Animal 18 (2024) 101059

Contents lists available at ScienceDirect

Animal

The international journal of animal biosciences

Assessing the environmental impacts of beef production chains integrating grazing and landless systems

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ARTICLE INFO

Article history:
Received 11 July 2023
Revised 7 December 2023
Accepted 12 December 2023
Available online 20 December 2023

Keywords:
Climate change
Life cycle assessment
Meat
Mixed systems
Pollution

ABSTRACT

Livestock production systems contribute significantly to environmental impacts at the global level, and meat consumption is projected to increase with the population. There is a need to reduce the impact of food production, including that from beef systems. Different production systems, ranging from traditional grazing to landless systems, coexist within the beef sector. Among these, mixed systems have emerged as a promising alternative. These mixed systems typically involve adult cattle in grazing systems alongside fattening calves in landless systems, potentially achieving higher productivity while reducing the overall environmental impacts. The first step towards proposing mitigation strategies involves identifying the impacts of the sector. This study aimed to estimate the main environmental impacts of four types of mixed beef systems based on the origin of the calves that are raised, fattened, and slaughtered. Using life cycle assessment, the study evaluated the environmental impacts from the cradle to the slaughterhouse gate, expressed per kilogram of carcass weight. The four systems assessed include suckler cow farms that fatten their own offspring (beef single farm, **BSF**), a system in which calves raised on a suckler farm are fattened on a different farm (beef fattening unit, **BFU**), and systems in which dairy calves are fattened on growing units, with calves either from Spain (dairy national, **DN**) or from farms located abroad (dairy abroad, **DA**). Primary data were obtained from representative surveys of farmers and slaughterhouses, and allocation between co-products was performed according to the updated guidelines of Environmental Product Declarations and the Product Category Rules for meat. Seven environmental impact categories were assessed: climate change, marine eutrophication, freshwater eutrophication, stratospheric ozone depletion, terrestrial acidification, photochemical ozone formation on ecosystems, and photochemical ozone formation on human health. The results indicate that meat production from BSF and BFU has greater environmental impacts than that from DN and DA systems, primarily due to the lower environmental burden allocated to dairy calves, whereas the contribution of slaughterhouse activities to the environmental impacts was minimal. This study highlights the importance of mitigating the environmental impacts associated with feed production, enteric fermentation, and manure management in beef systems. Future studies should consider potential environmental benefits of grazing animals such as carbon sequestration and biodiversity promotion.

Implications

Enteric fermentation and manure management are the main contributors to the environmental impacts of beef production under combined mixed systems. Feed and manure management are key targets to mitigate emissions throughout the production chain. Fattening animals from dairy farms have lower overall impacts for most impact categories. This study identified key contributors to environmental impacts under different production systems, thus helping to identify mitigation strategies adapted to each type of system.

Introduction

Meat is a crucial source of protein for humans, with animal-source foods accounting for 58% of the protein in diets worldwide, of which beef represents ca. 16% (FAOSTAT, 2022). However, livestock systems contribute greatly to global greenhouse gas (**GHG**) emissions, accounting for 11.2% of total GHG emissions in 2015

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https://doi.org/10.1016/j.animal.2023.101059
1751-7311/

(FAO, 2022). Beef production alone accounts for 35% of livestock emissions, primarily due to CH_4 emissions from enteric fermentation and manure management (Opio et al., 2013). Furthermore, meat production is responsible for a substantial share of pollutant emissions, such as reactive nitrogen (33% from livestock production) (Uwizeye et al., 2020), terrestrial acidification (8% from livestock production) (Stackhouse-Lawson et al., 2012), eutrophication (19% from livestock production) (Bustillo-Lecompte, 2015), water scarcity (29% from livestock production) (Mekonnen and Hoekstra, 2010), and uses ca. 40% of global arable land for feed production (Mottet et al., 2017).

Considering the projected global population of 9.7 billion by 2050 (FAO, 2017), the challenge of feeding the growing population while minimising environmental impacts becomes imperative for the global agricultural sector (IPCC, 2019; Lupo et al., 2014). Beef production plays a crucial role in achieving the United Nations Sustainable Development Goals (**SDGs**) by promoting food security (SDG 2 – Zero hunger), facilitating sustainable consumption and production (SDG 12), and combating climate change (SDG 13 – Climate action) (Mehrabi et al., 2020). Consequently, significant efforts are being made in both the public and private sectors to increase the sustainability of livestock production.

In Europe, various policies and initiatives are aimed at improving the environmental performance of livestock products. The European Commission has established the Product Environmental Footprint as a method to communicate environmental performance throughout a product's life cycle, including livestock products. Additionally, the Farm to Fork Strategy, at the core of the European Green Deal, strives to make food systems fair, healthy, and environmentally friendly (European Commission, 2021). The Livestock Environmental Assessment and Performance Partnership, a multistakeholder group, is focused on improving the environmental, economic, and social viability of livestock production systems (FAO, 2017).

The first step in proposing mitigation strategies is to identify the impacts of agri-food products. Life Cycle Assessment (**LCA**) is a widely used methodology for estimating the environmental impacts of these products (Bragaglio et al., 2017). LCA involves a comprehensive analysis of multiple types of resource use and emissions and their associated impact categories throughout the product's life cycle, encompassing resource extraction, processing, production, transportation, use, and end-of-life stages. The LCA framework is standardised by ISO 14040/14044 (ISO, 2020a; 2020b). LCA research on beef production reveals significant differences in environmental impacts among different production systems (de Vries et al., 2015), with trade-offs observed across diverse impact categories. For example, favouring intensive beef systems to reduce climate change (**CC**) and land occupation impacts results in higher acidification impact (Pelletier et al., 2010; Bragaglio et al., 2017; McAuliffe et al., 2018).

