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Comparative life cycle assessment of plant and beef-based patties, including carbon opportunity costs

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ABSTRACT

Legume-derived foods have been shown to have comparatively low greenhouse gas (GHG) intensities whilst providing high amounts of nutrients. However, processing legumes into meat analogues can incur significant energy costs. Here, we undertake a comprehensive life cycle assessment of plant-based and (Brazilian and Irish) beef burger patties. Sixteen impact categories are supplemented with the carbon opportunity cost of land occupation, and benchmarked against nutrient density units (NDU) to provide holistic evidence on the potential contribution of plant-based patties to environmentally-sustainable nutritional density. Plant-based patties have a smaller environmental footprint across most categories, including a 77% smaller climate change burden, but incur 8% more energy use compared with Brazilian beef patties. Normalised scores (person equivalents) were significantly larger ($p < 0.05$) for the beef products across key categories including land use, acidification, and marine and terrestrial eutrophication. Sensitivity analyses indicated significant variance across impact categories if beef cattle are reared in South Africa, France or the United States, including a 16-fold difference in land occupation. Biophysical allocation of co-products reduced environmental burdens of beef burgers. However, owing to a 68% higher NDU per serving, reflecting higher fibre and essential fatty acid content, plant-based patties are associated with 81–87% less climate change and 92–95% less marine eutrophication per NDU compared with beef burger patties. Accounting for carbon opportunity cost of land further increased the climate change advantage of plant-based patties by 25–44%. A simple extrapolation indicates that switching from beef to vegetable patties in the UK could save between 9.5 and 11 million tonnes CO_2e annually, representing up to 2.4% of territorial GHG emissions.

1. Introduction

Beef burger patties are a major component of Western diets, the average adult consuming approximately 1 kg burger patties per year when eating out in the United Kingdom (Department for Environment Food and Rural Affairs, 2020). Due to growing concerns about the effect of excessive red meat consumption on human health and the environment (Gerber et al., 2013; Richi et al., 2015; Steinfeld et al., 2006; Willett et al., 2019), purchases of animal-free alternatives, such as legume-based patties are on the increase (Forbes, 2019).

There are many environmental and health benefits to considering legume-derived foods. Primarily, they have a much reduced greenhouse gas (GHG) intensity (aka “carbon footprints”) per unit of nutritional density when compared with other foods (Williams et al., 2020b, 2020a). Legume cropping doesn’t require the application of nitrogen fertiliser, by virtue of their capacity to biologically fix atmospheric nitrogen (McCrory et al., 2010; Wagner, 2011). Legume cropping bypasses the inefficient livestock production stage involved in producing animal-derived protein foods (Nadathur et al., 2017), fertilises soils naturally, and improves soil structure and health (Meena and Lal, 2018), and grain legumes provide a rich source of protein and fibre to the human diet (Foyer et al., 2016).

However, without substantial processing, legumes are not as palatable as meat for many consumers, and current legume con-

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Nomenclature

BB (BR)	Beef burger (Brazilian beef)
BB (IE)	Beef burger (Irish beef)
COC	Carbon opportunity cost
DV_{EFA}Recommended daily value intake of essential fatty acids	Recommended daily value intake of essential fatty acidsgrams
DV_{prot}Recommended daily value intake of protein	Recommended daily value intake of proteingrams
DV_{fib}Recommended daily value intake of fibre	Recommended daily value intake of fibregrams
EFAAmount of essential fatty acids in 100 g of product	Amount of essential fatty acids in 100 g of productgrams
EoL	End of life
EP	Eutrophication potential
FibAmount of fibre in 100 g of product	Amount of fibre in 100 g of productgrams
FU	Functional unit
GHG	Greenhouse gas
GWP	Global warming potential
HH	Human health
LU	Land use
NDU	Nutrient density unit
PCR	Product Category Rules
PEF	Product environmental footprint
ProtAmount of protein in 100 g of product	Amount of protein in 100 g of productgrams
RU	Resource use
S_iAmount of kilocalories in 100 g of product	Amount of kilocalories in 100 g of productkcal
VB	Vegetarian burger (plant-based burger)

sumption in Europe represents only 1% of daily calorie intake (FAO, 2019). Processing legumes into meat analogues that have the same appearance, texture, and taste as meat could support a sustainable and healthy transition away from meat consumption with little consumer effort while meeting growing global protein demand and complying with dietary guidelines (Harwatt et al., 2017; Heller and Keoleian, 2018; Khan et al., 2019; Kumar et al., 2017; Röös et al., 2018; Stehfest et al., 2009). In the United Kingdom, more than half of consumers over 16 years in age reported eating meat substitutes over the last six months to September 2020, and 55% reported eating alternatives to meat processed products, such as legume-based burgers (Mintel Group Ltd., 2020). The marketing of legume-based products could benefit by environmental and nutritional labelling. There remains a need therefore, to validate the simultaneous environmental and health credentials of these vegetarian alternatives, many of which contain ingredients of varying geographical provenance, and involve a high degree of processing associated with significant environmental burdens.

Table 2.

Life Cycle Assessment (LCA) is a method used to quantify the environmental impacts of a product, 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 disposal (ISO, 2006)**.** Existing LCA studies comparing vegetarian burger patties with beef patties though, fail to integrate nutritional content as part of the functional unit (Heller and Keoleian, 2018; Khan et al., 2019), despite the fact that improving the nutrition of global diets is one of the key challenges of the food sector today (Willett et al., 2019). Fibre, for example, is a key nutrient lacking in Western diets, and a lack of it is associated with diabetes and obesity (Brennan, 2005; van Dooren et al., 2014), cancer, and heart disease (Kendall et al., 2010). Here, we use the Nutrient Density Unit (NDU) as proposed by van Dooren (2016) as a functional unit to compare the environmental burdens of the meat and vegetarian patties.

Another significant limitation of previous LCA studies on plant versus beef-based patties is their limited approach to calculating the carbon impact of the patties. Existing studies do not include the Carbon Opportunity Costs (COCs) associated with the comparatively large land requirements of cattle rearing as opposed to plant protein production (Heller and Keoleian, 2018; Khan et al., 2019; Lynch and Pierrehumbert, 2019). Land is a critically constrained resource with respect to multiple competing uses in relation to net zero GHG emission targets. As large areas will be needed for GHG offset activities (Masson-Delmotte et al., 2019), including COCs of land use in the comparison is key in determining the environmental benefits of plant and beef-based patties.

In addition to the carbon footprint limitations of existing comparative LCA studies of meat substitutes, the range of environmental impacts investigated is scarce, looking solely at carbon footprint, aquatic eutrophication, non-renewable energy use, land occupation, and water consumption (Heller and Keoleian, 2018; Khan et al., 2019). The Product Environmental Footprint (PEF) guidelines used in our study follow a standardisation initiative and offer a much more complete impact assessment package (European Commission, 2018). Additionally, although different food production methods have a wide range of environmental impacts, especially for beef systems (Poore and Nemecek, 2018), the existing comparative studies of meat and meat substitutes only include one beef system. To address this limitation, this study assesses different cattle rearing systems, from Brazil, Ireland, South Africa, France, and America.

The purpose of our study was to determine whether the consumption of a vegetarian burger patty is associated with a lower environmental impact than that of a burger patty made with beef from different cattle rearing systems, based on their nutrient density. Furthermore, we expand the boundaries to include carbon opportunity costs associated to the production of the different burger alternatives, and contextualise their impacts to achieve the net zero GHG emission and wider climate neutrality targets of the United Kingdom (Shepheard, 2020).

2. Materials and methods

2.1. Goal, scope, and boundary definition

This study is a comparative assertion of the overall environmental impacts arising from the consumption of a vegetarian burger patty (VB) with a conventional beef burger (BB) with Irish (IE) or Brazilian (BR) beef, accounting for their nutritional functionality. Inputs and outputs for all processes involved in the life cycle of the VB were recorded, but due to intellectual property protection, ingredients were grouped into categories of product in Table A.1 of the Appendix. The aim was to assess the relative environmental performance of the three products by performing an attributional LCA. Three central products were compared:

1) VB – 4 oz burger patty made in the UK with plant-based ingredients sourced globally.

2) BB (IE) – 4 oz burger patty made with Irish beef in the UK.

3) BB (BR) – 4 oz burger patty made with Brazilian beef in the UK.

The open-source software OpenLCA v1.10.2 (GreenDelta, 2020) was used to calculate the environmental footprint of the two products from cradle to fork, using Agrifootprint v3.0 (Durlinger et al., 2017), Ecoinvent v3.6 (Wernet et al., 2016) international databases. End of life was excluded from the analysis, as it was assumed to be similar for all three products, and not a major contributor to life cycle burdens of meat products. Inventory data for the VB were collected specifically for this study from a British company manufacturing the VB (Pers. Comm., 2019). Data on the BB were modelled as though the burgers were produced in the UK with beef received from either Brazil or Ireland using secondary data. Economic allocation was used to allocate burdens between the beef co-products and the processing co-products of the VB. Economic allocation percentages for beef co-products were extracted from the PEF guidelines (European Commission, 2018). As a sensitivity analysis, the environmental performance of the three products were also compared when using a simple mass allocation used for VB co-products, and biophysical allocation for the BB (IE) and BB (BR) beef co-products (Chen et al., 2017). Allocation factors are reported in Table A.2. of the Appendix. Biophysical allocation represents allocation of co-products based on energy flows and other causal relationships (Chen et al., 2017). To determine whether results were statistically significant, a modified Null Hypothesis at the additional beef systems, the Bonferroni correction was $\alpha b = 0.05/96 = 0.0005208$ due to the 6 pairs of alternatives. The effect size was set at $\delta 0$=0.2.

