ENVIRONMENTAL ADVANTAGES OF COPRODUCING BEEF MEAT IN DAIRY SYSTEMS

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ABSTRACT

Beef meat, one of the more environmentally costly animal-based foods, can be produced in two general ways, as the main product on specialised farms or as a coproduct on dairy farms. In this study, two cases (a semi-confinement dairy farm (A) and a pasture-based dairy farm (B)) have been analysed by means of LCA to evaluate the environmental impacts associated with the coproduction of beef meat.

In both cases, purchased feed production was found to be the main cause of environmental impacts in most of the categories considered. Additionally, cow emissions to air were the main contributor for the global warming category. Comparing the two dairy systems, notably lower environmental impacts were obtained for B in 13 of the 18 categories analysed. Regarding CF, 8.10 and 8.88 kg CO_2eq/kg LW were obtained for A and B, respectively. These CF values were within the wide range found in the literature for beef meat (1.2-42.6 kg CO_2eq/kg LW).

Beef calves and cull cows are an important output of dairy farming, so that coproduction enables milk and meat with lower CF and associated environmental impacts to be obtained. In addition, the variability of the data found in literature and the lack of LCA studies based on real data for beef meat coproduced on dairy farms evidence the importance of in-depth study of this interesting topic.

Keywords: beef meat; carbon footprint; coproduct; LCA; dairy farm; environmental impacts.

1. INTRODUCTION

Nowadays, food production has become an important contributor to global environmental impacts, since this sector requires large amounts of raw materials, energy and water, and originates a considerable quantity of wastes. Specifically, it is responsible for approximately one third of the environmental impacts derived from household consumption in Europe (Laca et al., 2021). In addition, the environmental impacts derived from food systems are expected to worsen in the future, due to global trends of population growth and dietary choices (Cucurachi et al., 2019).

It is well known that animal-based foods entail higher environmental impacts than vegetable-based foods (Pechey et al., 2021; Kovacs et al., 2021). In particular, meat and dairy products, whose consumption is increasing worldwide (FAO, 2021), generate great environmental burdens (Westhoek et al., 2014; Canellada et al., 2018). The negative impacts of animal production have been increasingly acknowledged, and these include GHG emissions, eutrophication, biodiversity loss, degradation of soils, negative human health effects, etc. (Abín et al., 2018; Payen et al., 2020; Moberg et al., 2021; Saerens et al., 2021).

World meat production was 327 million tons in 2018 and it is projected to reach more than 360 million tons in 2028 (FAO, 2021). EU citizens consume 51 kg of meat per capita yearly (approximately twice the global average value). This means that, representing less than 7% of the global population, the EU consumes 12% of the world´s beef meat (Buckwell & Nadeu 2018). Current patterns of food production are unsustainable in several ways and many studies have drawn attention to the need to increase efficiency in the farming sector (Buckwell & Nadeu 2018). Livestock systems are responsible for a wide range of environmental impacts (Dopelt et al., 2019). To be more specific, almost 15% of all anthropogenic greenhouse gas (GHG) emissions are originated by global livestock (FAO, 2021), and beef production is responsible for about 41% of those emissions (De Vries et al., 2015).

The environmental impacts derived from beef production are determined to a great extent by the characteristics of the farming system used and this differs widely from one country to another and even within the same country (Beauchemin et al., 2011; Bureš & Bartoň, 2018). Quantifying these differences with respect to environmental performance is key to mitigate impacts of future global beef production (De Vries et al., 2015).

On dairy farms, milk and beef meat are frequently coproduced, i.e., although dairy cows produce milk, meat is obtained from culled cows and surplus calves. In fact, approximately 21% percent of the commercial beef supply in the US comes from dairy cows (FoodPrint, 2021). In contrast, specialised beef production systems produce only meat from beef cattle. Several examples that show the environmental benefits of coproduction in different food production systems, including fisheries and farms, can be found in the literature (Cederberg & Stadig, 2003; Cooper et al., 2013; De Vries et al., 2015; Laca et al., 2021).

Life cycle assessment (LCA) has been recommended as the reference technique for making a standardized assessment of the environmental impacts derived from food production (Herrero et al., 2020). Additionally, carbon footprint (CF) is an integrated and unified environmental indicator, which has been commonly employed to reflect GHG emissions of products (Yang & Meng, 2020).

When a process does not produce single outputs, but rather multiple coproducts, LCA must divide (or allocate) the environmental impacts of the whole process to these various coproducts. So, an allocation procedure in a multi-input/output process is carried out to attribute the shares of the total environmental impacts to the generated functional units resulting from the production system. Allocation between meat and milk based on mass is the most common strategy found in literature to approach the study of dairy farms from an LCA perspective (Baldini et al., 2017).

Although several LCA analyses of milk production have been published to date, few of these works have focused specifically on beef when it is coproduced (Baldini et al., 2017; Noya et al.; 2018). In addition, most LCA studies on beef meat production have targeted the estimation of GHG emissions, but have scarcely paid attention to other impact categories, such as eutrophication potential or land use (Flysjö et al., 2012; Huerta et al., 2016; Payen et al., 2020). Moreover, much of this work has been carried out employing simulations or model farms designed according to global databases, which are sometimes not representative of the reality of production systems.

Approximately 50% of Spanish bovine livestock are in the Northwest region of the country (Cantabria, Asturias and Galicia regions), more than 80% of this livestock corresponding to dairy farms that are usually of small size (with less than 100 cows) (MAPA, 2020). It is noticeable that, in Spain, the coproduction of beef meat and milk has not previously been analysed from an environmental perspective. In this work, two differently managed dairy farms in NW Spain have been selected as study cases, one a semi-confinement farm and the other a pasture-based farm. Derived environmental impacts and carbon footprints have been analysed and compared with other production systems worldwide. Additionally, the literature on the carbon footprint of beef meat has been reviewed and this is the first time that an overview of carbon footprint values of meat produced on dairy farms and specialised beef farms is provided. Thus, the final aim of this study has been to obtain objective information about the expected benefits of coproducing beef meat.

2. MATERIALS AND METHODS

2.1. Objectives and functional unit definition

LCA methodology was employed with the aim of determining the environmental impacts of beef meat coproduced on two dairy farms with different livestock systems. According to Payen et al. (2020), in both cases, the functional unit was defined as 1 kg of live-weight (LW).

2.2. System description and boundaries

The farms were located in NW Spain (Asturias), where dairy farms are usually semi-confinement systems of small/medium size, with an average number of 42 animals in 2020 (MAPA, 2020). The environmental assessment of both systems was carried out considering a “cradle to farm gate” perspective.

2.2.1 Case study A

This production system (A), which corresponds with a medium size system according to Table 1, is typical of this region, i.e., a semi-confinement farm where cows were housed and fed with fodder concentrate and forages (alfalfa, hay, maize silage and meadow grass silage). When the weather was warm, animals were left to graze freely for a few hours at midday. In the year of the study, the farm consisted of 72 head of livestock (Holstein) with a milk production of 365000 L; 21 male calves and 7 culled cows were sold for slaughtering (a total of 5355 kg LW). The farm had 30.45 Ha of land for farming. Manure and slurry were employed as fertiliser and wastewater was used to irrigate the fields and the crops.

2.2.1 Case study B

This case study analyses a pasture-based farm (B), which are commonly small size systems. In this farm, cows were left to graze freely on grass fields during the warm months of the year (May-October), whereas during the cold months (November-April) they were housed and fed fodder concentrate, maize and dry grass. This case study has been chosen since there are many challenges and opportunities for grazing in milk production systems in Europe. Specifically, increasing the practice of grazing on dairy farms would entail economic, environmental, animal welfare and social benefits, among others (Hennessy et al., 2020).

The year of the study, the farm comprised 13 head of livestock (12 Holstein and 1 Jersey with a total milk production of 40730 L); 6 male calves and 3 culled cows were sold for slaughtering (a total of 2068 kg LW) and 2 dead calves were managed as dangerous waste for incineration. The farm had 14 Ha of land for farming. Manure and slurry were employed as fertiliser, and wastewater was treated as municipal wastewater.