Globally, the FAO (2017) defines three major livestock systems as a function of the degree of crop-livestock integration: grassland-based, landless, and mixed. Grassland-based systems depend almost exclusively on grazing, while landless and mixed systems rely on a combination of concentrate (food crops) and roughage, consisting of grass, fodder crops, crop by-products, and other sources of feedstuffs (Bouwman et al., 2006). The distribution of ruminant production among regions is typically driven by the local availability of land and feed resources. However, the increasing demand for meat, coupled with limited grassland area, has prompted a shift towards intensified production systems that prioritise resource optimisation, such as mixed beef systems. Mixed systems have slightly lower impacts per kg carcass than grassland-based ones (Opio et al., 2013). Landless systems tend to have lower climate change impact than grazing systems per kg carcass, while the opposite holds true for acidification and eutrophication impacts (de Vries et al., 2015). Grazing systems contribute to biodiversity conservation and carbon sequestration, while landless systems have higher feed-conversion efficiency (Bragaglio et al., 2017). Furthermore, Benoit and Mottet (2023) highlight the resource optimisation ability of ruminants, as they produce 40% more human-edible protein than they consume. The feeding system also influences the quality traits and fatty-acid profile of beef. In general, beef from grazing animals has higher vitamin A and E and conjugated-linoleic acid contents than animals fed a diet consisting of concentrate (FAO, 2023). Therefore, combining grazing and landless systems, on a regional or national level, has the potential to decrease the environmental impacts of beef production.

Spain is among the top three European countries in meat production, trailing only France and Germany, accounting for 8% of the number of cattle and 10.6% of the beef produced in the European Union (**EU**) (O'Brien et al., 2020; MAPA, 2022a). The beef sector in Spain is a clear example of mixed systems, consisting of two different segments (MAPA, 2022a): (i) adult animals in grazing systems and (ii) fattening animals in landless systems, in which animals remain indoors during the entire fattening period. This system can be considered a representative example of a highly efficient system of mixed beef production. Although some studies have estimated the environmental impacts of beef production in Spain (Batalla et al., 2014; Eldesouky et al., 2018; O'Brien et al., 2020; Horrillo et al., 2022; Zira et al., 2023), they are specific case studies that lack of an integrated systemic view. In this context, the Interprofessional Agrifood Organization for Beef in Spain (PROVACUNO, according to its Spanish acronym) is aware of the need to reduce these impacts with systematic modifications both on farms and in the sector. In particular, they have been working on a "Carbon Neutral 2050" strategy, whose objective is to achieve a net balance of zero GHG emissions from the beef sector in Spain by that year by reducing emissions throughout the entire beef value chain. Based on this, the main goal of this study was to perform an environmental assessment using LCA of mixed beef production systems, which integrate grazing and landless systems for adults and fattening animals, respectively, while also considering both breed and dairy calves. Spain served as a case study, and the assessment was based on specific surveys carried out by PROVACUNO. From the results, the environmental hotspots within these production systems are identify.

Material and methods

Description and characterisation of beef production systems in Spain

Characterisation of beef production systems: Surveys

A survey was carried out to gather information on the main characteristics of beef production systems in Spain. The survey gathered essential information like the general characteristics of the farm, farm infrastructure, feeding strategy, manure management, productivity, and energy consumption. The survey was conducted in 2020 and involved individual interviews with 260 farms. The surveys were distributed according to a stratified sampling by region (Nomenclature of Territorial Units for Statistics 2 level) based on the number of farms in each region. The information was uploaded to a digital platform created expressly for this purpose. The digitised information was processed using SPSS software (IBM SPSS Statistics, Armonk, NY, United States) to perform statistical analyses. Information on the structure of the surveys and systematic analysis of the results was published by PROVACUNO (2022). In the supplementary material (Section S1 and Table S1), a description of the statistical procedure followed to determine the sample size and distribution is provided.

For the composition of concentrate, information on the types of feed used, their ingredients, and their origin was extracted from five representative feed factories in Spain. Information on the slaughterhouse stage was obtained from a survey of six representative slaughterhouses in Spain.

Description of the main types of beef production in Spain

Beef production in Spain is composed of two subsystems (Fig. 1): (i) grassland-based units for adult animals and suckling calves and (ii) landless units for fattening animals. In the former, farms are connected to the land, relying heavily on grassland production (grazing system). In contrast, the latter are landless systems, which may be located on the same farm or set in different locations. In these facilities, animals come from both beef grassland units (as described in (i)) and dairy cattle systems either in Spain or abroad, corresponding to females and males not wanted for dairy production (MAPA, 2022a).

Beef calf feeding changes depending on the stage of growth. For the first 5–6 months, beef calves remain with the mother, and natural lactation is performed under a grassland regime, which is supplemented with external feed when there is a shortage of grass. In the fattening units, three feeding phases are distinguished: adaptation, growth, and finishing. In each of these phases, the animals consume forage and highly digestible feed with different protein and energy contents depending on their needs. The calves from dairy systems are fed artificial milk replacers until weaning and then follow the same feeding phases as beef cattle (MAPA, 2019; MAPA, 2022a).

Based on this configuration, and the survey results, four types of mixed production systems representative of Spanish beef production were developed in this study (MAPA, 2022a; PROVACUNO, 2022). The four systems assessed are suckler cow farms that fatten their own offspring (beef single farm, **BSF**), a system in which calves raised on a suckler farm are fattened on a different farm (beef fattening unit, **BFU**), and systems in which dairy calves are fattened in landless growing units, including calves either from Spain (dairy national, **DN**) or from farms located abroad (dairy abroad, **DA**), mainly France, Ireland and Germany. The characteristics of the animals in the grassland-based units and those of the calves in the landless units are common across the four systems studied, and differences lie in how these phases are arranged (Fig. 2). To characterise each production system, mean data from the surveyed farms were used and also data from MAPA (2019b) on the age of the calves in each phase (Tables S2–S4 in S2).