Fig. 1 illustrates the system boundaries for the cradle to fork assessment of the VB and BBs (IE and BR). The environmental footprints of the burgers were assessed across the sixteen environmental impact categories recommended in the PEF Category Rules Guidance (European Commission, 2018). To assist in the interpretation of environmental burdens across several categories, results were normalised by global person equivalents with the PEF recommended factors to generate comparable normalised scores across impact categories (European Commission, 2018).

2.2. Functional units

Two functional units (FUs) were used. First, a simple weight FU expressed as a single 4 oz burger patty was applied, as per recent vegetarian burger LCAs (Heller and Keoleian, 2018; Khan et al., 2019). Second, the Nutrient Density Unit (NDU) was used to account for differences in nutrient density between products (Saget et al., 2020; Van Dooren, 2016; Williams et al., 2020b, 2020a). The use of the latter was to ensure that products were compared per unit of nutrient density, which favours foods that have a high ratio of nutrients to energy. The NDU correlates with the more complete Nutrient Rich Foods index 12.3 (Saget et al., 2020). A nutritional analysis of the VB and BBs was performed with the pan-broiled method with one sample in triplicates, so that no additional fat was added and nothing else but cooking itself would alter the nutritional values. Protein content was analysed using the Kieldahl method (ISO 1871:2009) (ISO, 2009), energy content following the EU regulation 1169/2011 (European Union, 2011), fibre content using the Enzymatic-Gravimetric Method from the AOAC 991.43 and AOAC 985.29 (Lee et al., 1992; Prosky et al., 1985), and essential fatty acids content using gas chromatography (FID) from ISO 12,966–1:2014; 12,966–2:2011; 12,966–3:2016 (ISO, 2016, 2014, 2011). It was assumed that the nutritional content of BBs was the same, regardless of the geographical origin of beef (BR or IE).

The NDU was applied following Van Dooren's (2017) formula (1).

$$\mathrm{NDU} = \frac{\left(\frac{\mathrm{EFA}}{\mathrm{DV_{EFA}}}\right) + \left(\frac{\mathrm{Protein}}{\mathrm{DV_{prot}}}\right) + \left(\frac{\mathrm{Fibre}}{\mathrm{DV_{fibre}}}\right)}{3 \times \left(\frac{S_i}{2000\ \mathrm{kcal}}\right)} \quad (1)$$

Table 1
Summary of the nutritional composition of 100 g of the vegetarian and beef burger patties, pan-broiled.

Content per 100 g cooked	VB	BB (IE and BR)
Energy (kcal)	210	248
Protein (g)	15.9	23.4
Dietary fibre (g)	5.8	0
EFAs (g)	2.1	0.40
NDU	2.28	1.35
NDU (adjusted)	2.20	Non applicable

Nutritional results for the pan-broiled products, NDU results for the cooked VB and for the cooked BB (IE and BR) are presented in Table 1.

The energy content of the two products was similar, with 210 kcal per 100 g VB, cooked, versus 248 kcal per 100 g BB (IE and BR), cooked. Nutritional content varied greatly between the VB and BB (IE and BR), with the BBs (IE and BR) having 32% more protein, but no dietary fibre versus 5.8 g of fibre per 100 g cooked VB, and the VB having 81% more essential fatty acids.

The WHO (2007) states that adults have a net protein utilization that is comparable across all protein types. Moreover, the BB and VB assessed are sold in countries in which protein requirements are largely exceeded. Therefore, protein digestibility should not be of concern when comparing the two products. Nevertheless, we calculated the NDU of the VB with adjusted protein digestibility, assuming all protein in the VB originates from peas for simplicity. Pea concentrate protein digestibility amounts to 92% (Gilani and Lee, 2003), versus 100% digestibility assumed for animal protein. Therefore, the NDU for the VB was adjusted to account for 14.6 grams digestible protein per serving (Equation 4), versus 15.9 grams when not adjusted. The adjusted NDU delivered by a VB portion is 2.20 (versus 2.28 unadjusted).

2.3. Vegetarian burger inventory

The VB is made of 16 different crops, with legume-based additives, fibrous and oil ingredients, legume- and cereal-based proteins, flavouring and seasoning ingredients, bulking ingredients, and vitamins. The VB ingredients come from various countries worldwide, and often are shipped to a first factory where they are processed, then shipped to the UK. In the UK, the ingredients are assembled and the obtained burger is packaged. The amount of energy required to mix the ingredients and form the patty was extracted from Davis & Sonesson (2008). The VB is then sent to the point of sale, with 73**%** of the products sold within the United Kingdom, 5% in other European countries, and 22% outside of Europe (Pers. Comm., 2019). Transportation modes and distances were defined using the PEF guidelines, using Searates (2020) to estimate transoceanic distances. Land transport distances were calculated using centroids of countries (Google, accessed 2020). Following the PEF guidelines (European Commission, 2018), 0.38 km of consumer transport from the home to the retail centre was attributed to the patty component of an average shopping trip. The VB is then stored for two days in the fridge, requiring 0.099 Wh of energy, calculated with the formula from EPD International AB (2019). The consumption phase was modelled following EPD International AB (2019), with a cooking time of 3 minutes each side for the VB, using 0.55 kWh. Trace elements that represent less than 0.5% of the VB were excluded from the LCA, due to lack of data on the environmental impact of these elements.

2.4. Beef burger inventory

Beef of Irish origin was assessed since it represents 38% of beef imports to the UK, with a total of 384 thousand tonnes of Irish

Table 2
Inventories for a 4 oz (113 g) vegetarian (VB) and beef burgers (Irish and Brazilian beef), from “field to fork” .

Stage	Input / output / process	Units	VB		BB (IE)		BB (BR)		Source of information
			Input	Output	Input	Output	Input	Output	
Beef production and transport	Fertiliser (N) w/o grain and meal	kg			0.020		0.007		Database
	Urea, as N w/o grain and meal	kg			0.005		0.005		Database
	Fertiliser (P_2O_5) w/o grain and meal	kg			0.003		0.012		Database
	Fertiliser (K_2O) w/o grain and meal	kg			0.003		0.010		Database
	Feed for cattle (grain+meal)	kg			0.64		0.067		Database
	Manure, from cow	kg			1.6				Database
	Lime	kg			0.1		0.2		Database
	Land, total of crops and grazing	m^2			7.7		17.3		Database
	Water	L			0.3		0.03		Database
	Beef cattle for slaughter	kg				0.23		0.23	Database
	Beef transport, lorry with refrigeration machine	kg.km			14.7		113.4		(European Commission, 2018)
	Beef transport, train with refrigeration machine	kg.km			27.2				(European Commission, 2018)
	Beef transport, barge/ship with refrigeration machine	kg.km			30.6		1136		(European Commission, 2018)
Legume-based additive	Legume-based additive	kg	0.0011						Company
	Transport, transoceanic ship with refrigeration machine	kg*km	1829						Company
	Transport, lorry with refrigeration machine	kg*km	295						Company
Fibrous ingredients	Fibrous ingredients	kg	0.2						Company
	Transport, lorry >32t	kg*km	7.7						Company
	Transport, train	kg*km	1.6						Company
	Transport, barge	kg*km	1.8						Company
Oil ingredients	Oil ingredients	kg	0.009						Company
	Transport, lorry >32t	kg*km	3.8						Company
	Transport, train	kg*km	2.1						Company
	Transport, transoceanic ship	kg*km	47.8						Company
	Transport, barge	kg*km	2.4						Company
Legume-based protein	Protein extract	kg	0.030						Company
	Protein extract transport, lorry, with refrigeration machine	kg*km	23.4						Company
	Protein transport, transoceanic ship, with refrigeration machine	kg*km	171.5						Company
	Protein extract transport, train, with refrigeration machine	kg*km	2.7						Company
	Protein extract transport, barge, with refrigeration machine	kg*km	3.1						Company

(*continued on next page*)

Table 2 (*continued*)

