Fantke, Peter, Jolliet, Olivier, Evans, John S., Apte, Joshua S., Cohen, Aaron J., Hänninen, Otto, O., Hurley, Fintan, Jantunen, Matti, J., Jerrett, Michael, Levy, Jonathan, I., Loh, Miranda, M., Marshall, Julian D., Miller, Brian G., Preiss, P., Spadaro, J.V., Tainio, Marko, Tuomisto, Jouni, T., Weschler, C.J., McKone, Thomas E., Fantke, P., Jolliet, O., Evans, J.S., Apte, J.S., Cohen, A.J., Hänninen, O.O., Jantunen, M.J., Tuomisto, J.T., Hurley, F., Miller, B.G., Jerrett, M., McKone, T.E., Levy, J.I., Loh, M.M., Marshall, J.D., Preiss econcept, P.A., V Spadaro, S.J., Tainio, M., 2015. Health effects of fine particulate matter in life cycle impact assessment: findings from the Basel Guidance Workshop. Int. J. Life Cycle Assess. 20, 276–288. https://doi.org/10.1007/s11367-014-0822-2.

FAO, 2016. Environmental Performance of Large Ruminant Supply Chains Guidelines for Assessment.

FAO, 2018. Global Livestock Environmental Assessment Model.

FAO, 2019a. OECD-FAO Agricultural Outlook 2017-2026 : MEATS - OECD-FAO Agricultural Outlook 2017-2026 [WWW Document].

FAO, 2019b. FAOSTAT [WWW Document].

FAOSTAT, 2020. Annual Population [WWW Document].

Fulgoni, V.L., Keast, D.R., Drewnowski, A., 2009. Development and validation of the nutrient-rich foods index: a tool to measure nutritional quality of foods. J. Nutr. Nutr. Requir. Optim. Nutr. https://doi.org/10.3945/jn.108.101360.

Gapper, J., 2018. Fake meat's brand identity is too squishy. BUSINESS. Financ. Times, 13–13.

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. https://doi.org/10.1126/science.aam5324.

GreenDelta, 2020. OpenLCA [WWW Document].

Harwatt, H., Sabaté, J., Eshel, G., Soret, S., Ripple, W., 2017. Substituting beans for beef as a contribution toward US climate change targets. https://doi.org/10.1007/s10584-017-1969-1.

Hayek, M.N., Harwatt, H., Ripple, W.J., Mueller, N.D., 2020. The carbon opportunity cost of animal-sourced food production on land. Nat. Sustain. 1–4 https://doi.org/10.1038/s41893-020-00603-4.

Heller, M.C., Keoleian, G.A., 2018. Beyond Meat's beyond Burger Life Cycle Assessment: A Detailed Comparison between a Plant-Based and an Animal-Based Protein Source.

Henderson, B.B., Gerber, P.J., Hilinski, T.E., Falcucci, A., Ojima, D.S., Salvatore, M., Conant, R.T., 2015. Greenhouse gas mitigation potential of the world's grazing lands: modeling soil carbon and nitrogen fluxes of mitigation practices. Agric. Ecosyst. Environ. 207, 91–100. https://doi.org/10.1016/j.agee.2015.03.029.

Hu, F.B., 2011. Globalization of diabetes: the role of diet, lifestyle, and genes. In: Diabetes Care. American Diabetes Association, pp. 1249–1257. https://doi.org/10.2337/dc11-0442.

IGV, 2019. IGV GmbH • Your Partner in Food Technology and Biotechnology [WWW Document].

IKEA, 2015. IKEA Takes a New Course in its Food Offering Veggie Balls First of New Nutritious and Sustainable Offering.

Jensen, E.S., Peoples, M.B., Boddey, R.M., Gresshoff, P.M., Hauggaard-Nielsen, H., Alves, B.J., Morrison, M.J., 2012. Legumes for mitigation of climate change and the provision of feedstock for biofuels and biorefineries. Rev. Agron. Sustain. Dev. 32, 329–364. https://doi.org/10.1007/s13593-011-0056-7.

JRC, 2010. ILCD Handbook: General Guide for Life Cycle Assessment-Provisions and Action Steps. https://doi.org/10.2788/94987.