The BSF and BFU systems consist of adult cows, bulls, and replacement heifers in a grazing regime, in addition to suckling male and female calves intended for slaughter. The calves are raised in a mixed system. In particular, they remain with their mothers in a grazing regime during natural lactation (183 days, on average), whereas the subsequent phases of adaptation (14 days, on average), growth (137 and 122 days for males and females, respectively, on average) and finishing (31 and 22 days for males and females, respectively, on average) correspond to a landless regime either on the same farm (BSF) or in a fattening unit (BFU). In the dairy calf systems (DN and DA), the male calves are separated from the dairy cows soon after birth. In these systems, the calves are fed milk replacers for 63 days, on average, and the subsequent fattening has a mean duration of 272 and 263 days for males and females, respectively.

Feed for adult animals (cows, bulls and heifers) consists of grass, silage, straw, and concentrate. For the BSF and BFU systems, the mixed diet considered in the adaptation, growth, and finishing stages is concentrate, straw, forage, and silage. For the DN and DA systems, during the lactation, the calves consume mainly concentrate and some straw, forage, silage, and milk replacer, whereas during the fattening stage, the mixed diet is the same as that for the BSF and BFU systems.

Regarding the manure management reported in the surveys, deep bedding was used the most in the landless regime, whereas manure was excreted on grassland in the grazing regime. See Supplementary Material S2 (Tables S2–S4) for the characteristics of the four production systems.

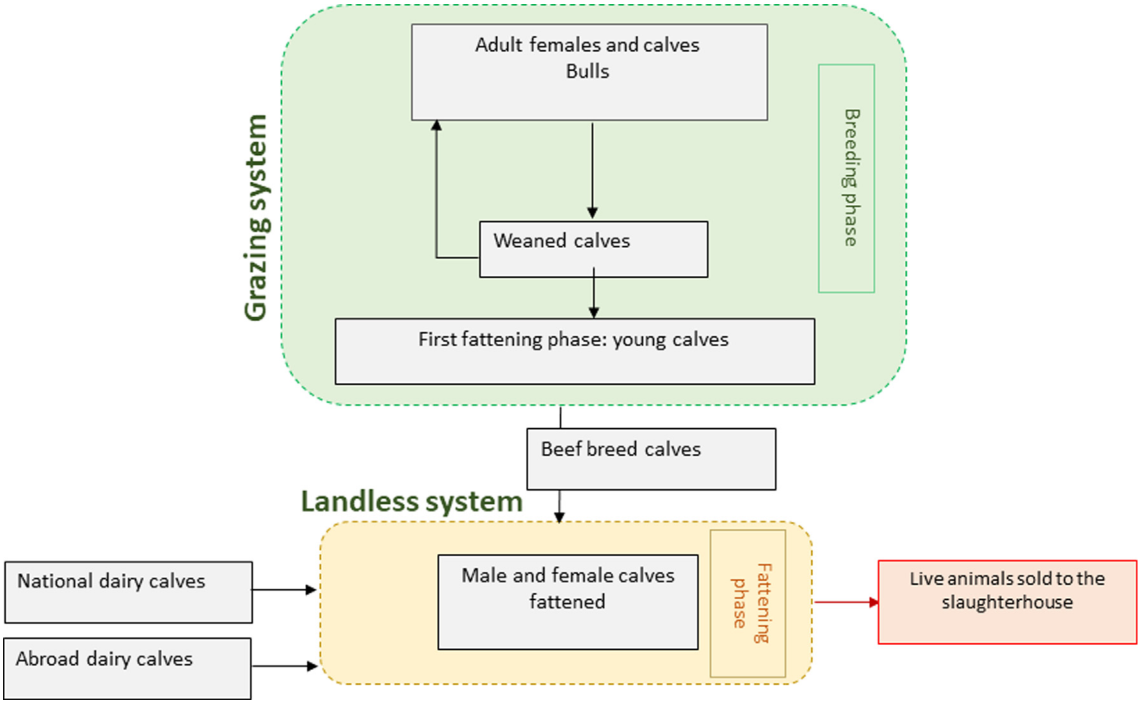

Fig. 1. Framework of beef production in mixed grazing-landless systems.