Stage	Input / output / process	Units	VB		BB (IE)		BB (BR)		Source of information
			Input	Output	Input	Output	Input	Output	
Cereal-based protein	Protein extract	kg	0.006						Company
	Protein extract, >32t lorry	kg*km	0.7						Company
	Protein extract transport, barge	kg*km	1.5						Company
	Protein extract transport, train	kg*km	1.4						Company
Flavouring and seasoning ingredients	Flavouring & seasoning ingredients	kg	0.037						Company
	Heat, natural gas	kWh	0.028						Company
	Flavouring & seasoning transport, >32t lorry	kg*km	23						Company
	Flavouring & seasoning transport, barge	kg*km	43.5						Company
	Flavouring & seasoning transport, train	kg*km	38.7						Company
Bulking ingredients	Bulking ingredient	kg	0.012						Company
	Bulking ingredient transport, >32t lorry	kg*km	11.4						Company
	Bulking ingredients transport, transoceanic ship	kg*km	68.5						Company
Vitamins	Vitamins	kg	0.0015						Company
	Vitamin transport, >32t lorry	kg*km	1.4						Company
	Vitamin transport, transoceanic ship, with refrigeration machine	kg*km	27.2						Company
	Vitamin transport, train, with refrigeration machine	kg*km	0.11						Company
	Vitamin transport, barge, with refrigeration machine	kg*km	0.13						Company
Packaging	Extrusion, plastic film	g	6.55		6.55		6.55		Company
	Folding boxboard production	g	4.05		4.05		4.05		Company
	Packaging transport, lorry, >32t	kg*km	1.56		1.56		1.56		Company
	Packaging transport, train	kg*km	2.97		2.97		2.97		Company
	Packaging transport, ship	kg*km	3.82		3.82		3.82		Company
Burger production	Energy for grinding/mixing electricity	MJ	4.20		4.20		4.20		(Kamdem and Hardy, 1995)
Distribution	Burger transport, lorry with refrigeration machine	kg*km	130.3		130.3		130.3		(European Commission, 2018)
	Burger transport, transoceanic ship with refrigeration machine	kg*km	491.0		491.0		491.0		(European Commission, 2018)
	Burger transport, passenger car	km	0.159		0.159		0.159		(European Commission, 2018)
Storage	Energy for cooling	kWh	0.099		0.099		0.099		(European Commission, 2018)
Cooking	Energy for cooking gas	kWh	0.28		0.69		0.69		(European Commission, 2018)
	Energy for cooking electricity	kWh	0.09		0.23		0.23		(European Commission, 2018)
	Cooked burger patty	Item		1		1		1	

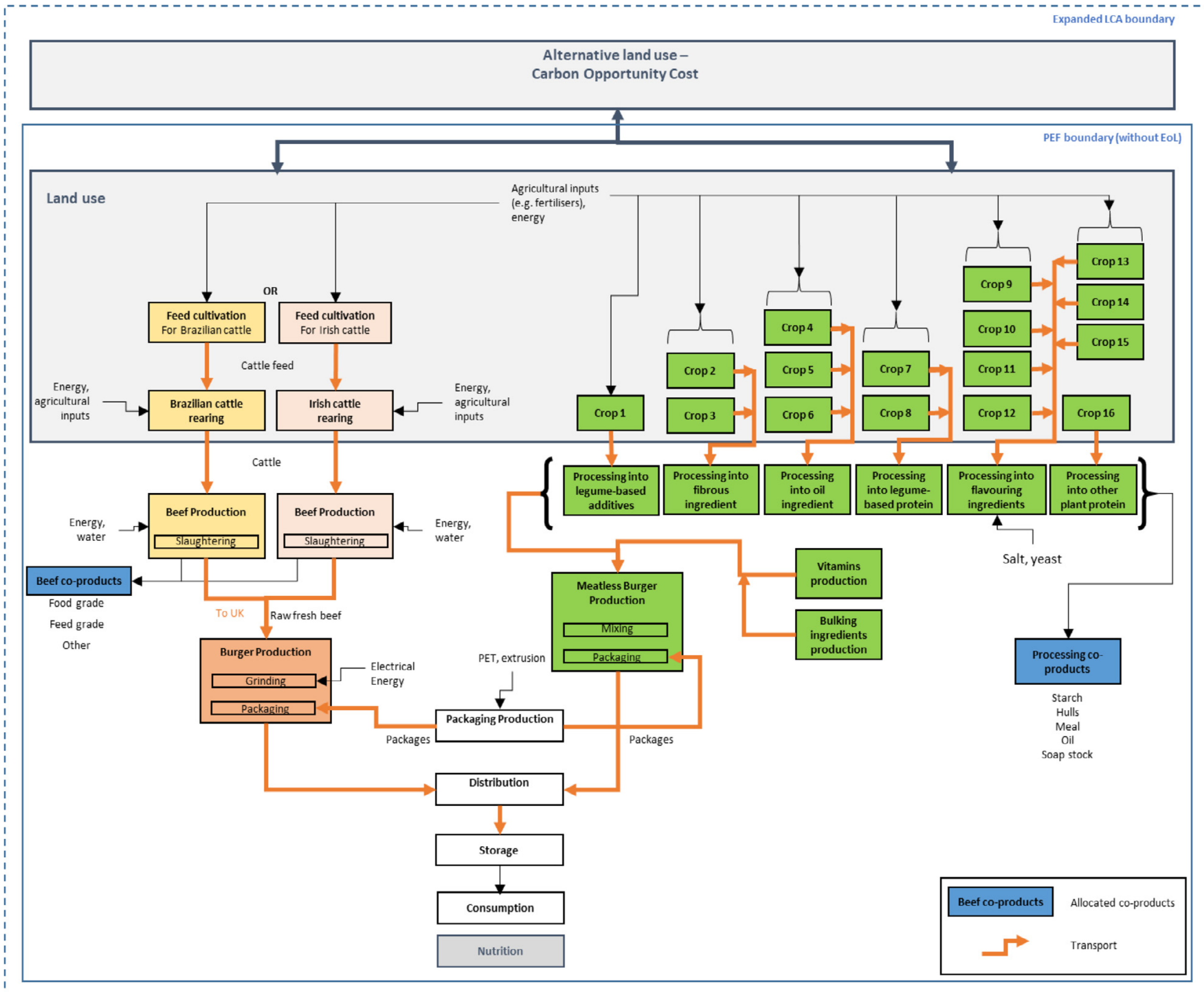

Fig. 1. System boundary of vegetarian (VB) and beef burger production BB (BR and IE), from cradle to fork. Beef burger production is represented in red (left), vegetarian burger in green (right), and the bottom middle represents the common stages to both products in white.

beef import reported by the UK (United Nations, 2020). Brazilian beef was also assessed, as Brazil is the largest international exporter of beef and is targeting greater exports into European countries, for example with the Mercosur agreement (European Commission, 2019; Zu Ermgassen et al., 2020). These two origins of beef are representative of different grass-fed systems. Sensitivity analyses were also run using beef from cattle systems in South Africa, France, and the United States in order to show the full range of possible outcomes for BBs. Data on the VB was collected from a manufacturing company in the UK.The BBs modelled were made of 100% beef using secondary life cycle inventory data from Agri-footprint v3.0 and Ecoinvent v3.6 (Durlinger et al., 2017; Wernet et al., 2016). Farm level processes and transport to and from the slaughterhouse are specific to BB (IE) and BB (BR). For the BB (IE), the beef system used in the inventory was of an average beef farm in Ireland from Agrifootprint v3.0 (Durlinger et al., 2017). For the BB (BR), the beef system is a representative combination of several cattle farming systems in Brazil. Intensive beef cattle and fat steers rearing dominated the market, representing half of the market process. An amount of 4 oz (0.113 kg) raw fresh beef requires 0.247 kg of beef cattle live weight. This involves 0.69 kg of compound feed made with wheat, barley, corn, oats, rapeseed, soybean, and sugar cane products. In addition to the compound feed, 2.58 kg of grass silage and 13.1 kg of grazed grass over two years complete the cattle diet to obtain the 4 oz (0.113 kg) patty. A distance of 100 km is covered by truck to transport the cows between the farm and the slaughterhouse (Durlinger et al., 2017). The slaughtering process of 0.247 kg of cattle produces 0.113 kg of fresh meat, the rest being category 1, 2, and 3 co-products, food grade bones and fat, and hides and skins. Beef transport from the slaughterhouse to the factory was modelled according to the PEF guidelines (European Commission, 2018). To grind the meat into a burger, 4.2 kJ of electricity were used, based on Kamdem & Hardy (1995). The obtained BB is then packaged, transported, and stored as described in Section 2.3. Energy use during the cooking stage was calculated based on a cooking time of 5 minutes on each side for the BB, using 0.92 kWh of electricity (EPD International AB, 2019a).

Because of the diversity of cattle rearing systems globally, a sensitivity analysis was run with additional cattle systems from South Africa (ZA), France (FR), and the United States (US) across the categories in which at least one burger patty had a burden of at least 5E-4 global person equivalents, as determined by our assessment in the first part of the publication (Section 3.1). These beef cattle systems were selected due to the limited availability of cattle data in existing databases. The South African system was taken from Ecoinvent v3.6 (Wernet et al., 2016), and is representative of large commercial feedlots, with a combination of pastures

Table 3
Summary of environmental burdens for the 4 oz (0.113 kg) vegetarian burger (VB) and beef burgers (BB) made with beef from Ireland or Brazil, expressed per cooked product and per NDU with economic allocation performed for co-products. Cells in green indicate that the product has a significantly lower environmental burden ($p < 0.05$) than the other two alternatives in the respective impact category, while cells in red indicate that the product has a significantly higher environmental burden ($p < 0.05$) than the other two alternatives in that category.