More details for both farms are given in Laca et al. (2020a) and Laca et al (2020b).

2.3. Inventory analysis

In both systems, average values corresponding to one year of production were employed. Inventory data, which were mainly collected through personal interviews with farmers, are summarized in Table 2.

The crops grown on the farms were not considered in the feed subsystem, but they were included in the inventory as “land occupation”. Emissions of CO_2, CH_4 and N_2O, derived from diesel combustion during farm activities were included with reference to the values reported for agricultural vehicles (IPCC; 2006), whereas CO, HC (hydrocarbons), NOx and PM (particulate matter) were calculated according to the maximum emissions established for heavy-duty vehicles in Directive 70/156/EC (Reşitoğlu, et al., 2015). Cow emissions to air were calculated according to the Technological Institute of Renewable Energies of Spain (ITER, 2008). Fertilisation emissions were obtained by assuming that dairy cattle slurry contains 3.08 g of nitrogen per kg (Parera i Pous et al., 2010) and about 30% of this nitrogen is emitted to the atmosphere as ammonia when manure and slurry are applied to soil (Misselbrook et al.; 2000).

Bull calves and culled cows were sold for slaughter and the mass allocation factor for meat was calculated as indicated by the International Dairy Federation (IDF, 2015), obtaining a value of 0.09 and 0.31 for semi-confinement and pasture-based systems, respectively. These allocation factors were employed to consequently correct the inventory data.

Additional information about inventory analysis, assumptions and calculations can be found in Laca et al. (2020a) and Laca et al (2020b).

2.4. Environmental impact assessment

Environmental impacts were analysed using the ReCiPe 2016 Midpoint (H) V1.01 method and the carbon footprints were determined by employing the Greenhouse Gas Protocol V1.01 / CO2 eq (kg) by means of the LCA software package SimaPro v8 in both cases. The databases used were USLCI and EcoInvent v3.

3. RESULTS AND DISCUSSION

3.1. Coproduction of beef meat in dairies

3.1.1 Case study A

As is shown in Figure 1A, cow feeding contributed more than 50% of the damaging impact for 13 of the 18 categories evaluated and more than 20% for the remaining 5 categories. It is noticeable that the cattle feed purchased subsystem was responsible for more than 90% of the environmental impact of the following categories: stratospheric ozone depletion, freshwater and marine eutrophication, mineral resource scarcity and water consumption. This agrees with literature data, since environmental impacts derived from livestock systems have been mainly attributed to animal feed production, not only in the case of ruminants, but also in case of monogastric animals (Abín et al., 2018; Fathollahi et al., 2018). Specifically, Roer et al. (2013), who studied the environmental burdens from combined milk and meat production in Norway, found that forage production accounted for 50% or more for most of the impact categories considered, which agrees with the results found here.

The fertilisation emissions subsystem (i.e., emissions originated by the release of NH_3 to the air due to the treatment of farmland with manure and slurry) contributed 60% and 74% to the fine particulate matter formation and terrestrial acidification categories, respectively, whereas the electricity subsystem comprised 50% of ionizing radiation category impacts. Electricity was also responsible for 28% and 20% of impact in human non-carcinogenic toxicity and freshwater and marine ecotoxicity categories, respectively. Transport contributed 24% and 15% to the terrestrial ecotoxicity and human non-carcinogenic toxicity categories, respectively, and diesel production represented 16% of the impacts in the fossil resource scarcity category.

Regarding the cow emissions subsystem, its contribution to global warming is considerable (53%), mainly due to the products of enteric fermentation, as it is well known that cattle production is associated with large CH_4 emissions (De Oliveira and Bourscheidt, 2017).

3.1.2 Case study B

In Figure 1B, the characterization results for a pasture-based dairy farm can be seen. Excepting global warming, fine particulate matter formation, terrestrial acidification and land use, purchased feed (in this case only fodder concentrate) was responsible for 50% or more of environmental impacts. In particular, this subsystem contributed 90% or even more, to the categories related to eutrophication and ecotoxicity and also to mineral resource scarcity category.

Cow emissions contributed 77% to the global warming category, whereas indirect emissions from manure and slurry employed as fertilisers were responsible for 89% and 78% of the impacts in the terrestrial acidification and fine particulate matter formation categories, respectively. It is important to highlight that methane manure emissions depend strongly on treatment technology (Moset el al., 2019; VanderZaag et al, 2021). For example, Sokolov et al. (2020) reported that manure acidification has a long-term treatment effect in reducing CH_4 production. Additionally, Van der Velden (2021) proposed recycling organic wastes on small-scale farms by means of closed-loop technological systems, which allows the production of fertiliser and biogas, thereby generating revenue. Diesel combustion emissions contributed approximately 10% to the ozone formation categories. Diesel production made up 36% of the fossil resource scarcity category and electricity accounted for 23% of the ionizing radiation impact. As most of the feed was produced in situ in study B, in this case the transport effect was almost negligible and only showed an observable effect on the terrestrial ecotoxicity category (3%). For this same reason, land occupation was the main contributor to the land use category, as adverse impacts in this category are mainly originated by farming practices (Lehmann et al., 2013).

3.2. Carbon footprint of beef meat in dairy farms and specialised beef farms

Ruminant meat production is associated with large environmental costs compared to other livestock products. Specifically, beef meat implies higher GHG emissions than meat from small ruminants, pork and chicken (Clune et al., 2017; Salami et al., 2019). Compared with a pig or a broiler, a beef animal is less efficient in converting the ingested nutrients into edible meat (De Vries & De Boer, 2010). The feed conversion ratio (amount of feed needed to increase the animal’s bodyweight by one kilogram) is approximately 7, 3 and 2 in beef, pork and chicken, respectively (STATISTA, 2020).

Tables 3 and 4 show an overview of the main papers on the carbon footprint of beef meat production worldwide that have appeared in the literature from 2003 until the time of writing. A notable rise in the number of studies on this topic can be observed, with more than 50% of the total having been published between 2017 and 2021, which clearly indicates the increasing importance of this issue. In addition, more than half of these papers describe work from the Americas (specifically, around 22% have been conducted in Brazil), whereas 36% have been carried out in Europe. It is noticeable that there is a lack of this kind of study in Spain. It should also be noted that almost all the investigations carried out in America employed simulations or model farms designed according to global databases. On the contrary, in Europe, many assessments analysed real case studies, so the results can be considered to be more reliable. However, very few employed real data to study the environmental performance of meat coproduced on dairy farms, as in the present work.

According to the reviewed literature (Tables 3 and 4), production of cattle feed and cow emissions are usually the main contributors to the meat CF, which agrees with results found in this assessment, since, as can be seen in Figure 2, these two subsystems together represent more than 90% of the CF in both systems analysed.

Different authors (Cerri et al., 2016; Bonesmo et al., 2013; Buratti et al., 2017; Morel et al., 2016) reported that 50-80% of the global CF value of beef meat was originated by enteric fermentation. This is in accordance with results found here, where cow emissions were responsible for approximately 50% and 80% of CF value in A and B. For this reason, diverse strategies have been proposed to reduce direct emissions from animals by modifying their diet. For example, Alvarez-Hess et al. (2019) found that feeding nitrate to ruminants decreases CH_4 emissions by between 16% and 32% in dairy cows and beef cattle, whereas Hünerberg et al. (2014) indicated that using low levels of high-fat distillers' grains in the feedlot diet can decrease enteric CH_4 emissions by approximately 7%. In addition, grain processing has been used for many decades to improve the digestibility of grains fed to finishing beef cattle and used to improve animal performance (Cole et al., 2020). More recently, Kinley et al. (2020) reported the effectiveness of *Asparagopsis taxiformis* as an anti-methanogenic for cattle feed. According to these authors, employing this marine red macroalga as a feed ingredient led to a decrease in steer methane emissions of up to 98%, without negative effects on feed intake, feed conversion efficiencies or rumen function. Additionally, no residues or changes in meat quality for the consumer were detected.