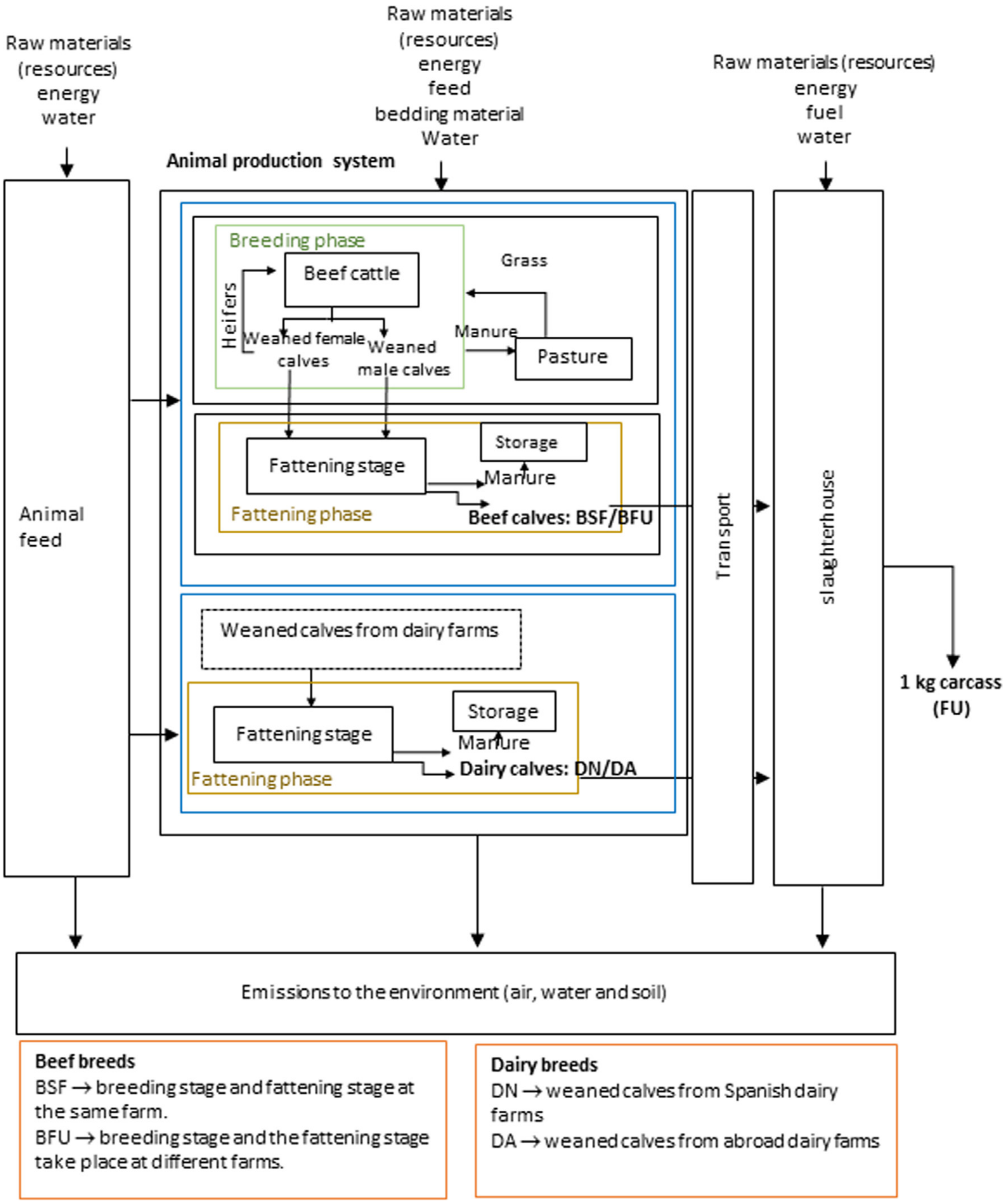

Fig. 2. System boundaries of the beef production systems assessed.

Life cycle assessment

This study followed the LCA methodology according to ISO standards using LCA for Experts 10.7 software (Sphera Solutions, Chicago, IL, USA). In addition, Product Category Rules (**PCRs**) 2012:11V4.0.1 for Meat of Mammals (Environmental Product Declaration (EPD), 2022) and the Footprint Category Rules for Red Meat V1.1 (European Livestock and Meat Trades Union (UECBV), 2020) guided the methodological choices adopted.

Goal and scope definition

The main goal of this LCA was to provide a baseline of the environmental impacts of mixed beef production (grazing and landless systems for adults and fattening animals, respectively), using Spain as a case study. The functional unit (**FU**) in which the impact results were expressed was 1 kg beef carcass. The system boundaries were set from the cradle to the slaughterhouse gate (Fig. 2) and included all material and energy inputs at the feeding, farm production, and slaughterhouse stages, as well as the transport of animals from the farm to the slaughterhouse and the transport of raw feed ingredients to the feed mills.

Life cycle inventory

The main input and output data required for the life cycle inventories (**LCIs**) included the resources used and the outputs to the environment (emissions) related to concentrate, beef production, and slaughterhouse stages. Data on animal management, the ingredients of the rations used in feeding, and manure management systems were obtained from the surveyed farms. Additional information was obtained from secondary sources, especially MAPA (2019b) and commercial LCI databases, in particular Managed LCA Content 2023.1 (Sphera Solutions GmbH, 2022) and ecoinvent v3.8 (Wernet et al., 2016). See Table S5 for the metadata of these reference LCIs. Based on the information provided by the surveys, the mean composition of the feed used to feed farm animals was obtained (Table S6).

Emissions of methane (CH_4) from enteric fermentation, as well as those of CH_4, nitrous oxide (N_2O), ammonia (NH_3), nitrogen monoxide (NO), and non-methane volatile organic compounds (NMVOC) from manure management of the four production systems, were estimated using the Tier 2 method of the IPCC (2019) and EMEP/EEA (2019). See Table S7 for the parameters used to calculate these emissions.

According to IPCC (2019), the Tier 2 method requires defining the composition of the diet to estimate feed intake and CH_4 emissions from enteric fermentation and nitrogen excretion. To determine the DM intake of the animals, energy requirements at each stage and diet composition were considered (Table S8). The nutrient composition of each feed ingredient was obtained from the Spanish Association for Animal Nutrition (FEDNA, 2019), while energy and nitrogen needs were calculated according to IPCC (2019) (Table S7). Additionally, parameters for digestibility, nitrogen excretion, gross energy intake, and volatile solids were used to estimate emissions (Table S9) and were calculated following the IPCC (2019).

Based on the characteristics of each production system and the mean data from the surveys, the LCIs of the farming stage for the four production systems were determined (Table S10). To estimate water consumption at each growth stage, the equations of Wagner and Engle (2021) were used. Regarding water, "water use" and "water consumption" were distinguished (Table S10). The former refers to the total amount of water withdrawn from its source for use, while "water consumption" represents the amount of water used that is not returned to the original water source after withdrawal (Boulay et al., 2018). Total water use was estimated as 4.63 m^3/FU for BSF and BFU, and 6.58 m^3/FU for DN and DA. Mean blue water consumption was estimated as 0.507 m^3/FU for BSF and BFU, and 0.570 m^3/FU for DN and DA.

Transportation of calves from the farm to the fattening unit and that of feed ingredients to the feed mill was included within the system boundaries. The locations of the breeding and fattening units were extracted from the surveys, and the countries of origin of imported calves were taken from a study by the Spanish Ministry of Agriculture, Food and Environment (MAPA, 2019): France (56% of total imports), Ireland (8%), Germany (8%), Portugal (6%), Belgium (5%), Czech Republic (4%), United Kingdom (3%), Netherlands (3%), and Poland (2%). The distances travelled to the fattening unit, feed mill, and slaughterhouse were obtained from Google Maps. Using these data, the weighted mean distances were calculated as 197.05 km for Spanish dairy calves and 1 305.93 km for imported dairy calves.