Impact Category	Unit	Impact per 4 oz burger, cooked			Impact per NDU		
		BB (IE)	BB (BR)	VB	BB (IE)	BB (BR)	VB (adj.)
Acidification ter. & freshwater	mol H^+ eq	0.109	0.025	0.009	0.080	0.018	0.004
Cancer human health	CTUh	7.1×10^{-8}	1.3×10^{-6}	1.4×10^{-8}	5.3×10^{-8}	9.4×10^{-7}	6.5×10^{-9}
Climate change (w/o COC)	kg CO_2 eq	4.5	6.6	1.5	3.4	4.9	0.7
Climate change (with COC)	kg CO_2 eq	19.7	21.8	3.0	14.6	16.1	1.4
Ecotoxicity freshwater	CTUe	8.4	436.8	23.9	6.2	323.6	10.9
Eutrophication freshwater	kg P eq	0.0008	0.0003	0.0003	0.0006	0.0002	0.0001
Eutrophication marine	kg N eq	0.045	0.029	0.004	0.034	0.022	0.002
Eutrophication terrestrial	mol N eq	0.48	0.10	0.02	0.35	0.08	0.01
Ionising radiation, HH	kBq U-235 eq	0.34	0.35	0.24	0.25	0.26	0.11
Land use	Point	561	1906	75	415	1411	34
Non-cancer human health	CTUh	3.7×10^{-6}	6.8×10^{-4}	3.3×10^{-7}	2.8×10^{-6}	5.0×10^{-4}	1.5×10^{-7}
Ozone depletion	kg CFC11 eq	6.7×10^{-8}	1.0×10^{-7}	9.1×10^{-8}	5.0×10^{-8}	7.4×10^{-8}	4.1×10^{-8}
Photochem. ozone form.	kg NMVOC eq	0.011	0.007	0.005	0.008	0.005	0.002
Resource use, energy carriers	MJ	21.7	14.4	15.5	16.1	10.7	7.1
Resource use mins. & metals	kg Sb eq	4.7×10^{-7}	4.4×10^{-9}	3.7×10^{-8}	3.5×10^{-7}	3.3×10^{-9}	1.7×10^{-8}
Respiratory inorganics	disease inc.	7.8×10^{-7}	1.7×10^{-7}	7.1E-08	5.8×10^{-7}	1.3×10^{-7}	3.2×10^{-8}
Water scarcity	m^3 depriv.	1.39	0.41	0.40	1.03	0.31	0.18

and pens. Pastures are mainly natural, with few inputs. The French system was taken from Agribalyse v3.0 (ADEME, 2020) and is a mix of conventional production in extensive and semi-intensive grassland areas. The US system was taken from the EF database (Green Delta, 2019) and is characterised by intensive systems with no grazing in open-front barns. These cattle systems were then connected to the burger manufacturing and consumption steps, with transport from the beef country of origin to the UK calculated following the same methodology as for the BB (IE) and BB (BR). As a result, three additional BB scenarios were created for sensitivity analyses:

1) BB (FR) – 4 oz burger patty made with French beef in the UK.
2) BB (ZA) – 4 oz burger patty made with South African beef in the UK.
3) BB (US) – 4 oz burger patty made with US beef in the UK.

2.5. Carbon opportunity costs for UK scenario

The average person in the UK consumes around 1.06 kg of burger patty yearly (Department for Environment Food and Rural Affairs, 2020). Assuming all beef burger patties consumed by the UK population of 67 million (Office for National Statistics, 2020) could be substituted with vegetable patties, we calculated the potential carbon sequestration achieved by the resulting land sparing (Searchinger et al., 2018). For this, we utilised the COC data per ingredient type defined by Searchinger et al. (2018): 144 kg CO_2 eq per kg of beef, and at most 10.5 kg CO_2 eq per kg ingredient used in the VB.

3. Results

3.1. General results

The environmental impact results of the three products across the sixteen categories are recorded in Table 3 for the two functional units described previously. Per patty, The VB had a significantly lower ($p < 0.05$) environmental burden across 9 categories out of 16 per when compared to both BBs (IE and BR). The VB patty was associated with an environmental burden that was between 67% and 95% smaller than the BB (IE) and between 77% and 96% smaller than the BB (BR) in the climate change, marine and terrestrial eutrophication categories, land use, and acidification categories, respectively. Including COC increased the climate change burdens of the BBs by 15.2 kg CO_2e, and the VB by 1.5 kg CO_2e, resulting in burdens 3.3, 2.3, and 1 times higher than without COC for the BB (IE), BB (BR), and VB, respectively. The VB was not associated with significantly higher ($p < 0.05$) environmental burdens across any categories when compared to BBs (IE and BR), although its energy use resource carriers burdens were insignificantly different to those of the BB (BR).

The wide discrepancy in nutritional composition between the BBs (IE and BR) and VB resulted in significantly different NDU values**.** Due to a comparatively higher NDU even after adjustment for protein digestibility, the VB had a significantly lower ($p < 0.05$) environmental burden across 11 categories out of 16 per NDU (adjusted) when compared to both NDUs of BBs (IE and BR). One VB NDU was associated with an environmental burden that was between 80% and 97% smaller than the BB (IE) and 79% and 98% smaller than the BB (BR) in the climate change, marine and terrestrial eutrophication categories, land use, and acidification categories, respectively.

To determine which categories were the most relevant in the comparison, environmental burdens normalised per person equivalents across all categories (except for the toxicity-related categories owing to uncertain normalisation data) are shown per burger patty in Fig. 2. Categories with scores that exceeded 5E-4 person equivalents in at least one product were the land use, marine and terrestrial eutrophication, acidfication, respiratory inorganics, and climate change. Normalised scores were comparatively lower for the few impact categories where VB had higher burdens than the BBs (resource use minerals and metals and ozone depletion).

3.2. Process contributions

Process contributions across the sixteen environmental impact categories for the burger patties are recorded in Fig. 3. Beef production is responsible for most of the burdens across all categories in the BBs. It was responsible for at least 75% of the total climate change, land use, marine and terrestrial eutrophication, cancer and non-cancer human health, freshwater ecotoxicity, resource use minerals and metals, respiratory ingorganics, water scarcity, and acidification burdens. The climate change burden of the BB was due mostly to enteric methane emissions from cattle, a signif-

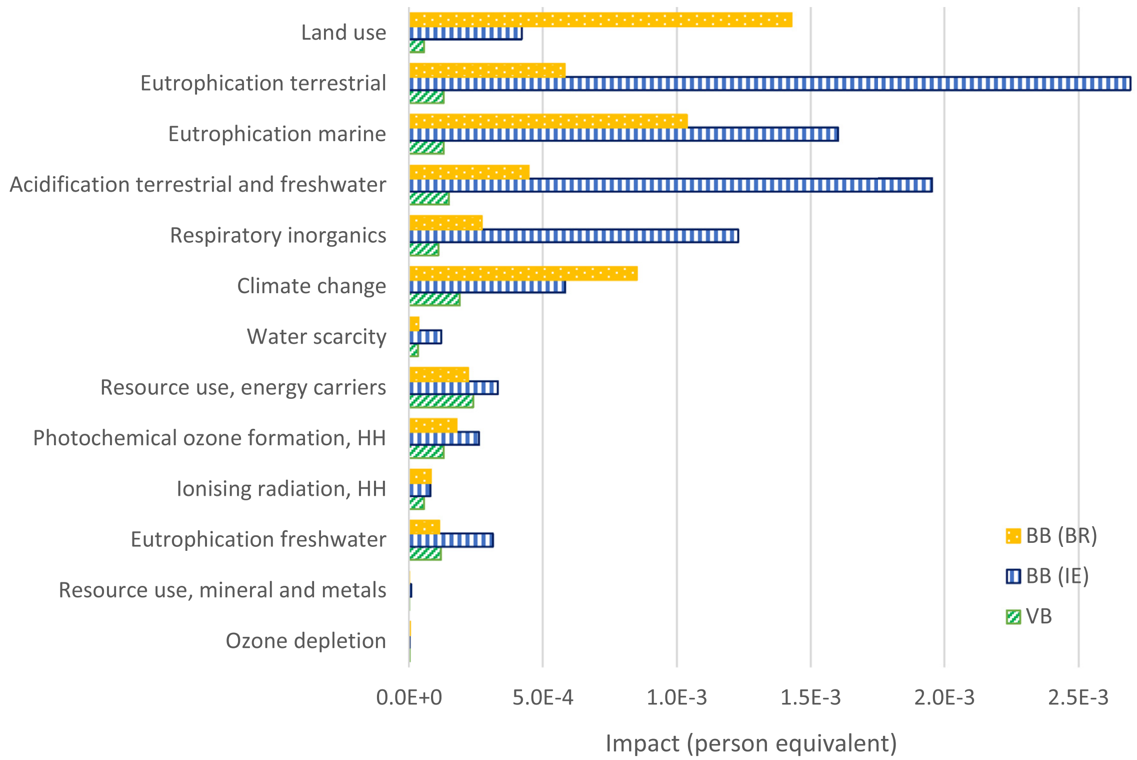

Fig. 2. Normalised environmental burdens of a vegetarian (VG) or beef patty from Irish BB (IE) or Brazilian beef BB (BR) across 13 impact categories per 4 oz burger Toxicity-related impact categories were excluded from the graphs.

icant proportion of acidification and terrestrial eutrophication due to ammonia emission to air from cattle raising and grass cultivation, and the high land use for raising the cattle (pastures) and growing all the crops for feed.