Additionally, since feed production is another main contributor to CF, cattle diet can be designed with the aim of reducing not only methane emissions derived from metabolism, but also GHG emissions associated with feed production. As is well known, in Europe a large contribution to GHG emissions in animal feed production is attributed to imported soybean products (mainly from Brazil), due to the CO_2 released by land use change. So the use of local crops could potentially decrease the GHG emissions derived from livestock systems (Zucali et al., 2018). Del Prado et al. (2013) reported lower CF values for cow diets containing small proportions of food that could be used to feed humans (e.g. cereals). So, one approach to move towards reducing the carbon footprint of beef meat could be improving the utilisation of plant by-products in animal diets (Salami et al., 2019). Harrison et al. (2015) proposed that the use of leucaena as forage reduced the emissions intensity compared to grazing Rhodes grass. Vasconcelos et al. (2018) suggested that depending on the grazing system, a reduction of approximately 29% in CO_2eq emissions could be achieved, whereas Cardoso et al. (2018) found that the change from extensively grazed degraded pastures to grass-legume mixed swards or N-fertilized improved pastures can reduce the meat CF by between one third and a half.

The carbon footprint values reported for beef meat (Figure 3) showed a high degree of variability around the world since, as mentioned above, they depend on different factors such as the farming system, cattle diets, methodological issues and system boundaries. The CF values found when considering a cradle to farm gate approach ranged between 1.2 and 42.6 kg CO_2eq/kg LW. The ranges of values reported for meat CF were, in general, similar for Europe and America, with a wider range of CF values when meat was produced in specialised beef farms than in dairy farms. The range of CF values found for the dairy farms is generally lower, but does overlap with the bottom part of the range for specialised beef farms, so CF values in the range 5-16 kg CO_2eq/kg LW were found for both specialised beef and for dairy farms. However, it is important to point out that in dairy farms the maximum CF was 16, while for the specialised beef farms a CF value of 9 kg CO_2eq/kg represented the minimum for real (not simulated) farms. The values obtained for carbon footprints in the case studies analysed in this study were within the range found in literature for coproduced beef meat (8.10 kg CO_2eq/kg LW for A and 8.88 kg CO_2eq/kg LW for B) (Figure 2). It should be mentioned that coproduction allows a decrease in CF that situates the GHG emissions derived from beef meat production in the same order of magnitude as those associated with the production of pork and even broiler meat (1.1-5.8 kg CO_2eq/kg LW for broiler meat and 1.1-9.4 kg CO_2eq/kg LW for pork meat at farm gate) (Andretta et al., 2021).

Finally, some analyses take into account GHG emissions and carbon sequestration in the calculation of CF, which contributes to obtaining lower carbon footprint values. For example, Horrillo et al. (2020), who analysed the carbon footprint of seven extensive organic farming systems in various *dehesas* in the southwest of Spain, included carbon sequestration, i.e., carbon fixation due to pasture and crop waste and carbon fixation in soil due to manure fertilization. According to these authors, the levels of carbon sequestration achieved compensation values near to 90% in meat-producing ruminant farms.

3.3. Environmental comparison of coproduction systems in case studies

As can be seen in Figure 4, when the environmental performances of the two dairy farms were compared, lower environmental impacts were associated with PBF in 13 of the 18 categories studied. Specifically, in these categories, the environmental impacts of A were 30-70% higher than those for the pasture-based farm. However, the PBF showed impacts between 10% and 29% higher than those found in the semi-confinement system for global warming, fine particulate matter formation, terrestrial acidification, human non-carcinogenic toxicity and land use. This agrees with results reported by Huerta et al., (2016) who compared the environmental impact of two typical production systems of meat beef in Mexico and found that the extensive system had better environmental performance than the intensive system for nine of the twelve studied categories. In addition, if not only environmental aspects, but also other factors such as socio-economic viability of rural areas, meat quality or animal welfare are considered, then grass-based systems could be a better option in comparison to confinement systems (Bragaglio et al., 2018; De Vries et al., 2015).

Regarding CF, the value obtained for B was approximately 10% higher than that found for A. This is in accordance with results found in Italy and USA, which indicates that intensive systems showed lower GWP values than systems partially based on pasture (Bragaglio et al. 2018; Tichenor et al. 2017). In both cases, CFs were in the same other of magnitude as those values reported in Italy and Canada for intensive dairy farms (1.2-8.4 kg CO_2eq/kg LW) and those found in Ireland for grass-based dairy systems (5.2-12.5 kg CO_2eq/kg LW) (Casey & Holden, 2006; McGeough et al. 2012; Zucali et al., 2017). In addition, it is conspicuous that, in this study, the fossil CO_2 in the PBF was approximately half that found in A. Biogenic carbon may be considered better in some respects, since the emission of fossil carbon is a permanent addition of carbon to the atmosphere and the emission of biogenic carbon is part of the carbon cycle (Breton et al., 2018).

Finally, it must be said that from an environmental perspective, in general, dual purpose systems (i.e., farms that coproduce milk and meat) have advantages over specialised systems (Marton et al. 2016; Vellinga and De Vries, 2018). In this sense, Cederber and Stadig (2003) indicated that meat and milk produced in combination need to occupy less land in comparison to specialised dairy farms. Another key aspect is the amount of beef produced in relation to the milk production, since the allocation between milk and meat is determining in LCA results (Gollnow et al., 2014; Laca et al, 2020a).

4. CONCLUSIONS

The CF of beef meat reported in assessments carried out around the world showed high variability (1.2-42.6 kg CO_2eq/kg LW). This can be attributed to a variety of factors such as different production systems, breeds of cattle, degrees of intensification, farm multi-functionality, etc. It is noticeable that coproduction of meat and milk in dairy farms is determining for reducing the CF of both products. Specifically, the values reported for the CF of beef meat coproduced in dairies were always lower than 13 kg CO_2eq/kg LW.

In the case studies analysed here, feed production was the main contributor to the environmental impacts derived from meat production in 14 of the 18 categories evaluated, which is in agreement with literature data. So, the feeding system and meat productivity were found to be fundamental factors from an environmental perspective. When meat production in the two case studies, A and B, was compared, lower environmental impacts were associated with B in almost all the studied categories, mainly due to the longer grazing time, which reduced the amount of fodder purchased.

However, the CF values were in both cases in the same order of magnitude as values reported in the literature for coproduced meat (8.10 kg CO_2eq/kg LW in A and 8.88 kg CO_2eq/kg LW in B). Finally, it should be pointed out that pasture-based systems could entail social and economic benefits in rural areas and, in addition, could improve meat quality or animal welfare. Moreover, since meat is an important component of a healthy and well-balanced human diet, further research into the environmental aspects of its production would be necessary to move forward towards more sustainable production systems.

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DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author, A. Laca, upon reasonable request.

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Table 1. Size of dairy systems located in Northwest of Spain (MAPA, 2020).

		Rate of farms classified according to the range of dairy cows per farm						
Region	**Dairy cows per farm (average value)**	**<15 cows**	**15-30 cows**	**30-45 cows**	**45-60 cows**	**60-75 cows**	**75-90 cows**	**>90 cows**
Asturias	42	6%	33%	22%	17%	8%	0%	14%
Cantabria	54	0%	10%	17%	16%	20%	20%	17%
Galicia	45	0%	11%	26%	22%	17%	11%	13%

Table 2. Inventory data of the systems analysed, expressed per functional unit (FU = 1 kg live weight).