Khan, S., Dettling, J., Hester, J., Moses, R., Foods, I., 2019. Comparative Environmental LCA of the Impossible Burger with Conventional Ground Beef Burger.

Larsson, S.C., Wolk, A., 2006. Meat consumption and risk of colorectal cancer: a meta-analysis of prospective studies. Int. J. Canc. 119, 2657–2664. https://doi.org/10.1002/ijc.22170.

Lawrence, M.A., Friel, S., Wingrove, K., James, S.W., Candy, S., 2015. Formulating Policy Activities to Promote Healthy and Sustainable Diets. https://doi.org/10.1017/S1368980015002529.

Leip, A., Weiss, F., Wassenaar, T., Perez, I., Fellmann, T., Loudjani, P., Tubiello, F., Grandgirard, D., Monni, S., Biala, K., 2010. Evaluation of the Livestock Sector's Contribution to the EU Greenhouse Gas Emissions (GGELS). Publications Office of the European Union.

Lynch, J., Pierrehumbert, R., 2019. Climate impacts of cultured meat and beef cattle. Front. Sustain. Food Syst. 3, 5. https://doi.org/10.3389/fsufs.2019.00005.

Macdiarmid, J.I., Douglas, F., Campbell, J., 2016. Eating like there's no tomorrow: public awareness of the environmental impact of food and reluctance to eat less meat as part of a sustainable diet. Appetite 96, 487–493. https://doi.org/10.1016/j.appet.2015.10.011.

Mackenzie, S.G., Leinonen, I., Kyriazakis, I., 2017. The need for co-product allocation in the life cycle assessment of agricultural systems—is "biophysical" allocation progress? Int. J. Life Cycle Assess. 22, 128–137. https://doi.org/10.1007/s11367-016-1161-2.

Masson-Delmotte, V., Zhai, P., Pörtner, H.-O., Roberts, D., Skea, J., Shukla, P.R., Pirani, A., Moufouma-Okia, W., Péan, C., Pidcock, R., Connors, S., Matthews, J.B.R., Chen, Y., Zhou, X., Gomis, M.I., Lonnoy, E., Maycock, T., Tignor, M., Waterfield, T., 2019. Global Warming of 1.5°C. Global Warming of 1.5°C: A Special Report on the Impacts of Global Warming of 1.5°C above Pre-industrial Levels.

McCrory, M.A., Hamaker, B.R., Lovejoy, J.C., Eichelsdoerfer, P.E., 2010. Pulse consumption, satiety, and weight management. Adv. Nutr. 1, 17–30. https://doi.org/10.3945/an.110.1006.

Mejia, M., Fresán, U., Harwatt, H., Oda, K., Uriegas-Mejia, G., Sabaté, J., 2020. Life cycle assessment of the production of a large variety of meat analogs by three diverse factories. J. Hunger Environ. Nutr. 15, 699–711. https://doi.org/10.1080/19320248.2019.1595251.

Mendoza Beltran, A., Prado, V., Font Vivanco, D., Henriksson, P.J.G., Guinée, J.B., Heijungs, R., 2018. Quantified uncertainties in comparative life cycle assessment: what can be concluded? Environ. Sci. Technol. 52, 2152–2161. https://doi.org/10.1021/acs.est.7b06365.

Milà i Canals, L., 2003. Contributions to LCA Methodology for Agricultural Systems. Site-Dependency and Soil Degradation Impact Assessment. Universitat Autònoma de Barcelona, Barcelona.

Muller, S., Lesage, P., Ciroth, A., Mutel, C., Weidema, B.P., Samson, R., 2016. The application of the pedigree approach to the distributions foreseen in ecoinvent v3. Int. J. Life Cycle Assess. 21, 1327–1337. https://doi.org/10.1007/s11367-014-0759-5.

Nguyen, T.L.T., Hermansen, J.E., Mogensen, L., 2010. 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, T.T.H., Van der Werf, H.M.G., Doreau, M., 2012. Life cycle assessment of three bull-fattening systems: effect of impact categories on ranking. J. Agric. Sci. 150, 755–763. https://doi.org/10.1017/S0021859612000123.