Regarding the transport of raw ingredients for feed manufacturing, it was assumed that those grown in Spain or other European countries were transported by truck, whereas those from overseas were transported by container ship to a port and then by truck to the feed mills. The feed mills surveyed reported that Barcelona was the main receiving port. The origin of the raw ingredients was provided mainly by the feed mills, and for the ingredients of unknown origin, the leading country from which each was imported was taken from official import data (MINCOTUR, 2022; PROVACUNO, 2022). Due to the commercial sensitivity of this information, the origin of the raw ingredients will be discussed in general terms. Cereals originated from Spain, oilseeds mainly from Thailand and Indonesia, protein sources from Argentina, and the ingredients for the artificial milk replacer from the EU.

Regarding the slaughtering stage, the inputs used, the products and by-products obtained, the waste generated, and the distance travelled by the animals from the farm to the slaughterhouse were obtained from the surveys of the slaughterhouses (Table S11).

Allocation was applied at multiple points of the system. First, surplus calves were considered a co-product of dairy farms, as the main focus of these farms is milk production. Environmental burdens of dairy farms between the milk and the surplus calves sold were allocated based on biophysical criteria, as recommended by the PCR 2021:08V1.0 for dairy products (EPD, 2021). The data on milk and meat production, farm emissions, animal feed, transport, electricity, and waste treatment were obtained from a study of milk production in Catalonia, northern Spain (Noya et al., 2017), which produces a large percentage of the milk in Spain. As a result, 1.26% of the overall impacts of dairy farms were attributed to the calves sold for fattening in the DN and DA production systems.

To allocate environmental burdens among co-products in the breeding, fattening, and slaughterhouse stages, economic allocation was applied as recommended by EPD (2022). The outputs of the farm were animals and manure, and based on the mean price for the animals sold for slaughter from 2020 to 2022 from MAPA (2022b) (290.79€/100 kg live weight), the allocation factors were 98.84 and 1.16%, respectively. Hides and carcasses were the co-products of the slaughterhouse, whose mean prices from 2020 to 2022 were 0.135 euros/hide and 5.40 euros/kg carcass (MAPA, 2022a), and the resulting allocation factors were 99 and 1% for carcasses and hides, respectively.

Impact assessment

The impact assessment was performed using the ReCiPe 2016 v10 method using a hierarchist value choice (Huijbregts et al., 2017), available in LCA for Experts v.10.7 software. The impact categories were selected based on previous studies of beef production (Lupo et al., 2014; Berton et al., 2017; Noya et al., 2017; Poore and Nemecek, 2018; Presumido et al., 2018; Asem-Hiablie et al., 2019): CC (kg CO_2 eq.), freshwater eutrophication (**Fw-Eu**, kg P eq.), marine eutrophication (**M-Eu**, kg N eq.), terrestrial acidification (**TA**, kg SO_2 eq.), stratospheric ozone depletion (**SOD**, kg CFC-11 eq.), photochemical ozone formation on ecosystems and human health (**POF-Ecosys** and **POF-HH**, respectively, kg NOx eq.).

A contribution analysis was performed to analyse the results. To facilitate interpretation, the processes involved in the LCA were grouped into: (i) production of imported raw ingredients; (ii) production of Spanish raw ingredients; (iii) bedding material, (iv) forage, including silage; (v) transport of animals and raw ingredients for the feed, (vi) dairy calves, which includes all the impacts allocated to them until the day they leave the dairy farm; (vii) housing, which includes water and energy consumption at the fattening and breeding farm and the management of dead animals; (viii) enteric fermentation at the fattening and breeding farm; (ix) manure management at the fattening and breeding farm; and (x) the slaughterhouse.

Sensitivity and uncertainty analyses

To better understand the influence of certain parameters on potential impacts, sensitivity and uncertainty analyses are recommended by the ISO standards 14040/44 and PCRs, especially for comparative LCAs. These analyses considered the variability in inventory data obtained from the survey and the uncertainty in the emission factors (**EFs**) used to estimate emissions from enteric fermentation and manure management. See Table S12 for the baseline values, limits, and sources of the key parameters for the four systems.

To identify the parameters that influenced model results the most, a sensitivity analysis was performed in which changes in all input parameters defined in the baseline scenarios were evaluated. Parameters that changed one or more impacts by at least 2% were selected for subsequent Monte Carlo analysis. The sensitivity and Monte Carlo analyses were performed using the Analyst Tool in LCA for Experts 10.7 software. Due to software limitations, a normal distribution was assumed for all parameters, and the impact values were expressed as a 95% confidence interval. The Monte Carlo simulation consisted of 10,000 runs to assess the contribution of selected parameters to the overall uncertainty.

Results

Environmental impacts and contribution analysis

The DN and DA production systems had lower impacts for six of the eight categories analysed compared to the BSF and BFU production systems. Differences among the highest and lowest impact among systems ranged from 55% for CC, TA, and SOD to 25 and 13% for POF-Ecosys, and POF-HH, respectively (Table 1). This was due mainly to the lower environmental burden of calves that were fattened for slaughter in the DN and DA production systems than in BSF and BFU, since in the former systems, most of the burden of the breeding phase is allocated to milk, whereas in the latter systems, most is allocated to the meat. In contrast, M-Eu and Fw-Eu were ca. 25% higher for DN and DA than for BSF and BFU, as the final weight of the calves during the fattening phase of dairy calves was lower, and thus, more animals were needed, and more manure, the main cause of this impact, was produced, as shown in the contribution analysis. See Table S13 for the environmental impacts of the four production systems.

Regarding CC, enteric fermentation and manure management contributed the most to emissions from all production systems (Fig. 3). For BSF and BFU, enteric fermentation contributed ca. 55% of the total CC impact, while manure management contributed ca. 30%. For DN and DA, the percentages were lower: 32% attributed to enteric fermentation and 21% to manure management. This difference was due to higher emissions from adult animals during the breeding phase in BSF and BFU, whereas only 1.26% of emissions were allocated to the dairy farm for calves entering the fattening phase in DN and DA. For DN and DA, the imported raw ingredients used in the feed also had a strong influence, contributing ca. 23% of the CC impact, whereas for BSF and BFU, it contributed only ca. 5% of the CC impact.