Inputs semi-confinement (A)			Inputs pasture-based (B)		
1. Cattle feed purchased (kg)		4.20	1. Cattle feed purchased (100% fodder concentrate) (kg) (32% maize, 22% soybean flour, 17% barley, 10% colza, 7.3% beet pulp, 5% wheat bran, 4.4.% cottonseed, 2.3% calcium soaps)		1.79
a. Fodder concentrate (32% maize, 20% soy, 19% wheat, 16% barley, 13% sunflower seed)	48%				
b. Alfalfa	20%				
c. Maize silage	20%				
d. Hay	12%				
2. Tap water (m^3)		0.0351	2. Water (m^3)		0.0369
			a. Well water	82%	
			b. Tap water	18%	
3. Electricity (J)		1343160	3. Electricity (J)		184680
4. Diesel (production) (kg)		0.0560	4. Diesel (production) (kg)		0.0867
5. Cleaning elements (kg)		0.0060	5. Cleaning elements (kg)		0.0031
a. NaOH	13%		a. NaOH	52%	
b. Phosphoric acid	8%		b. NaClO	43%	
c. Sorbitol	62%		c. HCl	5%	
d. Detergents	17%				
6. Bedding material (kg)		0.0855	6. Transport by truck (kg.m)		47100
a. Sawdust	85%				
b. Straw	15%				
7. Drugs (propylene glycol) (kg)		0.0013	7. Land occupation (m^2.a)		17.9
			a. Pasture	83%	
			b. Maize	17%	
8. Transport by truck (kg.m)		700800			
a. Alfalfa	75%				
b. Maize	15%				
c. Hay	10%				

9. Land occupation (m^2.a)		5.1
a. Pasture	85%	
b. Maize	15%	

Outputs semi-confinement (A)			Outputs pasture-based (B)		
1. Fertilisation emissions (from the application of manure and slurry) (100% ammonia) (kg)		0.0293	1. Fertilisation emissions (from the application of manure and slurry) (100% ammonia) (kg)		0.0471
2. Cow emissions to air (kg)		2.72	2. Cow emissions to air (g)		4.36
a. CO_2	98.03%		a. CO_2	98.03%	
b. CH_4	1.94%		b. CH_4	1.94%	
c. NH_3	0.03%		c. NH_3	0.03%	
3. Diesel emissions to air (from diesel combustion) (kg)		0.1807	3. Diesel emissions to air (from diesel combustion) (kg)		0.2799
a. CO_2	99.1968%		a. CO_2	99.1968%	
b. CH_4	0.0057%		b. CH_4	0.0057%	
c. N_2O	0.0358%		c. N_2O	0.0358%	
d. CO	0.5591%		d. CO	0.5591%	
e. HC	0.0502%		e. HC	0.0502%	
f. NO_x	0.1487%		f. NO_x	0.1487%	
g. PM	0.0037%		g. PM	0.0037%	
			4. Dead calves (dangerous wastes for incineration) (kg)		0.0134
			5. Wastewater (for treatment) (m^3)		0.0065

Table 3. Summary of works on carbon footprint (CF) of beef meat produced in specialised farms found in literature from 2003 until time of writing.

Reference	Country	Aim and methodology	System boundaries	Main conclusions	CF
Angerer et al. (2021)	Italy	- Use LCA to examine the environmental impact of different organic and conventional beef production systems in South Tyrol.	From cradle to farm gate	The limited use of concentrate feed and the non-use of artificial fertilisers and herbicides in this area contribute to a sustainable production. No significant differences were found for most of the considered impact categories between the organic and the conventional system.	32.7 (calf-fattening) 19.8 (organic suckler cow) 17.1 (conventional heifer fattening) (kg CO_2eq/kg LW)
Chen et al. (2020)	Canada	- Develop an emission assessment model to quantify the amount of GHG generated from the beef cattle production.	-	Enteric CH_4, manure CH_4 and manure N_2O emissions accounted for more than 90% total GHG. The main factors affecting GHG emission were manure handling system, cattle diets and feed additives.	119 (kg CO_2eq/kg protein)
Horrillo et al. (2020)	Spain	- Calculate the balance of GHG emissions in seven farms (beef cattle, meat sheep, dairy goat and Iberian pig) of the organic livestock production systems of *dehesas* employing LCA.	From cradle to farm gate	The beef cattle farms provided the highest CF values. The soil sequestration ranged between 420 and 576 kg CO_2eq/ha/year. These systems cannot be compared with other more intensive systems in terms of product units, so the CF values of *dehesas* must be always associated to the territory.	10.4 (yearlings) 16.3 (calves) (kg CO_2eq/kg LW)
Li et al. (2020)	USA	- Analyse the impacts of the beef processing industry using process-based and integrated hybrid LCA.	From cradle to post-farm gate	Management practices should focus on increasing energy and water efficiency and minimizing nutrient emissions and heavy metal contents in sludge.	250 (kg CO_2eq/kg LW)
Molossi et al. (2020)	Brazil	- Use the Integrated Farm System Model (IFSM) software to study two beef farms. - Three sustainable agricultural intensification strategies were simulated with double the beef cattle stocking density compared to extensive grazing	-	Beef productivity, which improved CF, was greater for intensification strategies (grain supplementation, pasture re-seeding and pasture fertilization) compared to extensive grazing. Water footprint was greater for intensification strategies compared to extensive grazing. Grain supplementation had the best beef productivity, economic profitability and lowest CF of all simulated systems	15.9-19.3 (kg CO_2eq/kg LW)
Bilotto et al. (2019)	Argentina	- Explore cow-calf operations including strategies on productivity, profitability and GHG emissions. - Modelling tools (NDVI, SIMUGAN, OVERSEER® and @Risk).	-	Backgrounding strategies provide opportunities to farmers to increase farm productivity and profitability at the lowest risk for a given level of expected return, while reducing GHG emissions per unit of product.	18-22 (kg CO_2eq/kg LW)

Cucurachi et al. (2019)	-	- Describe the application of LCA to assess food production systems.	-	LCA should not be used in isolation but complemented with other methods. Collaboration across disciplines is needed to analyse the diversity of food systems.	500 (kg CO_2eq/kg protein)
De Souza et al. (2019)	Brazil	- Evaluate the feasibility of sugarcane ethanol and cattle integration. - Simulations were performed using the Virtual Sugarcane Biorefinery (VSB). and climate impacts were assessed via LCA.	From cradle to farm gate	Sugarcane and livestock integration was technically feasible due to the nutritional value of sugarcane ethanol by-products that can replace grazing as cattle feed ingredients. This model increased ethanol production without compromising cattle production or pasture land. Emissions per kg of meat were 14% lower than with extensive management.	13.5 (pasture) 11.6 (feedlot) (kg CO_2eq/kg LW)
Navarrete-Molina et al. (2019)	Mexico	- Quantify the economic impact of the water stress index (WSI), water footprint (WF) and carbon footprint (CF) during 1994-2018 in the cattle fattening industry of the North.	-	The environmental and economic impact of the blue water footprint and the GHG emissions were significantly greater than the economic value that this activity generates in the region. The main environmental and economic cost was associated with the water footprint.	17.4 (without forage production) 24.0 (with forage production) (kg CO_2eq/kg meat)
Samsonstuen et al. (2019)	Norway	- Develop a whole farm GHG model, (HolosNorBeef) to evaluate the GHG emissions form typical suckler beef cow herds.	-	Enteric CH_4 was the largest source of total GHG emissions (> 40%), followed by nitrous oxide from manure and soil (21%). Inclusion of soil C change is important when calculating emission intensities.	29.5-32.0 (British breeds) 27.5-29.6 (Continental breeds) (kg CO_2eq/kg carcass)
Bragaglio et al. (2018)	Italy	- Compare different beef production systems (specialized extensive, fattening, cow-calf intensive and Podolian). - LCA.	From cradle to farm gate	Intensive systems showed lower GWP values and land occupation than systems partially based on pasture. Pasture-based systems could provide “ecosystem services” (preservation of biodiversity, conservation of cultural landscapes, contribution to the socio-economic viability of rural areas, enhancement of meat quality and animal welfare…). Some of the intensive systems were more impactful at acidification and eutrophication levels.	17.6-21.9 (intensive) 25.4-26.3 (partially pasture-based) (kg CO_2eq/kg LW)
Cardoso et al. (2018)	Brazil	- Investigate the impact on GHG emissions of increasing productivity using fertilizers, forage legumes, supplements and concentrates, in five scenarios for beef production. - LCA (Tier 2 methodologies).	From cradle to farm gate	The largest GHG emission was enteric CH_4. The intensification of beef production systems leads to a reduction in GHG emissions. Changing from extensively-grazed degraded pastures to grass-legume mixed swards or N-fertilized pastures reduces the CF.	29-58 (kg CO_2eq/kg carcass)
Florindo et al. (2018)	Brazil	- Evaluate possible improvement actions that allow the reduction of the CF originating from Brazilian beef exports - Multiple criteria Decision-Making (MCDM) methods.	From cradle to final destination	Due to enteric fermentation, the animal production stage contributed more than 93% to total GHG emissions. The use of protein-energetic supplementation and pasture fertilization-rotation on the farm and the replacement of road transport units by more modern vehicles in the industrial phase would decrease the impact.	9.0 (kg CO_2eq/kg LW)
McAuliffe et al.	UK	- Propose a novel approach to	From gate to	Depending on pasture management strategies, the total emissions	16.0-20.2