For the VB burger, flavouring and seasoning contributed to at least 20% of the total burdens across 8 categories out of 16. The climate change, photochemical ozone formation human health, resource use energy carriers and freshwater eutrophication burdens from flavouring were partly due to heat for production of one natural raw material. This aspect of the life cycle of the VB was the main reason for an insignificant difference between the energy use resource carriers burdens of VB and those of BB (BR), as mentioned in Section 3.1. The cereal-based protein production also contributed to at least 20% of the total burdens across 8 categories out of 16. It represented 25%, 21%, 18%, 43%, 31%, and 36% of total acidification, cancer human health, climate change, resource use minerals and metals, and terrestrial and marine eutrophication, respectively. The high freshwater ecotoxicity burden in the VB was due to cereal-based protein cultivation, which emitted cypermethrin, a neurotoxin insecticide, to the water.

It should be noted that the burger production happened to take place in the UK, and that producing it elsewhere would have little impact on the overall environmental performance of the burger patties assessed in this study, as the only process using British data was the electricity required for assembling the ingredients/grinding the beef, for which the electricity amount was assumed to be the same across all products. Transport was responsible to a relatively low share of the overall environmental burdens across all categories.

3.3. Extrapolation scenario results

Substituting the consumption of 19 grams of BB per week over the period of one year across the entire UK population with the consumption of VB could derive considerable environmental savings. Acidification saving could amount to 4 to 56 million mol H^+, and marine eutrophication between 13 and 23 thousand tonnes N equivalents.

The climate change burden including COC associated with the scenario in which all beef burgers were from Irish or Brazilian beef was of 12 or 14 million tonnes CO_2e, respectively. This represents a positive difference of 9.5 to 11 million tonnes CO_2e when compared to the equivalent amount of VB burgers consumed (eating the same quantity of VB burgers would represent 2.8 million tonnes CO_2e). This amount is equal to 2.1 to 2.4% of the annual territorial GHG emissions in the UK in 2019 (Department for Business, 2020).

3.4. Sensitivity analyses

Table 4 represents the environmental impact of one VB with physically-allocated burdens for the protein concentrates, oils, starches, and emulsifiers co-products, and one BB (IE and BR) biophysically-allocated between beef and beef processing co-products. Per patty, The VB had a significantly lower ($p < 0.05$) environmental burden across 6 categories out of 16, and significantly higher photochemical ozone formation and resource use energy carriers burdens when compared to both BBs (IE and BR). Biophysical allocation between beef and beef co-products greatly reduced the cattle rearing burdens attributable to beef (Table 5). For example, beef carbon footprints reduced by 63 and 65% when shifting from economic to biophysical allocation for the BB (IE) and BB (BR), respectively. In comparison, going from economic allocation to physical allocation of VB co-products decreased environmental burdens by a smaller magnitude (Table 5). For example, the climate change burden of the VB decreased by 10% when going from economically allocated burdens to physically allocated ones. On the other hand, the energy use resource carriers burden of the VB was higher than the one of both the BBs (IE and BR) when physical allocation was applied, due to a 35% or 10% reduction of the BBs

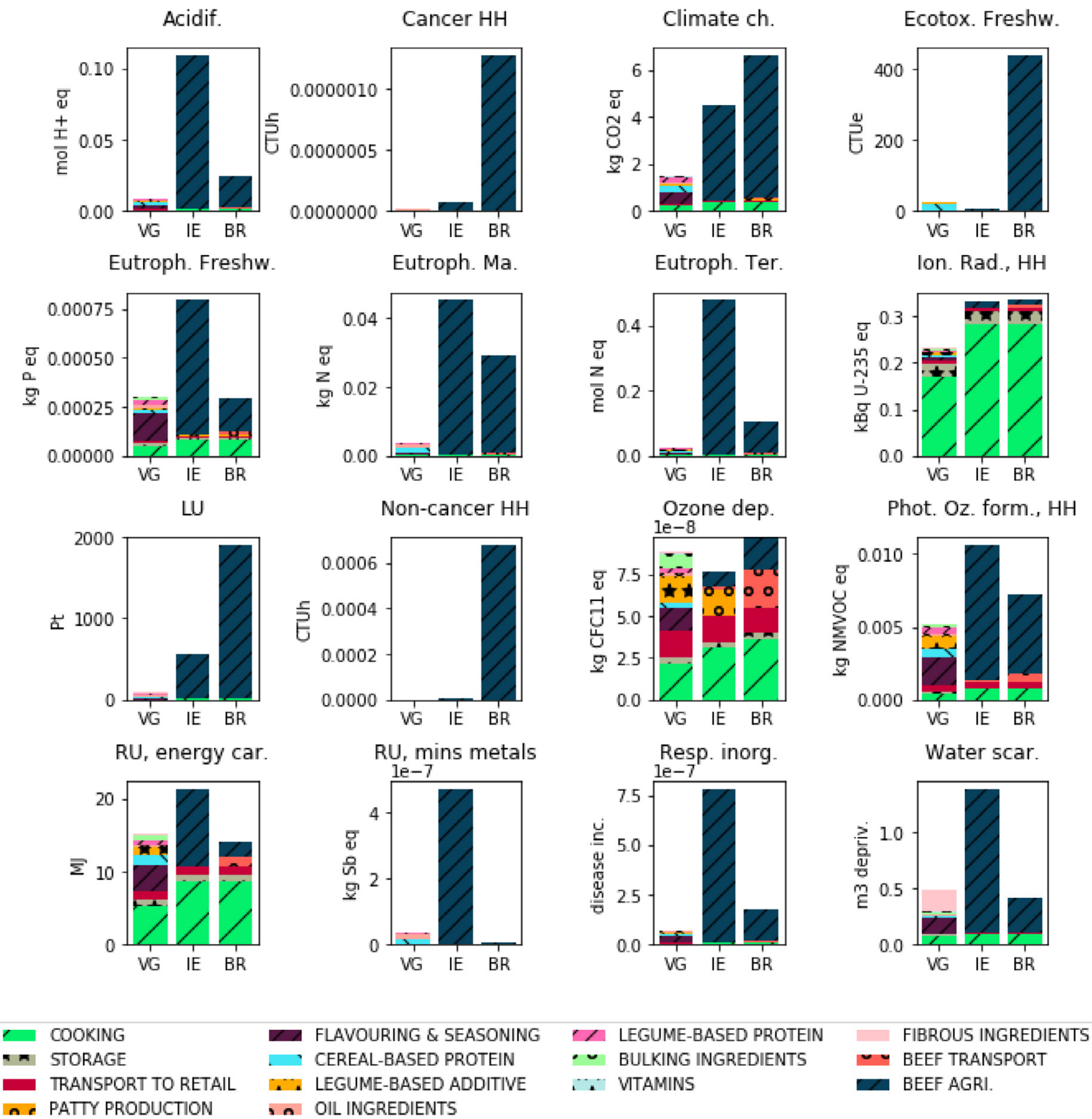

Fig. 3. Process contributions of one 4 oz (0.113 kg) patty cooked, from Irish beef (IE), Brazilian beef (BR), and vegetarian ingredients (VB) across 16 impact categories with economically-allocated burdens for beef production and plant ingredients processing co-products.

footprints. Per NDU, however, the VB had no significantly higher burdens per NDU when compared to both NDUs of BBs (IE and BR).

The results of the modified NHST that were significantly ($p < 0.05$) higher or lower than the other alternatives and that were common to all four modelling choices (economic allocation with weight or NDU functional units, and (bio)physical allocation with weight or NDU functional units) were recorded in Table A.3 of the Appendix. The VB alternative had a significantly lower environmental burden than both the BBs (IE and BR) across 6 categories out of 16. The VB had significantly higher cancer human health and ecotoxicity freshwater burdens than the BB (IE) for all scenarios.

Fig. 4 displays the relative environmental burdens arising from the production and consumption of a VB or a BB made of French, American, South African, Irish, and Brazilian beef across the categories in which at least one burger patty had a burden of at least 5E-4 global person equivalents. The water scarcity burden of the French cattle system was excluded due to the water data being not calculated across the full cattle life cycle (ADEME, 2020). Results of the modified NHST for these burgers were recorded in Table A.4. of the Appendix. Categories that were excluded because burdens from all systems were below the defined threshold were ozone depletion and ionising radiation human health. In addition to these excluded categories, the toxicity-related categories were also excluded, following the PEF guidelines, owing to uncertain normalisation data (European Commission, 2018).

The two products that had a higher footprint than 0.0015 person equivalents across some categories were the BB (ZA) and BB (IE). The BB (ZA) appeared to have the highest land use footprint, with a burden that was between 0.7 and 5 times higher than the other BBs. The land use footprint of BB (ZA) was 43 times higher

Table 4
Summary of environmental burdens of the burger patties with biophysically allocated beef co-products for the beef patties (Irish and Brazilian) physically allocated co-products of the vegetarian patty, expressed per burger patty and per Nutrient Density Unit adjusted, cooked. Cells in green indicate that the product has a significantly lower environmental burden ($p < 0.05$) than the other two alternatives in the respective impact category, while cells in red indicate that the product has a significantly higher environmental burden ($p < 0.05$) than the other two alternatives in that category.