Regarding TA, manure management contributed ca. 78% for the BSF and BFU systems, but it contributed ca. 15% for DN and DA. This difference was due to the allocation of impacts to milk production in the dairy systems. Imported raw ingredients contributed 46% of TA for DN and DA but ca. 10% for BSF and BFU. These differences were due to ammonia emissions from fertiliser application to feed crops and manure management. The large amount of concentrate required in dairy systems, due to the need for more animals in the fattening phase, also contributed to the differences.

Fw-Eu and M-Eu were influenced mainly by the use of phosphate and nitrogen fertilisers for feed crops and grassland. Crops and grassland used for animal feed contributed 83 and 77% of M-Eu for BSF/BFU and DN/DA, respectively, while for Fw-Eu, the contributions were 68 and 63%, respectively. Bedding material also contributed to Fw-Eu, accounting for 31% for BSF and BFU and ca. 35% for DN and DA. For M-Eu, forage contributed 34% for BSF and BFU and 32% for DA and DN, primarily due to the use of nitrogen fertilisers.

Manure management contributed the most to SOD, accounting for 88% of the impact for BSF and BFU and 62% for DN and DA. Manure management, imported raw ingredients, and transport were the stages that contributed the most to POF-Ecosys, contributing ca. 47, 18, and 11%, respectively, for BSF and BFU and ca. 9, 38, and 18%, respectively, for DN and DA. These stages were also major contributors to POF-HH. For BSF and BFU, manure management contributed ca. 37% of the impact, imported raw ingredients contributed 22%, and transport contributed ca. 14%. For DN and DA, the contributions were distributed among imported raw ingredients (38%), transport (18%), and manure management (7%).

Sensitivity and uncertainty analysis

The Monte Carlo simulation indicated significant differences among the production systems in various impact categories (Fig. 4). For example, the CC of BSF, BFU, DN, and DA ranged from 20.3 to 34.0, 20.3 to 34.2, 9.0 to 11.2, and 8.8 to 11.4 kg CO_2 eq./FU, respectively. The impact categories that varied the most for BSF and BFU were CC and SOD, which ranged from −3 to 64% and −2 to 74%, respectively. For DN and DA, CC ranged from −3 to 23%, while SOD ranged from −2 to 41%.

Differences in animal weight strongly influenced the performance of all production systems. The larger amount of feedstuff required to sustain more animals in DN and DA resulted in additional emissions, leading to increased Fw-Eu and M-Eu. Lower fertility and higher mortality rates also influenced CC, with higher burdens, which increased emissions for all production systems. In contrast, increasing yields decreased CC, Fw-Eu, M-Eu, TA, POF, and SOD impacts.

Discussion

Effects of the production system on environmental impacts

The environmental impacts differed among the types of production systems. DN and DA production systems had lower impacts than the BSF and BFU systems, except for M-Eu and Fw-Eu, which agrees with the results of previous studies (Lupo, et al., 2014; Mogasen et al., 2015; O'Brien et al., 2020).

Table 1

Environmental impacts of the four beef production systems per functional unit (1 kg carcass).

Impact category	BSF	BFU	DN	DA
Climate Change [kg CO_2 eq.]	20.80	20.90	9.25	9.27
Terrestrial Acidification [kgSO_2 eq.]	$8.62 \cdot 10^{-02}$	$8.62 \cdot 10^{-02}$	$3.57 \cdot 10^{-02}$	$3.58 \cdot 10^{-02}$
Marine Eutrophication [kg N eq.]	$1.03 \cdot 10^{-02}$	$1.03 \cdot 10^{-02}$	$1.32 \cdot 10^{-02}$	$1.32 \cdot 10^{-02}$
Freshwater Eutrophication [kg P eq.]	$1.09 \cdot 10^{-03}$	$1.09 \cdot 10^{-03}$	$1.42 \cdot 10^{-03}$	$1.42 \cdot 10^{-03}$
Stratospheric Ozone Depletion [kg CFC-11 eq.]	$2.50 \cdot 10^{-04}$	$2.50 \cdot 10^{-04}$	$1.05 \cdot 10^{-04}$	$1.05 \cdot 10^{-04}$
Photochemical Ozone Formation, Ecosystems [kg NOx eq.]	$2.12 \cdot 10^{-02}$	$2.13 \cdot 10^{-02}$	$1.59 \cdot 10^{-02}$	$1.61 \cdot 10^{-02}$
Photochemical Ozone Formation, Human Health [kg NOx eq.]	$1.75 \cdot 10^{-02}$	$1.77 \cdot 10^{-02}$	$1.52 \cdot 10^{-02}$	$1.54 \cdot 10^{-02}$

Abbreviations: BSF = Beef single farm; BFU = Beef fattening unit; DN = Dairy national; DA = Dairy abroad.