(2018)		complement the existing LCA methodology, using detailed on-farm data collected from Devon.	gate	intensity estimated by the proposed method was higher than the equivalent value recalculated using a representative animal approach.	(kg CO_2eq/kg LW)
Modernel et al. (2018)	Argentina Uruguay Brazil	- Study the economic and environmental performance of beef farming in the Río de la Plata grasslands region based on interviews and field measurements on 280 case study farms.	From gate to gate	In general, there is ample leeway to increase livestock productivity, reducing GHG emissions. According to Pareto-ranking, the positive deviant farms showed similar meat yields and CF compared to the case studies of the Organisation for Economic Cooperation and Development, with significantly lower use of fossil fuel energy.	15.0-32.0 (kg CO_2eq/kg LW)
Nieto et al. (2018)	Argentina	- Assess the on-farm GHG emissions in semi-arid rangelands in Argentina. - IIPCC Tier 2 protocols.	-	Emissions were low on farms that had improved livestock care management, rotational grazing, received technical advice, and had high animal and land productivities.	12.4-39.7 (cow-calf) 6.2-8.1 (backgrounding) 7.0-22.6 (cow-calf+backgrounding) (kg CO_2eq/kg LW)
Pereira et al. (2018)	Brazil	- Evaluate three common pastured beef grazing systems (Angus cattle). Estimate carbon, water and energy footprints. - Integrated Farm System Model.	From cradle to farm gate	The CF was the lowest for natural pasture with low levels of grain supplementation combined with soybean production. The energy and water footprints and erosion increased with the greater use of both purchased feed and inputs required for feed and cash crop production.	14.9-16.1 (kg CO_2eq/kg carcass)
Vasconcelos et al. (2018)	Brazil	- Analyse beef cattle production on three grass systems in the Pampa biome: Native Pasture, Fertilized Native Pasture and Improved Native Pasture. - LCA	From cradle to farm gate	Changes in grazing system led to a reduction of approximately 29% in CO_2eq emissions. Management adaptations contribute to the maintenance of the Pampa biome characteristics.	10.0-13.2 (kg CO_2eq/kg LW)
Buratti et al. (2017)	Italy	- Compare GHG emissions from two beef production systems (conventional and organic). - LCA.	From cradle to farm gate	Organic system produced more GHG emissions than the conventional one. More than 50% of the global CF value is originated by enteric fermentation.	18.2 (conventional) 24.6 (organic) (kg CO_2eq/kg LW)
Clune et al. (2017)	-	- Literature review of GHG emissions for different food categories. - LCA.	-	Meat from ruminants showed the highest impact. Different LCA approaches, i.e., methods, geographic location, processes included…, can be found.	29 ± 12 (kg CO_2eq/kg bone free meat)
De Figueiredo et al. (2017)	Brazil	- Estimate the CF of beef cattle production from the fattening cycle in three scenarios. - IPCC methodology / Brazil-specific database.	Only the fattening cycle of beef cattle is considered	The conversion of degraded pasture to well-managed pasture and the introduction of crop-livestock-forest integration systems can reduce GHG emissions, primarily due to the increase in cattle yields and the potential for C sinks.	18.5 (degraded pasture) 9.4 (managed pasture) 12.6 (crop-livestock-forest integration system) (kg CO_2eq/kg LW)
Cerri et al. (2016)	Brazil	- Evaluate the main sources of GHG in beef cattle production. - GHG emissions were estimated by	From cradle to farm gate	The largest source of GHG came directly from the animals (89-98%). From these, 67-79% were from enteric fermentation, followed by manure decomposition (20-33%).	4.8-8.2 (kg CO_2eq/kg LW)

		using data from 22 extensive farms and specific emission factors from IPCC.			
Morel et al. (2016)	France	- Compare GHG emissions, energy consumption and land use in two grassland-based cow-calf beef systems. - LCA.	From cradle to farm gate	Livestock emissions per animal were close between the two systems (autumn and spring) (75% of gross GHG emissions). The autumn-system had a higher animal productivity and less land use, but greater use of inputs (31% higher energy consumption).	15.4 (autumn) 16.0 (spring) (kg CO_2eq/kg LW)
Dick et al. (2015)	Brazil	- Analyse the environmental impacts of two simulated typical beef cattle production systems: the extensive system and the improved system.	-	The extensive system showed lower impacts on metal depletion and soil acidification (due to the pasture improvement practices and the salt supply to the animals) and higher impacts on GHG emissions, land use and freshwater depletion (compared with the improved system).	22.5 (extensive) 9.2 (improved) (kg CO_2eq/kg LW)
Harrison et al. (2015)	Australia	- Determine the effects of leucaena on emissions, production and profitability at the whole farm level by modelling a typical cattle farm.	-	Although income from carbon offsets associated with grazing leucaena is small, compared to grazing Rhodes grass, leucaena had significant potential to increase both animal production and gross margin, while reducing emissions intensity.	9.8 (Rhodes grass) 7.5 (leucaena) (kg CO_2eq/kg LW)
Petrovic et al. (2015)	-	- Provide an overview of environmental consequences of meat production and consumption.	-	The consumption of meat, dairy and eggs is increasing worldwide, which will aggravate the environmental impact related to livestock. In EU, beef had by far the highest GHG emissions.	22.6 (kg CO_2eq/kg meat)
Ruviaro et al. (2015)	Brazil	- Evaluate the CF for different scenarios (Aberdeen Angus cattle).	From cradle to farm gate	The ryegrass and sorghum pasture system showed the lowest CF and the natural grass system the highest one.	18.3-42.6 (kg CO_2eq/kg LW)
De Vries & De Boer (2010) De Vries et al. (2015)	-	- Review environmental assessments of livestock products.	From cradle to farm gate	Production of beef protein had the highest impact, followed by pork protein and chicken protein. Coproduction of beef and milk showed largest potential to mitigate environmental impacts of beef.	14-32 (kg CO_2eq/kg LW)
Wiedemann et al. (2015a)	Australia	- Conducted a multi-impact analysis of Australian red meat export supply chains. - LCA.	From cradle to market in USA	Environmental impacts and resource use were highest in the farm and feedlot phase. The maximum contribution of transportation to GHG emissions, water consumption and land use was 5%.	16.1-27.2 (kg CO_2eq/kg meat)
Wiedemann et al. (2015b)	Australia	- Quantify GHG emissions, fossil fuel energy demand and water use in the beef cattle industry during 1981-2010. - LCA (ABARES datasets).	From cradle to farm gate	Since 1981 there has been a decrease of 14% in GHG. The improvement was due to efficiency gains through heavier slaughter weights, increases in growth rates in grass-fed cattle, improved survival rates and greater numbers of cattle being finished on grain.	15.3 (1981) 13.1 (2010) (kg CO_2eq/kg LW)
Dudley et al. (2014)	USA	- Study GHG emissions from grain-fed beef cattle. - LCA (statistical data and previous studies).	-	Methods used by the USA Environmental Protection Agency (EPA) associated with beef production in feedlots were found to account for only 3-20% of life cycle GHG emissions.	2.5-9.6 (kg CO_2eq/kg LW)
Hünerberg et al. (2014)	Canada	- Evaluate the effect of feeding beef cattle with high fat corn distiller' grains plus solubles (CDDGS) or wheat distillers'	From cradle to farm gate	Using high-fat distillers' grains in the diet of feedlot cattle may decrease enteric CH_4 emissions, but at high dietary levels it increases N excretion and results in a net increase in GHG	15.0 (CDDGS) 15.4 (WDDGS) 14.1 (baseline scenario)