Norat, T., Bingham, S., Ferrari, P., Slimani, N., Jenab, M., Mazuir, M., Overvad, K., Olsen, A., Tjønneland, A., Clavel, F., Boutron-Ruault, M.-C., Kesse, E., Boeing, H., Bergmann, M.M., Nieters, A., Linseisen, J., Trichopoulou, A., Trichopoulos, D., Tountas, Y., Berrino, F., Palli, D., Panico, S., Tumino, R., Vineis, P., Bueno-de-Mesquita, H.B., Peeters, P.H.M., Engeset, D., Lund, E., Skeie, G., Ardanaz, E., González, C., Navarro, C., Quirós, J.R., Sanchez, M.-J., Berglund, G., Mattisson, I., Hallmans, G., Palmqvist, R., Day, N.E., Khaw, K.-T., Key, T.J., San Joaquin, M., Hémon, B., Saracci, R., Kaaks, R., Riboli, E., 2005. Meat, fish, and colorectal cancer risk: the European prospective investigation into cancer and nutrition. JNCI J. Natl. Cancer Inst. 97, 906–916. https://doi.org/10.1093/jnci/dji164.

Pan, A., Sun, Q., Bernstein, A.M., Schulze, M.B., Manson, J.A.E., Stampfer, M.J., Willett, W.C., Hu, F.B., 2012. Red meat consumption and mortality: results from 2 prospective cohort studies. Arch. Intern. Med. 172, 555–563. https://doi.org/10.1001/archinternmed.2011.2287.

Pelletier, N., Pirog, R., Rasmussen, R., 2010. Comparative life cycle environmental impacts of three beef production strategies in the Upper Midwestern United States. Agric. Syst. 103, 380–389. https://doi.org/10.1016/J.AGSY.2010.03.009.

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. Agroecosyst. Div. 123–143. https://doi.org/10.1016/B978-0-12-811050-8.00008-X.

Picasso, V.D., Modernel, P.D., Becoña, G., Salvo, L., Gutiérrez, L., Astigarraga, L., 2014. Sustainability of meat production beyond carbon footprint: a synthesis of case studies from grazing systems in Uruguay. Meat Sci. 98, 346–354. https://doi.org/10.1016/j.meatsci.2014.07.005.

Poore, J., Nemecek, T., 2018. Reducing food's environmental impacts through producers and consumers. Science 360, 987–992. https://doi.org/10.1126/science.aaq0216.

Rahman, M.M., Ali, M.E., Hamid, S.B.A., Mustafa, S., Hashim, U., Hanapi, U.K., 2014. Polymerase chain reaction assay targeting cytochrome b gene for the detection of dog meat adulteration in meatball formulation. Meat Sci. 97, 404–409. https://doi.org/10.1016/J.MEATSCI.2014.03.011.

Rajão, R., Soares-Filho, B., Nunes, F., Börner, J., Machado, L., Assis, D., Oliveira, A., Pinto, L., Ribeiro, V., Rausch, L., Gibbs, H., Figueira, D., 2020. The rotten apples of Brazil's agribusiness. Science (80-.) 369, 246. https://doi.org/10.1126/science.aba6646.

Richi, E.B., Baumer, B., Conrad, B., Darioli, R., Schmid, A., Keller, U., 2015. Health risks associated with meat consumption: a review of epidemiological studies. Int. J. Vitam. Nutr. Res. https://doi.org/10.1024/0300-9831/a000224.

Rust, N.A., Ridding, L., Ward, C., Clark, B., Kehoe, L., Dora, M., Whittingham, M.J., McGowan, P., Chaudhary, A., Reynolds, C.J., Trivedy, C., West, N., 2020. How to transition to reduced-meat diets that benefit people and the planet. Sci. Total Environ. https://doi.org/10.1016/j.scitotenv.2020.137208.

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-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. https://doi.org/10.1016/j.spc.2020.06.012.

Sandin, G., Røyne, F., Berlin, J., Peters, G.M., Svanström, M., 2015. Allocation in LCAs of biorefinery products: implications for results and decision-making. J. Clean. Prod. 93, 213–221. https://doi.org/10.1016/j.jclepro.2015.01.013.

Searates, 2020. Distances & Time [WWW Document].

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.

