Climate and biodiversity impact of beef and lamb production – A case study in Sweden

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Climate and biodiversity impact of beef and lamb production – A case study in Sweden

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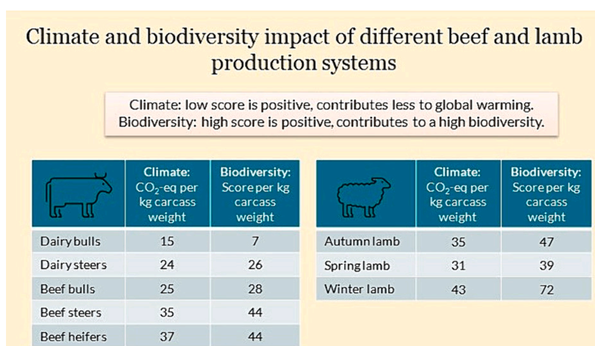
HIGHLIGHTS

- Meat production can have high climate impact, however grazing ruminants can contribute positively to biodiversity.
- This study quantitatively assesses climate and biodiversity impact of different beef and lamb production systems in Sweden.
- Dairy bulls have low emissions of GHGs, while beef breed steers and heifers give high contribution to biodiversity.
- Intensively reared lambs have low emissions of GHGs, while extensively reared lambs give high contribution to biodiversity.
- Grazing on semi-natural grasslands had the greatest positive effect on overall biodiversity scores.

GRAPHICAL ABSTRACT



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ABSTRACT

CONTEXT: The climate impact of meat production is a hotly debated topic. What is less often highlighted is that grazing ruminants can have positive impacts on biodiversity.
OBJECTIVE: The aim of this study was to use a life cycle perspective to assess both the climate and biodiversity impact of different beef and lamb production systems in Sweden.
METHODS: Applying a life cycle perspective, a quantitative method to assess biodiversity was used, with a scoring system based on land use. For the climate impact calculations, the ClimAg biophysical systems model was used, including emissions from drained organic soils and carbon sequestration in mineral soils. The functional unit was 1 kg carcass weight.
RESULTS AND CONCLUSIONS: The results indicated large differences in biodiversity and climate impact between the production systems studied. Dairy bulls had relative low emissions of greenhouse gases, but also a low biodiversity score (a high score indicates higher level of biodiversity). Beef breed steers and heifers had higher

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emissions of greenhouse gases but a higher biodiversity score, suggesting a trade-off between climate and biodiversity impact. Also for lamb meat, greenhouse gas emissions vary among production systems. A system with winter born lambs slaughtered in spring, closely followed by spring born lambs slaughtered in autumn, had the lowest emissions, while spring born lambs slaughtered in winter had the highest emissions. Winter lambs on the other hand, had a relatively high biodiversity score, due to a long rearing period and an extensive land use with a high proportion of semi-natural grasslands.

Climate impact was in all systems related to methane from enteric fermentation, emissions from manure storage, and emissions from organic soils. With the assumptions made in this study, soil carbon sequestration is suggested to reduce the climate impact by 5–7% of the total emissions. Biodiversity impact was in all systems positively related to the amount of grazing in permanent grasslands, in particular semi-natural grasslands. Because semi-natural grasslands are among the most species rich terrestrial ecosystems in Europe, a large surface area grazed resulted in high biodiversity scores in the present model.

SIGNIFICANCE: This study used a novel approach for biodiversity assessment, where the positive contribution of semi-natural grasslands to biodiversity was quantified and put in relation to the modelled climate impact.

Introduction

The environmental impact of meat production is a hotly debated topic. Previous life cycle assessments (LCAs) have demonstrated a particularly high climate impact of beef and other types of ruminant meat in comparison with meat from monogastric animals (de Vries and de Boer, 2010). Ruminant production give rise to greenhouse gas (GHG) emissions, especially methane (CH_4) from enteric fermentation, and can contribute to other environmental impacts such as nitrate pollution and biodiversity loss due to overgrazing.

What is less often highlighted is that ruminants are unique among livestock in their ability to digest forages and to graze on grasslands unsuitable for growing crops. Whilst doing this they produce meat and milk which are highly nutritional foods. Meat from ruminants are part of the diet in most cultures, and play an important role for food security in many countries (Godber and Wall, 2014). In addition, grasslands and pastures can contribute to soil carbon sequestration (Henryson et al., 2022; Poeplau et al., 2015). Last but not least, grazing is of uppermost importance in order to preserve biodiversity in species-rich semi-natural grasslands (Eriksson, 2021).