		grains plus solubles (WDDGS). - LCA and Holos model.		emissions.	(kg CO_2eq/kg LW)
Picasso et al. (2014)	Uruguay	- Quantify CF of different simulated grazing systems using various metrics and other variables. - LCA.	From cradle to farm gate	The use of CF as sole indicator has several serious limitations. Beef systems with grazing finishing had lower impact on climate change, soil erosion, pesticide ecotoxicity, water eutrophication by nutrients and grassland biodiversity than feedlot systems.	9.7-20.3 (kg CO_2eq/kg LW)
Roy et al. (2012)	Japan	- Evaluate the entire life cycle of meat and consumption scenarios to determine if the GHG emission from meat industry can be reduced.	From cradle to farm gate	A change in consumption patterns (from beef to chicken or pork) and the adoption of a healthy and balanced diet would help to reduce about 2.5-54.0 million tons (CO_2 eq) produced by the meat industry each year in Japan.	34.3 (kg CO_2eq/kg meat)
Crosson et al. (2011)	-	- Review IPCC and whole farm approaches for modelling GHG emissions from ruminant livestock production systems	-	Whole farm systems models were appropriate to evaluate GHG mitigation strategies for livestock farms. Improvements in productivity and fertility lessen GHG emissions. Intensification of production reduces emissions provided that requirements of feed and fertiliser are not excessive. Carbon sequestration into agricultural soils may offset emissions.	8.4-37.5 (kg CO_2eq/kg carcass)
Beauchemin et al. (2010) Beauchemin et al. (2011)	Canada	- Estimate GHG emissions from beef production. - LCA and Holos model.	From cradle to farm gate	Enteric CH_4 and N_2O from soil and manure accounted for 63% and 27% of total GHG emissions, respectively. Within the beef production cycle, the cow-calf phase was responsible for 80% of total GHG emissions.	22 (kg CO_2eq/kg carcass)
Pelletier et al. (2010)	USA	- Compare energy use, ecological footprint, GHG emissions and eutrophying emissions in three beef production models. - LCA.	From cradle to farm gate	Impacts were highest for pasture-finished beef for all impact categories and lowest for feedlot-finished beef. A sensitivity analysis indicated the possibility of substantial reductions in net GHG emissions for pasture systems.	14.8 (feedlot) 16.2 (backgrounding/feedlot) 19.2 (pasture) (kg CO_2eq/kg LW)
Vergé et al. (2008)	Canada	- Estimate bovine GHG emissions of the beef industry during 1981-2001.	From cradle to farm gate	Total GHG emissions from Canadian beef production increased from 25 to 32 Tg of CO_2eq between 1981 and 2001, mainly due to the expansion of the cattle industry. However, CF decreased from 16.4 to 10.4 kg CO_2eq/kg LW.	10.0-17.1 (kg CO_2eq/kg LW)
Ogino et al. (2004)	Japan	- Evaluate the environmental impacts of a beef-fattening system.	From cradle to farm gate	Feed production notably contributed to all categories. Enteric CH_4 emissions and NH_3 emissions were the major contributors to global warming and acidification and eutrophication categories, respectively.	36.4 (kg CO_2eq/kg carcass)

LW: live weight

FIGURE CAPTIONS

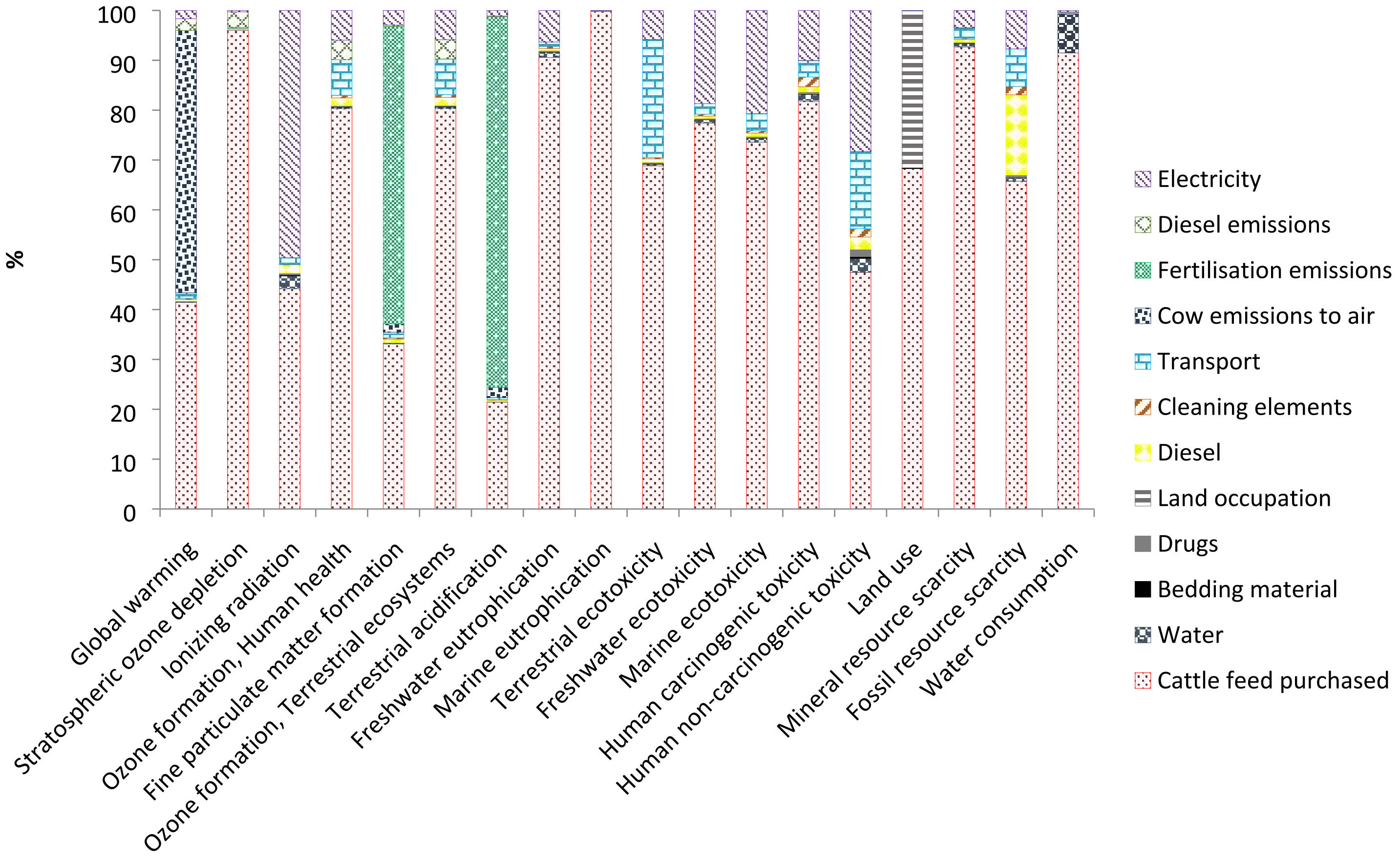
Figure 1. Characterization results of case A (A) and case B (B) obtained using ReCiPe Midpoint (FU=1 kg LW).

Figure 2. Carbon footprint obtained for 1 kg of beef meat (LW) using GreenHouse Gas Protocol: (A) case A and (B) case B. Only biogenic and fossil CO_2eq have been considered.