Shepon, A., Eshel, G., Noor, E., Milo, R., 2016. Energy and protein feed-to-food conversion efficiencies in the US and potential food security gains from dietary changes. Environ. Res. Lett. 11, 105002. https://doi.org/10.1088/1748-9326/11/10/105002.

Smetana, S., Mathys, A., Knoch, A., Heinz, V., 2015. Meat alternatives: life cycle assessment of most known meat substitutes. Int. J. Life Cycle Assess. 20, 1254–1267. https://doi.org/10.1007/s11367-015-0931-6.

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.

Spellberg, B., Hansen, G.R., Kar, A., Cordova, C.D., Price, L.B., Johnson, J.R., 2016. Antibiotic Resistance in Humans and Animals.

Stagnari, F., Maggio, A., Galieni, A., Pisante, M., 2017. Multiple benefits of legumes for agriculture sustainability: an overview. Chem. Biol. Technol. Agric. https://doi.org/10.1186/s40538-016-0085-1.

Statista, 2019. Alternative Meat Market Poised for Growth [WWW Document].

Statista, 2020. Meat- Per Capita Consumption in Germany 2019 | Statista [WWW Document].

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 (80-.) 333, 301–306. https://doi.org/10.1126/science.1259855.

Steinfeld, H., Gerber, P., Wassenaar, T., Castel, V., Rosales, M., de Haan, C., 2006. Livestock's Long Shadow.

Teagasc, 2020. Beef - Finishing Cattle at Grass [WWW Document].

The Irish Times, 2020. Irish Grass-Fed Beef Could Get Special EU Status [WWW Document].

Union, European, 2020. Farm to Fork Strategy.

United Nations, 2020. UN Comtrade: International Trade Statistics [WWW Document].

Van Dooren, C., 2016. Proposing the nutrient density unit as the functional unit in LCAs of foods. Int. Conf. Life Cycle Assess. Food, 2016 1–10.

van Dooren, C., Marinussen, M., Blonk, H., Aiking, H., Vellinga, P., 2014. Exploring dietary guidelines based on ecological and nutritional values: a comparison of six dietary patterns. Food Pol. 44, 36–46. https://doi.org/10.1016/J.FOODPOL.2013.11.002.

Wagner, S.C., 2011. Biological nitrogen fixation. Nat. Educ. Knowl. 3 (10).

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, 1218–1230. https://doi.org/10.1007/s11367-016-1087-8.

Westhoek, H., Lesschen, J.P., Leip, A.R.T., Wagner, S., De Marco, A., Murphy-Bokern, D., Pallière, C., Howard, C.M., Oenema, O., Sutton, M.A., 2016. Nitrogen on the Table: the Influence of Food Choices on Nitrogen Emissions and the European Environment.

HO, n.d. Obesity - Data and Statistics ([WWW Document]).

WHO, 2007. Protein and Amino Acid Requirements in Human Nutrition.

Willers, C.D., Maranduba, H.L., Adolfo, J., Neto, A., Rodrigues, L.B., Vázquez-Rowe, I., 2017. Environmental Impact assessment of a semi-intensive beef cattle production in Brazil's Northeast. Int. J. Life Cycle Assess. 22, 516–524. https://doi.org/10.1007/s11367-016-1062-4.

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 (London, England) 393, 447–492. https://doi.org/10.1016/S0140-6736(18)31788-4.

Williams, M., Suttle, M., Saget, S., Sheeran, S., Cotter, M., O'Leary, K., Bienkowski, D., Iannetta, P., Styles, D., 2020. The Environmental Assessment of Diets. Deliverable (D) 5.5 (D33) for the EU-H2020 Project, 'TRansition Paths to sUstainable Legume-Based Systems in Europe' (TRUE), Funded under Grant Agreement Number 727973. https://doi.org/10.5281/ZENODO.3732026. www.true-project.eu.

Wolk, A., 2017. Potential health hazards of eating red meat. J. Intern. Med. 281, 106–122. https://doi.org/10.1111/joim.12543.

Zhu, X., Van Ierland, E.C., 2003. Protein chains and environmental pressures: a comparison of pork and novel protein foods. Environ. Sci. 1, 254–276. https://doi.org/10.1080/15693430412331291652.