Impact Category	Unit	Impact per 4 oz burger, cooked			Impact per NDU		
		BB (IE)	BB (BR)	VB	BB (IE)	BB (BR)	VB (adj.)
Acidification terrestrial and freshwater	mol H^+ eq	0.033	0.009	0.008	0.024	0.007	0.004
Cancer human health effects	CTUh	2.5×10^{-8}	3.7×10^{-7}	1.3×10^{-8}	1.9×10^{-8}	2.8×10^{-7}	6.0×10^{-9}
Climate change (w/o COC)	kg CO_2 eq	1.7	2.3	1.3	1.2	1.7	0.6
Climate change (with COC)	kg CO_2 eq	6.0	6.7	2.3	4.5	5.0	1.0
Ecotoxicity freshwater	CTUe	3	126	4	2	94	2
Eutrophication freshwater	kg P eq	0.0003	0.0002	0.0003	0.0002	0.0001	0.0001
Eutrophication marine	kg N eq	0.013	0.009	0.003	0.010	0.007	0.001
Eutrophication terrestrial	mol N eq	0.14	0.03	0.02	0.10	0.03	0.01
Ionising radiation, HH	kBq U-235 eq	0.33	0.34	0.25	0.25	0.25	0.11
Land use	Point	171	559	84	126	414	38
Non-cancer human health effects	CTUh	1.1×10^{-6}	0.0002	2.3×10^{-7}	8.3×10^{-7}	1.5×10^{-4}	1.0×10^{-7}
Ozone depletion	kg CFC11 eq	6.1×10^{-8}	8.6×10^{-8}	1.2×10^{-7}	4.5×10^{-8}	6.3×10^{-8}	5.4×10^{-8}
Photochemical ozone formation, HH	kg NMVOC eq	0.004	0.003	0.006	0.0030	0.0025	2.7×10^{-3}
Resource use, energy carriers	MJ	14.1	12.9	16.0	10.5	9.6	7.3
Resource use, mineral and metals	kg Sb eq	1.4×10^{-7}	1.7×10^{-9}	1.9×10^{-8}	1.0×10^{-7}	1.3×10^{-9}	8.4×10^{-9}
Respiratory inorganics	disease inc.	2.3×10^{-7}	6.0×10^{-8}	6.6×10^{-8}	1.7×10^{-7}	4.4×10^{-8}	3.0×10^{-8}
Water scarcity	m^3 depriv.	0.47	0.20	0.83	0.35	0.14	0.38

Table 5
Summary of the climate change and resource use energy carriers footprints of the burger patties obtained with different allocation methods (economic and physical), different functional units (serving and nutrient density unit), and different beef origins (Irish and Brazilian), as well as the vegetarian product.

	Functional Unit	Allocation method	Impact per 4 oz burger, cooked		
			BB (IE)	BB (BR)	VB
Climate change (kg CO_2 eq)	Serving	Economic	4.5	6.6	1.5
		(Bio)physical	1.7	2.3	1.3
	Nutrient Density Unit	Economic	3.4	4.9	0.7
		(Bio)physical	1.2	1.7	0.6
Resource use energy carriers (MJ)	Serving	Economic	21.7	14.4	15.5
		(Bio)physical	14.1	12.9	16.0
	Nutrient Density Unit	Economic	16.1	10.7	7.1
		(Bio)physical	10.5	9.6	7.3

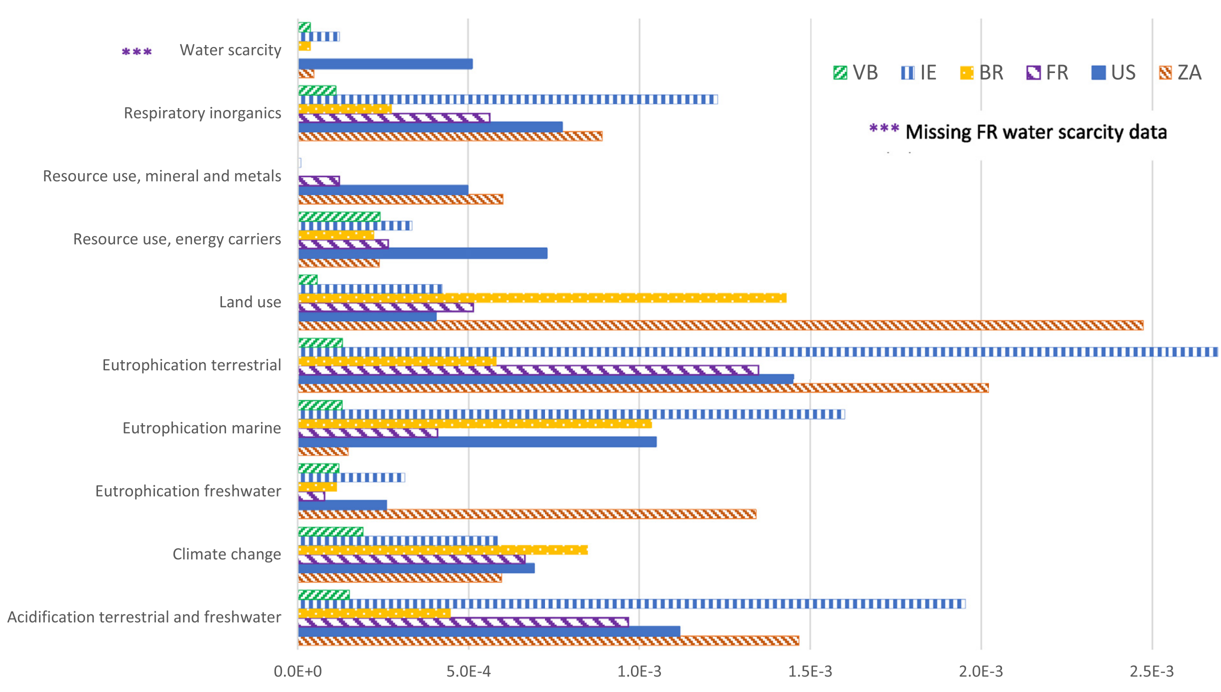

Fig. 4. Environmental impact per 4 oz burger of a vegetarian (VB) or beef patty from Irish BB (IE), Brazilian BB (BR), French BB (FR), American BB (US), or South African beef BB (ZA) across the nine impact categories with the highest environmental burdens, excluding the toxicity-related categories.

than that of the VB. Freshwater eutrophication was also the highest for the BB (ZA), with a burden between 3 and 16 times higher than that of all patties. The BB (IE) had a terrestrial eutrophication burden between 33 and 363% higher than that of all beef patties. The BB (US) appeared to have the highest burdens across water scarcity and energy use, resource carriers. The BB (FR) did not have the highest burden across any of the high impact categories displayed in Fig. 4, although data was missing across the water scarcity category.

4. Discussion

4.1. Superior nutrient density with lower environmental impacts

Overall, the VB is more nutrient dense whilst incurring a dramatically smaller environmental footprint across most impact categories than the BB. In addition to the higher environmental burdens in most categories incurred by the BB comes a comparatively lower NDU, due to a relatively higher protein content not compensating enough for the absence of dietary fibre and less essential fatty acids in the BB. To these nutritional contents, one can add the negative health effects stemming from red meat consumption mentioned in the introduction, namely cardiovascular diseases, cancer, and type 2 diabetes. Therefore, from a nutritional stance alone VB may carry a significant advantage over BB. Using an energy content FU (e.g. kcal) as a proxy for nutritional delivery can be misleading, as it results in the favouring of energy-dense nutrient-poor foods. Moreover, the vegetarian and beef burgers in this study have comparable amounts of kilocalories, hence the resulting environmental burdens per energy content would not yield significant differences when comparing with the serving-based FU. Using a simple protein FU as a proxy for nutritional delivery (Nijdam et al., 2012; Sonesson et al., 2017) would have been misleading, as the BB contains more protein than the VB, and as discussed previously, protein is not a limiting nutrient in developed countries, whilst nutrients such as fibre are lacking in modern diets. Vegetarian burger patties are alternatives to beef patties that consumers can opt for at the supermarket. With the double challenge of malnutrition and large negative environmental consequences of the food system in Europe, utilising the NDU as a FU allowed the integration of nutritional aspects for food alternatives in a more complete way than a limited energy content or single nutrient FU, yet in a more simple way than more extensive indices like the NRF 9.3 (Fulgoni et al., 2009). It would nevertheless be relevant to explore other nutritional FUs that are specifically adapted to the nutritional needs of the European population.

Besides the inclusion of nutritional contents in the FU, other approaches to integrate nutritional performance in LCA - and ultimately health effects - exist. One is to link epidemiological data to nutrients (Stylianou et al., 2015; Weidema and Stylianou, 2019), attributing health burdens scores to foods based on dietary risk factors. However, robustness of epidemiological data needs to be improved, and may differ between different populations.