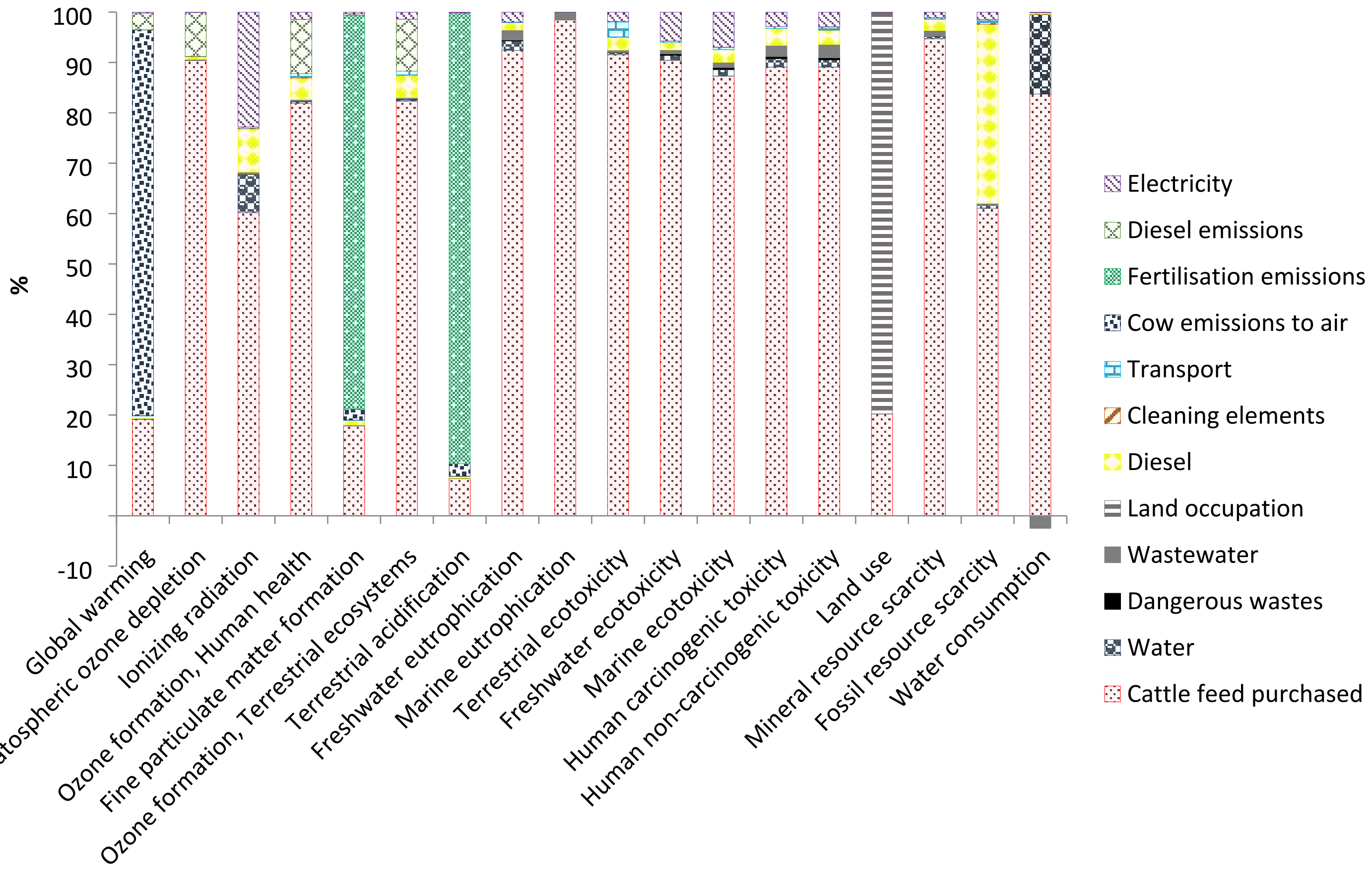
Figure 3. Carbon footprint (CF) of beef meat obtained as main product in specialised farms or as co-product in dairy farms reported in Tables 2 and 3 for America (USA, Brazil, Uruguay, Colombia and Canada) and Europe (Spain, Italy, Ireland, France, The Netherlands, Norway and Denmark) expressed per kg of live weight (LW). Intervals are represented as maximum and minimum values of the range. In green circles are shown those data obtained from specific case studies, whereas in red triangles are shown those data obtained from simulations or from model farms that employ global databases. Full symbols correspond with data obtained in this work for case A studies.

Figure 4. Comparison between the environmental impacts derived from the production of meat in both systems here analysed: case A (dark bars) and case B (light bars).

A)


%
0
10
20
30
40
50
60
70
80
90
100
Global warming
Stratospheric ozone depletion
Ionizing radiation
Ozone formation, Human health
Fine particulate matter formation
Ozone formation, Terrestrial ecosystems
Terrestrial acidification
Freshwater eutrophication
Marine eutrophication
Terrestrial ecotoxicity
Freshwater ecotoxicity
Marine ecotoxicity
Human carcinogenic toxicity
Human non-carcinogenic toxicity
Land use
Mineral resource scarcity
Fossil resource scarcity
Water consumption
Electricity
Diesel emissions
Fertilisation emissions
Cow emissions to air
Transport
Cleaning elements
Diesel
Land occupation
Drugs
Bedding material
Water
Cattle feed purchased

B)


%
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20
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40
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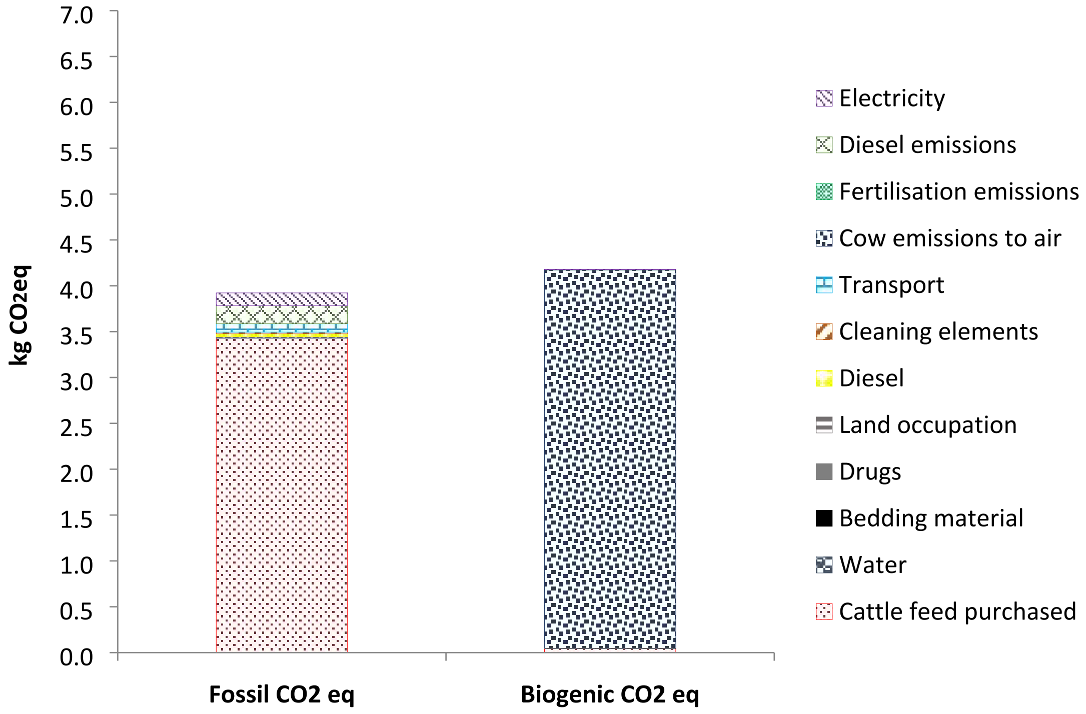
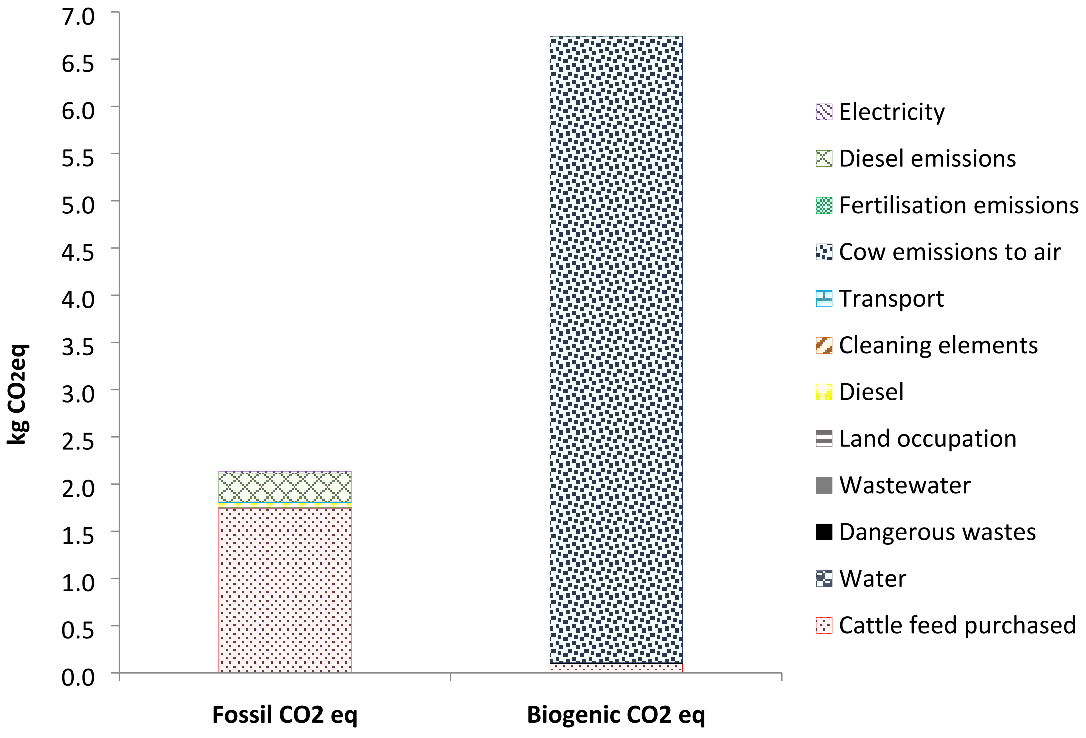
70
80
90
100
Global warming
Stratospheric ozone depletion
Ionizing radiation
Ozone formation, Human health
Fine particulate matter formation
Ozone formation, Terrestrial ecosystems
Terrestrial acidification
Freshwater eutrophication
Marine eutrophication
Terrestrial ecotoxicity
Freshwater ecotoxicity
Marine ecotoxicity
Human carcinogenic toxicity
Human non-carcinogenic toxicity
Land use
Mineral resource scarcity
Fossil resource scarcity
Water consumption
Electricity
Diesel emissions
Fertilisation emissions
Cow emissions to air
Transport
Cleaning elements
Diesel
Land occupation
Wastewater
Dangerous wastes
Water
Cattle feed purchased