There are large variations in the climate impact of different systems of beef and lamb production. In a review by Pishgar-Komleh and Beldman (2022) beef production in Europe can vary between 7 and 46 kg CO_2-eq. per kg carcass. Grain-fed ruminants in intensive systems tend to have lower climate impact than slower growing animals in extensive systems based on forage, which give rise to more methane emissions per kg meat (Klopatek et al., 2022). Further, beef originating from dairy systems tend to have lower calculated GHG emissions than beef originating from suckler-based systems since part of the environmental impact is allocated to the produced milk (Laca et al., 2023). Around 50%–80% of the carbon footprint of beef is methane from enteric fermentation. Manure handling, carbon dioxide emissions from energy use, production of input goods such as feed and land-use change are other sources of emissions (Ineichen et al., 2022; Laca et al., 2023). For lamb there are much fewer studies, however a global review highlight variations between 3 and 26 kg CO_2-eq. per kg live weight, variations attributed both to differences in rearing systems but also in LCA-methodologies e.g. allocation between meat and wool (Bhatt and Abbassi, 2021).

Small changes in the large stock of soil organic carbon can have a substantial influence on the climate impact of agriculture, and soil carbon sequestration is often cited as an approach to reduce the net climate impact of beef production (Henryson et al., 2022). In many cases, ley production stores more carbon in soil than annual cropping (Alemu et al., 2017; Knudsen et al., 2019). A Swedish study found that carbon sequestration could potentially offset 15–22% of emissions arising from beef production (Hammar et al., 2022). On the other hand, use of drained organic soils give rise to large emissions of carbon as well as nitrous oxide. In Sweden, about 7% of the agricultural land is on drained organic soil (Pahkakangas et al., 2016).

Regarding biodiversity, anthropogenic landscapes with traditionally managed semi-natural grasslands in low-intensity livestock systems harbor an exceptional richness of many taxa, such as plants, fungi, and invertebrates (European Environment Agency, 2020; Eriksson, 2021). The species richness in these landscapes reflects a species pool from Pleistocene herbivore-structured environments, which, after the extinction of Pleistocene megafauna, was rescued by the introduction of domestic herbivores in pre-historic agriculture (Eriksson, 2021). Semi-natural grasslands require continuous livestock grazing or traditional hay-cutting methods for their maintenance and the preservation of associated biodiversity (Bengtsson et al., 2019; Emanuelsson, 2009; Tälle, 2018).

There is a large amount of biodiversity indicators used for e.g. policy, national and corporate reporting (Harris et al., 2021). Quantification of biodiversity impact in LCA is however less common as most methods are restricted to specific areas or only one or a few organism groups (Crenna et al., 2020; Damiani et al., 2023; Gabel et al., 2016). To our knowledge, only two attempts to score biodiversity across several taxa and with a specific focus towards farming systems, have previously been reported in Sweden (Emanuelsson et al., 2024; Kvarnbäck and Emanuelsson, 2001). Emanuelsson et al. (2024) developed a farm tool with a scoring system that incorporated both land use (e.g. arable land, semi-natural grasslands, forest), and field boundaries in the landscape (e.g. field-forest edges, water streams, roads). The scoring systems suggested by Emanuelsson et al. (2024) and Kvarnbäck and Emanuelsson (2001) were further developed in the present study, summarizing the effects of both land use for feed production and grazing.

The overall aim of this study was to use a life cycle perspective to assess climate and biodiversity impact, as well as possible trade-offs in between these two impact categories, in case studies of different systems of beef and lamb production in Sweden.

1. Materials and methods

In this study, the environmental impact of beef and lamb production from farm to slaughterhouse was calculated using LCA methodology. The life cycle included, among other things, feed production (own and purchased), farmyard manure handling, transport to and energy use at the slaughterhouse. All inputs and energy use in both feed production and animal husbandry were included in the calculations.

1.1. System boundaries

The case study covered various systems of beef and lamb production located in the forest district of Götaland in southern Sweden which is the most ruminant dense area of Sweden. In a pre-study (Ahlgren et al., 2022), locations in other regions of Sweden were also evaluated in LCAs. However, as the differences between the regions were small, only results from the forest district of Götaland is presented in this paper. The functional unit was set to 1 kg carcass weight.