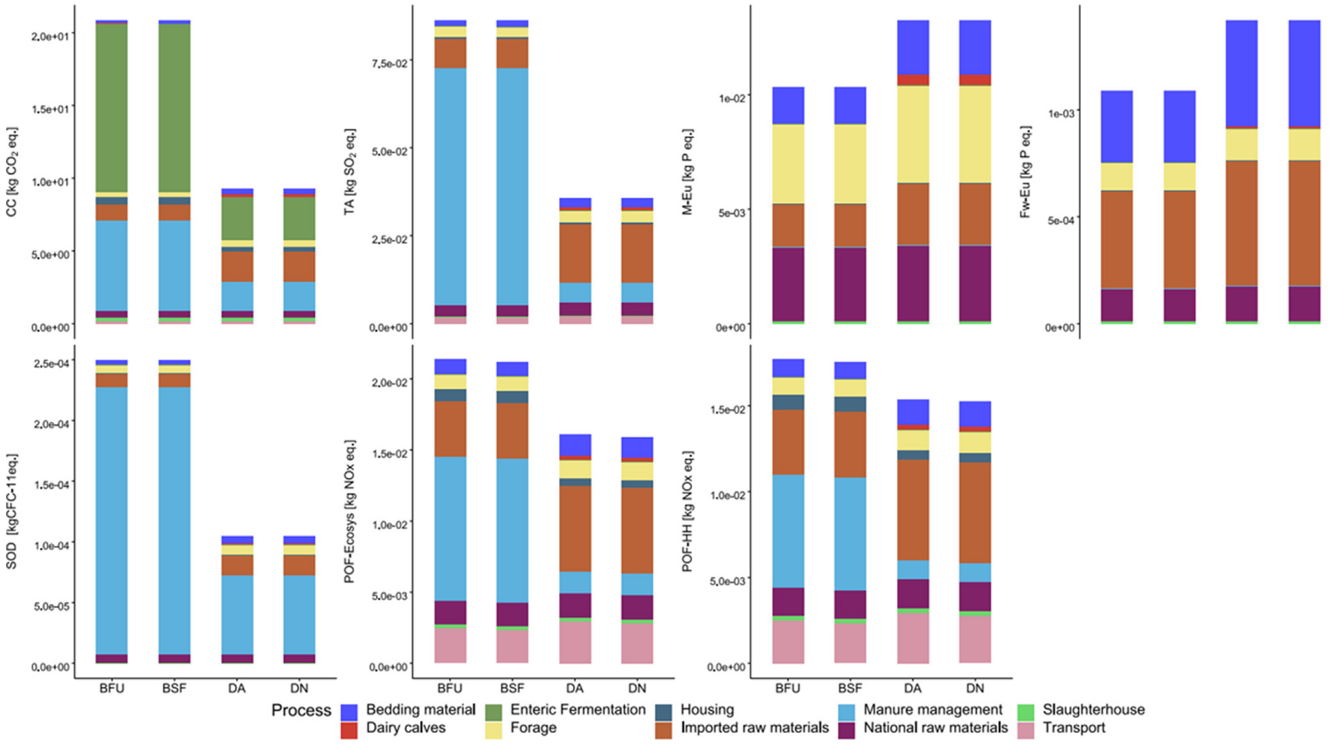

Fig. 3. Environmental impacts (climate change (CC), terrestrial acidification (TA), freshwater eutrophication (Fw-Eu), marine eutrophication (M-Eu), photochemical ozone formation-human health (POF-HH), photochemical ozone formation-ecosystems (POF-Ecosys), and stratospheric ozone depletion (SOD)) of the four beef production systems per functional unit (1 kg carcass). BSF (Suckler cow farms that fatten their own offspring), BFU (Calves from suckler farms fattened on different farms), DN (Fattening of dairy breed calves in growth units with national calves), and DA (Fattening of dairy breed calves in growth units with foreign calves).

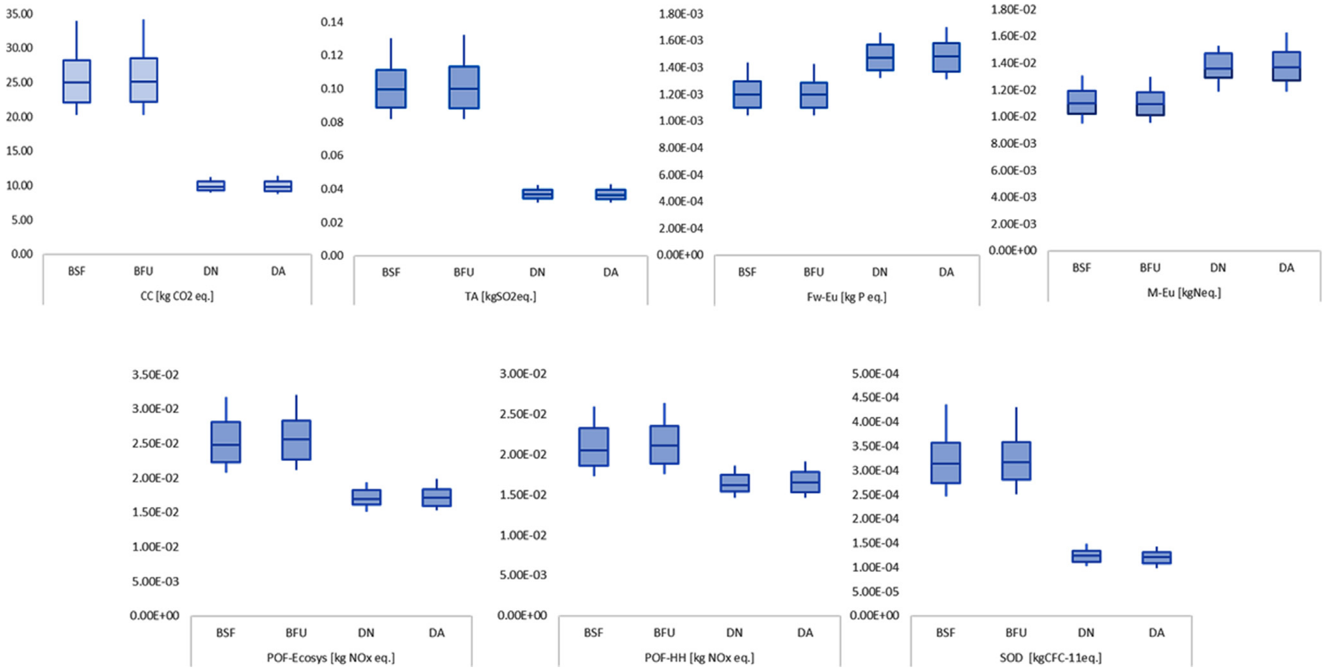

Fig. 4. Uncertainty in environmental impacts based on Monte Carlo analysis (climate change (CC), terrestrial acidification (TA), freshwater eutrophication (Fw-Eu), marine eutrophication (M-Eu), photochemical ozone formation- human health (POF-HH), photochemical ozone formation-ecosystems (POF-Ecosys), and stratospheric ozone depletion (SOD)) of the four beef production systems. BSF (Suckler cow farms that fatten their own offspring), BFU (Calves from suckler farms fattened on different farms), DN (Fattening of dairy breed calves in growth units with national calves), and DA (Fattening of dairy breed calves in growth units with foreign calves). Whiskers represent 1.5 times the interquartile range.