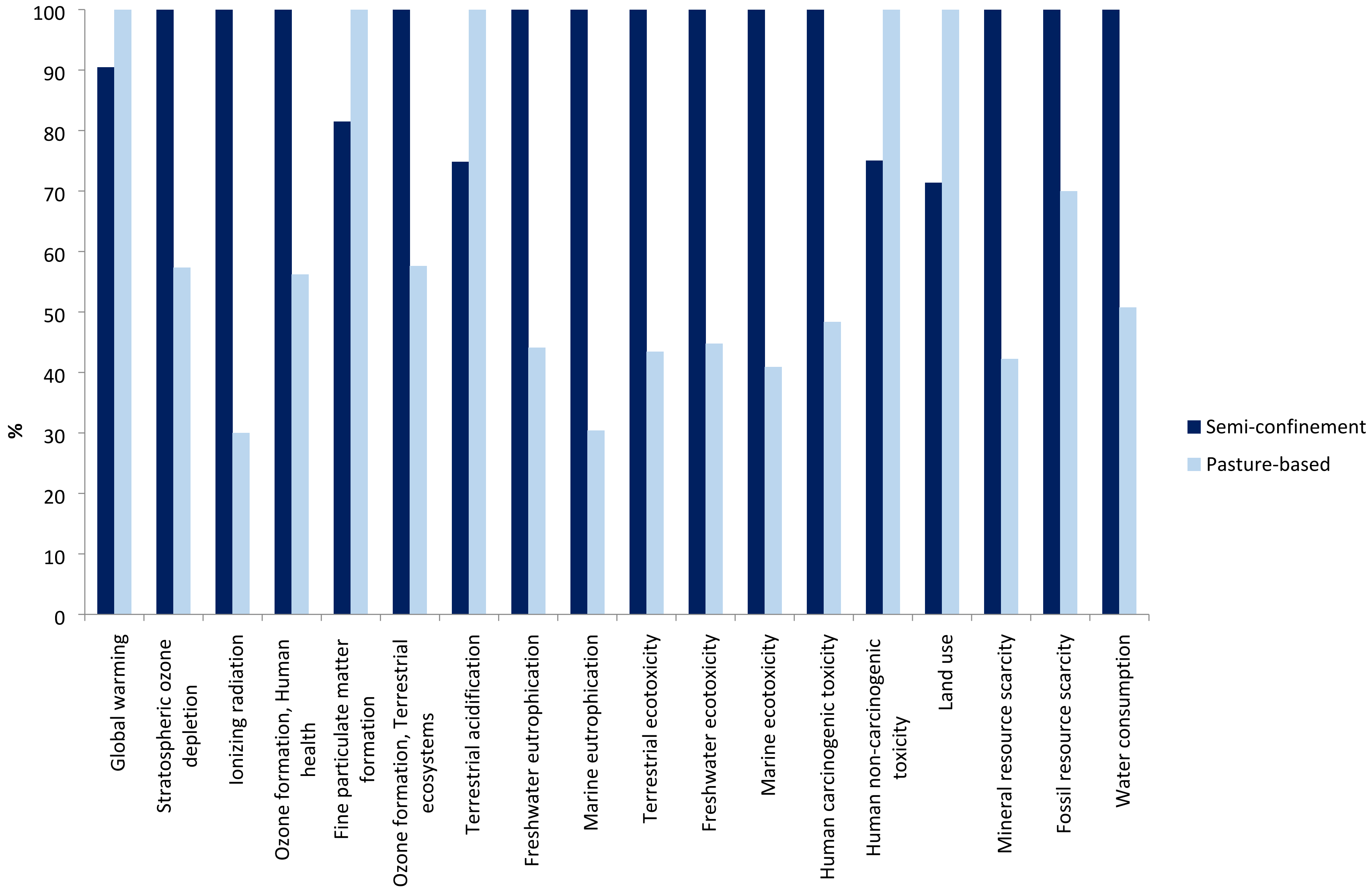
A)


kg CO2eq
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Fossil CO2 eq
Biogenic CO2 eq
Electricity
Diesel emissions
Fertilisation emissions
Cow emissions to air
Transport
Cleaning elements
Diesel
Land occupation
Drugs
Bedding material
Water
Cattle feed purchased

B)


kg CO2eq
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Fossil CO2 eq
Biogenic CO2 eq
Electricity
Diesel emissions
Fertilisation emissions
Cow emissions to air
Transport
Cleaning elements
Diesel
Land occupation
Wastewater
Dangerous wastes
Water
Cattle feed purchased


CF (kg CO2eq/kg LW)
45
40
35
30
25
20
15
10
5
0
America
Europe
America
Europe
SPECIALISED BEEF FARMS
DAIRY FARMS


100
90
80
70
60
50
40
30
20
10
0
%
Global warming
Stratospheric ozone depletion
Ionizing radiation
Ozone formation, Human health
Fine particulate matter formation
Ozone formation, Terrestrial ecosystems
Terrestrial acidification
Freshwater eutrophication
Marine eutrophication
Terrestrial ecotoxicity
Freshwater ecotoxicity
Marine ecotoxicity
Human carcinogenic toxicity
Human non-carcinogenic toxicity
Land use
Mineral resource scarcity
Fossil resource scarcity
Water consumption
Semi-confinement
Pasture-based