The VB belongs to Group 4 in the NOVA classification**,** and is thus an ultra-processed food. However, in contradiction with the description of ultra-processed foods in (Monteiro et al., 2018), this study showed that an ultra-processed food can be nutrient-dense, and a higher source of dietary fibre and essential fatty acids when compared to its direct meat alternative. Nevertheless, it would be relevant to analyse and compare the burgers' contents of saturated fats, trans-fats, free sugars, and key micronutrients, as these are typically decreased in ultra-processed foods (Monteiro et al., 2018). It is important to keep in mind that such a vegetarian patty could contribute towards a transition to eating less meat and more whole, plant-based foods (Hu, 2003).

For those categories in which the VB was associated with higher burdens, significant improvements could be achieved by modifying the flavouring/seasoning mix and the cereal-based protein. Substituting the cereal-based protein with a legume-based one may significantly reduce its related burdens, as the assessment showed that the legume-based proteins assessed had a lower environmental burden across all categories, with 99%, 88%, and 64% less freshwater ecotoxicity, water scarcity, and climate change, for an equal quantity, respectively. Another mitigation option could be to source the cereal and legume ingredients from a cereal-legume crop rotation (Costa et al., 2020).

However, in this study as shown in Table 5, per burger patty in only the scenario using (bio)physical allocation of co-products, the energy use resource carriers burden of the VB was significantly higher than the one of both the BBs (IE and BR). The fact that results were highly different when biophysical allocation was selected compared to economic allocation for the beef co-products shows that results are very sensitive to modelling choices. Nevertheless, the Product Category Rules (PCR) guidance of meat of mammals imposes an economic allocation for slaughterhouse activities, as mass of inputs is not linearly correlated to mass of outputs (EPD International AB, 2019b). Moreover, some studies put forward the limits of the biophysical approach, which is nonetheless sensitive to the economic values of products (Mackenzie et al., 2017).

4.2. Contribution to climate neutrality targets

Recent research highlights that the Paris Agreement target of maintaining a temperature elevation of 1.5° or 2 °C since the pre-industrial age will not be possible without reducing the food system's GHG emissions (Clark et al., 2020). In June 2019, the British parliament passed an act to commit the UK to a "Net Zero" GHG emission target by 2050, meaning that all carbon emissions will have to be offset (Committee on Climate Change, 2019; Shepheard, 2020). Our proposed scenario in which all burger patties in the UK would be vegetarian instead of beef-based showed a potential climate change saving of 9.5 to 11 million tonnes CO2e. This is an example of a small change in consumer habit that can make a significant difference towards achieving climate stabilisation.

The high energy use burdens for producing the VB may be criticised with similar arguments presented in Lynch and Pierrehumbert (2019), saying that beef burgers, which emit comparatively more methane and less carbon dioxide than cultured meat over their life cycle, could cause less warming over the next 1000 next years compared with culture meat – if meat consumption decreases over time. In response to the limitation of the GWP_{100} approach that does not make ans adequate distinction between long- and short-lived climate pollutants, GWP* was created to take into account the temporal evolution of warming-equivalent emissions instead of simple GWP_{100} CO_2 equivalents (Lynch et al., 2020). However, the findings of Lynch and Pierrehumbert (2019) are significantly constrained by the exclusion of COCs, thus neglecting the important implications of the comparatively very large land requirements of cattle rearing. Quite apart from having a much smaller production footprint, VB patties had a COC of just 1.5 kg CO_2e compared with 15.2 kg CO_2e for BBs. Moreover, the UK energy mix is decarbonising at a rapid pace (UK Government, 2020), and this will reduce the carbon footprint of energy used in VB patty production at a faster rate than cattle rearing is projected to decarbonise (Lanigan et al., 2018). In fact, the minor trade-offs identified for VB across a small number of impact categories were partly the result of heat requirements for production of one natural raw material, and could be mitigated by a shift towards a more sustainable heat source. Huge improvements in the efficiency of cattle rearing would be needed to match the low burdens of the vegetarian burger patty, and the potential for GHG emissions reduction in beef systems is ultimately constrained by the inherent characteristics of ruminant livestock feed conversion (Audsley and Wilkinson, 2014; Beauchemin et al., 2011; Clark et al., 2001). Environmental burdens of the beef burger could still decrease by adopting a more sustainable cattle raising system, as shown with the great contrast of environmental profiles stemming from the five cattle systems presented in this study, which are coherent with results of previous studies (FAO, 2018; Leip et al., 2010; Poore and Nemecek, 2018). Nonetheless, irrespective of how methane is dealt with in climate neutrality targets (and substantial redctions in methane emisisons are required (Rogelj et al., 2018)), it is clear that a shift from beef towards vegetarian burgers could make a substaintial contribution towards climate neutrality goals.

4.3. Limitations

A conservative approach was undertaken when selecting proxies due to lack of primary data. While energy required to make the vegetable extracts was ignored due to the lack of data, the total burdens were attributed to the ingredients used, even though the co-products of these ingredients have an economic value, for which the allocation was not modelled. Allocating burdens between co-products used in the VB would have decreased the overall burdens of the ingredients. Regarding the beef burger inventory, obtaining data for British beef cattle would have been highly relevant, however this data was not available in any of the databases. Additionally, the use of different databases was a key limitation to compare different products. However, the primary aim of the study was to present a detailed footprint for a plant based burger and compare it with what was readily available in existing databases. The wide range of beef cattle processes available provided an overview of the relative comparisons between all burger patties. COC values used in this study were generic, as they were not distinguishing the differences between land spared in the different countries assessed. However, this was not necessary to convey the comparatively larger magnitude of the COC effect of beef versus that of plants used in the VB.

Conclusions

Considering Nutrient Density Unit as a functional unit highlighted the more positive nutritional profile of the vegetarian burger compared with the beef burger considered here, especially the higher content of fibre, a key nutrient for health lacking in Western diets. The results of our attributional LCA are aligned with other studies showing that vegetarian burgers have smaller environmental burdens than beef burgers. Overall, with economically-allocated burdens for beef and plant ingredients processing co-products, per burger patty, the vegetarian burger was associated with significantly lower ($p < 0.05$) environmental burdens than beef burgers made from Irish or Brazilian beef, across 9 out of 16 impact categories analysed. The relative differences between the Irish, Brazilian, French, South African, and American cattle systems highlighted the potentially large variance within a particular food product depending on origin and production processes, leaving scope for improvements. This range, however, was generally not sufficient to surpass the comparatively lower environmental impact of the VB.

Our study also demonstrated the significance of carbon opportunity costs in relation to the much smaller land requirement for the vegetarian burger versus the beef burgers. This could be critical as land is subject to more intense competition amongst alternative uses in the context of climate change, especially for carbon dioxide removal – and negates any doubt about the comparative climate advantage of vegetarian burgers in light of debate about how to quantify the warming effect of methane emissions from beef production. Replacing the beef burger patties eaten in the UK with vegetarian ones was shown to potentially extend the climate change savings to 9.5–11 million tonnes CO_2e, which is equivalent to 2.1 to 2.4% of the annual territorial GHG emissions in the UK in 2019. However, the ultra-processing required to produce the vegetarian patties is responsible for their NOVA group 4 classification, suggesting their potential as a “transition” food only. This “transition” product can support individuals to switch to a more nutrient-dense and environmentally sustainable diet that comprises more legumes and less red meat, in harmony with the UK’s net zero targets.

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

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Table A.1
Ingredients in one vegetarian burger patty.

1.1 g	Legume-based additive
45.5 g	Fibrous ingredients
11.4 g	Oil ingredients
29.9 g	Legume-based protein
5.7 g	Cereal-based protein
36.3 g	Flavouring and seasoning ingredients
11.4 g	Bulking ingredients
1.5 g	Vitamins

Table A.2
Physical, biophysical, and economic allocation factors for all of the co-products used as ingredients in the study.

	(Bio)physical allocation	Economic allocation
Other legume-based ingredients	0%	1%
Lecithin	0%	1%
Oil 1	64%	92%
Legume protein concentrate 1	56%	63%
Starch 1	74%	86%
Oil 2	96%	99%
Starch 2	10%	3%
Legume protein concentrate 2	47%	93%
Oil 2	98%	99%
Cereal protein	7%	77%
Oil 3	53%	72%
Beef meat	27%	93%

Table A.3
Positive results of the modified null hypothesis significance tests that were common to the economic allocation with weight or Nutrient Density functional units, and the (bio)physical allocation with weight or Nutrient Density functional units. Negative values from the Monte Carlo analyses were adjusted to zero (Muller et al., 2016).