As mentioned, the low impacts per kg carcass of meat produced from dairy cattle (DA and DN) were lower because dairy calves were co-products of the dairy farm, and most emissions from dairy herds were attributed to milk, while in contrast, the specialised beef systems (BSF and BFU) include the entire impact of reproductive animals (cows, bulls and replacement animals), which represented up to 70% of the total environmental burden. These results were similar to those obtained by Pelletier et al. (2010), who reported that, for all impact categories, the breeding phase contributed the most (ca. 63%) to the impacts of beef produced from beef cattle.

Other production stages, such as transportation and meat processing, contributed little to impacts. Meat processing at the slaughterhouse represented a small percentage of impacts (1 and 3% for beef and dairy systems, respectively), similar to those of other studies (Mogasen et al., 2015). Similar results were found for animal transportation. For example, transporting calves to fattening units in the present study contributed less than 3% of CC regardless of their origin (local or abroad).

Main contributors to each impact category

Regarding CC, the main contributor during the breeding phase was, as expected, enteric fermentation, accounting for 45% for BSF and BFU due to the lower digestibility of diets. Similar observations of the contribution of enteric fermentation to CC were reported by Bragaglio et al. (2017), who estimated that enteric fermentation contributed 76% to the breeding stage and 47% to the fattening phase. Enteric fermentation emissions are influenced by the type of diet, feed intake, and digestibility (Eldesouky et al., 2018). A roughage diet in grazing systems, which has higher DM and lower digestible energy, results in higher enteric fermentation emissions than those from a concentrate-based diet in landless systems with equivalent nutritional value (Nguyen et al., 2010).

Nevertheless, one of the main limitations of the present study is the need for information on the potential benefits of grazing systems, such as carbon sequestration. According to previous studies (Eldesouky et al., 2018; Horrillo et al., 2022), carbon sequestration has resulted in estimates of CO_2 eq. reductions of 6 and 8 kg CO_2 eq./kg carcass and up to 21 kg CO_2 eq/kg carcass for organic production systems in Dehesa ecosystems. Dehesa typically consists of open woodlands or savannah-like landscapes where a variety of tree species, primarily oaks, are interspersed with grasslands and shrubs (Reyes et al., 2022). Due to the complexity of these processes (Bai and Cotrufo, 2022) and the need for specific information at a global scale, carbon sequestration was not considered in this study.

Regarding Fw-Eu and M-Eu, the breeding phase of the BSF and BFU systems generally had lower environmental impacts than the fattening phase for all systems. This can be attributed to the raw feed ingredients during the breeding phase. This was consistent with Nguyen et al. (2010), who reported that the feed contributed the most to eutrophication during the fattening phase (48%). Previous studies have highlighted that NH_3 emissions and NO_3 and PO_4 leaching were the main causes of eutrophication (Nguyen et al., 2010; Berton et al., 2017; de Vries et al., 2015).

Regarding TA, the main contributor for BSF and BFU was manure management (67%) due to grazing emissions, while manure management during the fattening phase contributed less, ranging from 11 to 16% for DN/DA and BSF/BFU, respectively. Similar results were reported by Nguyen et al. (2010) and de Vries et al. (2015), who estimated that manure management contributed 35% of TA of beef production from dairy cattle and 80% of TA of beef production from beef cattle.

The breeding and fattening phases were identified as the largest contributor to POF (98% for BSF and BFU and 96% for DN and DA), mainly due to manure management emissions. These results are consistent with those in Portugal reported by Castanheira et al. (2010) for dairy production.

Conclusion

This study analysed the main environmental impacts of mixed beef production systems in Spain, combining the benefits of grazing and landless production. In this way, the mixed system aims to increase production efficiency while minimising its environmental impacts. The study estimated multiple environmental impacts to obtain a more comprehensive understanding of the system's environmental performance.

Feed production, enteric fermentation, and manure management contributed the most to the impact categories studied. The BSF and BFU production systems generally had higher impacts than DN and DA, except for Fw-Eu and M-Eu impacts, primarily due to the lower environmental burdens associated with dairy calves.

To mitigate the environmental impacts of the assessed beef production systems, actions targeting feed and raw ingredient management, rumen function, genetics, reproduction, and manure management are recommended. Additionally, increasing the efficiency of animal production is identified as a crucial factor in reducing environmental impacts. Future studies should consider the potential environmental benefits of grazing animals, such as carbon sequestration in the soil and biodiversity promotion.

Supplementary material

Supplementary material to this article can be found online at https://doi.org/10.1016/j.animal.2023.101059.

Ethics approval

No animals were managed in this study. The animal surveys were approved by Spanish veterinarians.

Data and model availability statement

Microsoft Excel was used to store data, and LCA for Experts 10.7 software was used to build the LCA models, which are not publicly available.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this manuscript, the authors used OpenAI to improve the English language and readability. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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Declaration of interest

The authors declare that they have no conflicts of interest.

Acknowledgements

The authors thank PROVACUNO for their assistance in surveying farmers, slaughterhouses, and feed producers. They also extend their special thanks to Salvador Calvet from the Institute of Animal Science and Technology of the UPV and Gabriela Clemente from the Group ASPA of the Department of Food Technology of the UPV, for their valuable suggestions and recommendations that helped enhance the manuscript.

Financial support statement

This study received financial support from the project CARBON NEUTRAL 2050 from PROVACUNO (contract date 15/12/2021).

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