Common to all scenarios investigated			
Is the mean impact of *j* at least 0.2 standard deviation units significantly lower than that of *k*?			
j↓ k→	VB	BB (IE)	BB (BR)
VB		yes	yes
BB (IE)	no		no
BB (BR)	no	yes	
j↓ k→	VB	BB (IE)	BB (BR)
VB		no	yes
BB (IE)	yes		yes
BB (BR)	no	no	
j↓ k→	VB	MB (IE)	MB (BR)
VB		yes	yes
MB (IE)	no		yes
MB (BR)	no	no	
j↓ k→	VB	BB (IE)	BB (BR)
VB		no	yes
BB (IE)	yes		yes
BB (BR)	no	no	
j↓ k→	VB	BB (IE)	BB (BR)
VB		yes	no
BB (IE)	no		no
BB (BR)	no	no	
j↓ k→	VB	MB (IE)	MB (BR)
VB		yes	yes
MB (IE)	no		no
MB (BR)	no	yes	
j↓ k→	VB	MB (IE)	MB (BR)
VB		yes	yes
MB (IE)	no		no
MB (BR)	no	yes	
j↓ k→	VB	MB (IE)	MB (BR)
VB		no	no
MB (IE)	no		no
MB (BR)	no	no	
j↓ k→	VB	MB (IE)	MB (BR)
VB		yes	yes
MB (IE)	no		yes
MB (BR)	no	no	
j↓ k→	VB	BB (IE)	BB (BR)
VB		no	yes
BB (IE)	no		yes
BB (BR)	no	no	
j↓ k→	VB	BB (IE)	BB (BR)
VB		no	no
BB (IE)	no		yes
BB (BR)	no	no	
j↓ k→	VB	BB (IE)	BB (BR)
VB		no	no
BB (IE)	no		no
BB (BR)	no	yes	
j↓ k→	VB	BB (IE)	BB (BR)
VB		no	no
BB (IE)	no		no
BB (BR)	no	yes	
j↓ k→	VB	BB (IE)	BB (BR)
VB		yes	no
BB (IE)	no		no
BB (BR)	yes	yes	
j↓ k→	VB	BB (IE)	BB (BR)
VB		yes	yes
BB (IE)	no		no
BB (BR)	no	yes	
j↓ k→	VB	BB (IE)	BB (BR)
VB		yes	no
BB (IE)	no		no
BB (BR)	no	no	

Table A.4
Results of the modified null hypothesis significance tests comparing all burger options modelled in this study with economically-allocated burdens for co-products, with the weight functional units. Negative values from the Monte Carlo analyses were adjusted to zero (Muller et al., 2016).

Meaning of result >	Is the mean impact of *j* at least 0.2 standard deviation units significantly lower than that of *k*?						
			no	yes			
Impact							
Acidification terrestrial and freshwater	j↓ k→	VB	BB (IE)	BB (BR)	BB (ZA)	BB (US)	BB (FR)
	VB		yes	yes	yes	yes	yes
	BB (IE)	no		no	no	no	no
	BB (BR)	no	yes		yes	yes	yes
	BB (ZA)	no	yes	no		yes	no
	BB (US)	no	yes	no	no		no
	BB (FR)	no	yes	no	no	yes	
Cancer human health effects	j↓ k→	VB	BB (IE)	BB (BR)	BB (ZA)	BB (US)	BB (FR)
	VB		no	yes	yes	no	no
	BB (IE)	yes		yes	yes	yes	yes
	BB (BR)	no	no		no	no	no
	BB (ZA)	no	no	no		no	no
	BB (US)	yes	no	yes	yes		no
	BB (FR)	yes	no	yes	yes	yes	
Climate change	j↓ k→	VB	BB (IE)	BB (BR)	BB (ZA)	BB (US)	BB (FR)
	VB		yes	yes	yes	yes	yes
	BB (IE)	no		yes	no	yes	yes
	BB (BR)	no	no		no	no	no
	BB (ZA)	no	no	yes		yes	yes
	BB (US)	no	no	yes	no		no
	BB (FR)	no	no	yes	no	no	
Ecotoxicity freshwater	j↓ k→	VB	BB (IE)	BB (BR)	BB (ZA)	BB (US)	BB (FR)
	VB		no	yes	yes	yes	no
	BB (IE)	yes		yes	yes	yes	no
	BB (BR)	no	no		no	no	no
	BB (ZA)	no	no	yes		no	no
	BB (US)	no	no	yes	yes		no
	BB (FR)	yes	yes	yes	yes	yes	
Eutrophication freshwater	j↓ k→	VB	BB (IE)	BB (BR)	BB (ZA)	BB (US)	BB (FR)
	VB		yes	no	yes	yes	yes
	BB (IE)	no		no	yes	no	no
	BB (BR)	no	yes		yes	yes	yes
	BB (ZA)	no	no	no		no	no
	BB (US)	no	yes	no	yes		no
	BB (FR)	no	yes	no	yes	yes	
Eutrophication marine	j↓ k→	VB	BB (IE)	BB (BR)	BB (ZA)	BB (US)	BB (FR)
	VB		yes	yes	yes	yes	yes
	BB (IE)	no		no	no	no	no
	BB (BR)	no	yes		no	yes	no
	BB (ZA)	no	yes	yes		yes	yes
	BB (US)	no	yes	no	no		no
	BB (FR)	no	yes	yes	no	yes	
Eutrophication terrestrial	j↓ k→	VB	BB (IE)	BB (BR)	BB (ZA)	BB (US)	BB (FR)
	VB		yes	yes	yes	yes	yes
	BB (IE)	no		no	no	no	no
	BB (BR)	no	yes		yes	yes	yes
	BB (ZA)	no	yes	no		no	no
	BB (US)	no	yes	no	yes		no
	BB (FR)	no	yes	no	yes	yes	
Ionising radiation, HH	j↓ k→	VB	BB (IE)	BB (BR)	BB (ZA)	BB (US)	BB (FR)
	VB		yes	no	yes	yes	yes
	BB (IE)	no		no	no	yes	yes
	BB (BR)	no	no		yes	yes	yes
	BB (ZA)	no	no	no		yes	yes
	BB (US)	no	no	no	no		no
	BB (FR)	no	no	no	no	yes	
Land use	j↓ k→	VB	BB (IE)	BB (BR)	BB (ZA)	BB (US)	BB (FR)
	VB		yes	yes	yes	yes	yes
	BB (IE)	no		yes	yes	no	yes
	BB (BR)	no	no		yes	no	no
	BB (ZA)	no	no	no		no	no
	BB (US)	no	yes	yes	yes		yes
	BB (FR)	no	no	yes	yes	no	

(continued on next page)

Table A.4
(continued)

Non-cancer human health effects	j↓ k→	VB	BB (IE)	BB (BR)	BB (ZA)	BB (US)	BB (FR)
	VB		yes	yes	yes	yes	yes
	BB (IE)	no		yes	yes	no	no
	BB (BR)	no	no		no	no	no
	BB (ZA)	no	no	yes		no	no
	BB (US)	no	yes	yes	yes		yes
	BB (FR)	no	no	yes	yes	no	
Ozone depletion	j↓ k→	VB	BB (IE)	BB (BR)	BB (ZA)	BB (US)	BB (FR)
	VB		no	no	yes	yes	yes
	BB (IE)	yes		yes	yes	yes	yes
	BB (BR)	no	no		yes	yes	yes
	BB (ZA)	no	no	no		no	no
	BB (US)	no	no	no	no		no
	BB (FR)	no	no	no	no	no	
Photochemical ozone formation, HH	j↓ k→	VB	BB (IE)	BB (BR)	BB (ZA)	BB (US)	BB (FR)
	VB		yes	yes	no	yes	yes
	BB (IE)	no		no	no	yes	no
	BB (BR)	no	yes		no	yes	no
	BB (ZA)	yes	yes	yes		yes	yes
	BB (US)	no	no	no	no		no
	BB (FR)	no	yes	no	no	yes	
Resource use, energy carriers	j↓ k→	VB	BB (IE)	BB (BR)	BB (ZA)	BB (US)	BB (FR)
	VB		yes	no	yes	yes	yes
	BB (IE)	no		no	no	yes	no
	BB (BR)	no	yes		no	yes	yes
	BB (ZA)	no	yes	no		yes	yes
	BB (US)	no	no	no	no		no
	BB (FR)	no	yes	no	no	yes	
Resource use, mineral and metals	j↓ k→	VB	BB (IE)	BB (BR)	BB (ZA)	BB (US)	BB (FR)
	VB		yes	no	yes	yes	yes
	BB (IE)	no		no	yes	yes	yes
	BB (BR)	yes	yes		yes	yes	yes
	BB (ZA)	no	no	no		no	no
	BB (US)	no	no	no	yes		no
	BB (FR)	no	no	no	yes	yes	
Respiratory inorganics	j↓ k→	VB	BB (IE)	BB (BR)	BB (ZA)	BB (US)	BB (FR)
	VB		yes	yes	yes	yes	yes
	BB (IE)	no		no	no	no	no
	BB (BR)	no	yes		yes	yes	yes
	BB (ZA)	no	yes	no		no	no
	BB (US)	no	yes	no	yes		no
	BB (FR)	no	yes	no	yes	yes	
Water scarcity	j↓ k→	VB	BB (IE)	BB (BR)	BB (ZA)	BB (US)	BB (FR)
	VB		yes	no	no	yes	NA
	BB (IE)	no		no	no	yes	NA
	BB (BR)	no	no		no	yes	NA
	BB (ZA)	no	yes	no		yes	NA
	BB (US)	no	no	no	no		NA
	BB (FR)	NA	NA	NA	NA	NA	

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