Beef from two main types of production systems was studied: beef originating from dairy production (dairy bulls, dairy steers) and beef from suckler-based beef production (beef bulls, beef steers and beef heifers). For lambs three production systems were studied, defined by season of slaughter: autumn lambs, spring lambs, and winter lambs (Fig. 1).

For each production system a typical production was described regarding e.g. indoor feed-rations, grazing, housing, manure handling systems, slaughter age and weights. The description was worked out in an iterative process with experts in the field and with the support of literature and statistics. The descriptions aimed at representing a typical professional production, not hobby farms nor the most high-performing farms. Each system was modelled with input data for these typical farm descriptions, however the emissions from the dairy system was based on previous literature, since it only has a minor influence on the results; it is only a small part of the dairy system's emissions that is allocated to the calves that go to meat production (gray box in Fig. 1).

The assessment included emissions associated with production of all inputs during the life of the animal e.g. feed production, energy, transports, manure handling. Emissions from enteric fermentation was also included, as well as direct and indirect emissions from the soil. For both animal species, the environmental impact of the parental animals was included in the calculations. Economic allocation was used to manage by-products, for example to distribute the environmental impact between meat and slaughterhouse by-products (SM5). Slaughterhouse by-products include e.g. blood, fat, bone, intestines and skins. For lambs, the skins are assumed to have little economic value and is included in the category slaughterhouse by-products. Economic allocation was also used to distribute the environmental burden of feed production e.g. between rape seed oil and cake.

1.2. Animals

The beef-suckler herd was assumed to consist of 30 cows and the finishing cattle operations produced 150 dairy or beef bulls, 60 dairy or beef steers or 40 beef heifers for slaughter every year. The beef-suckler operation was assumed to run the cropping and livestock production according to the rules of organic farming, while the finishing cattle operations were assumed to be run in a conventional manner.

The dairy bulls and steers were of Holstein breed, the suckler cows crossbreeds Hereford x Simmental, and the breeding bulls Charolais. The dairy calves entered the beef system at a weaning liveweight of 100 kg, where the environmental and climate calculations for the dairy bulls were independent of birth date as they were kept indoors, whereas the calculations for the dairy steers were averages of steers born in January and August. The spring-borne beef suckler calves were weaned at seven months of age and hence entering the finishing system in the autumn. The various categories of young cattle considered were aged 15–30 months at slaughter with a 315–385 kg carcass weight. See Tables SM1 and SM2 for detailed description of the cattle.

The lamb production systems were all integrated with the lambs born and kept until slaughter at the same farm. All lamb production was assumed to be run in a conventional manner. Herd size varied between production systems, where operations with slaughter in spring, autumn, and winter had 300, 120 and 100 ewes respectively. The ewes in all production systems were of Finewool x Dorset crossbreed. The breeding ram for spring lamb was of pure Texel breed, whereas the breeding rams for autumn and winter lambs were of Suffolk breed. Hence, all slaughter lambs where three-way crossbreeds.

Spring lambs were born in winter, weaned at two months of age and slaughtered in the spring. Autumn lambs were born in spring, weaned at three months of age and slaughtered in the autumn. Winter lambs were born in spring, weaned at 3.5 months of age and slaughtered in the winter. The carcass weights were 20.2–20.5 kg. See Tables SM3 and SM4 for detailed descriptions of the sheep.

1.3. Indoor feed and grazing

Nutritional requirements and feed intake for cattle was calculated in Typfoder version 6.34 (NorFor, 2012), whereas requirement and feed intake for sheep was calculated in an spreadsheet-tool based on National Research Council (2007) and modified by Salomonsson et al. (2003).

Grass-clover silage was the basic forage feed for all production systems. The average yield of grass-clover silage was set to 7.9 ton dry matter per hectare and year. The leys were assumed to be harvested two or three times a year, depending on production system.

Suckler cows, breeding bulls and weaned beef steers and heifers are assumed to eat roughage only. The feed for the dairy and beef bulls is 40% grain and compound feed especially during finishing period, while the dairy steers eat some compound feed at a young age but then mostly roughage.

Lambs in the spring system were reared indoors on ewe's milk, grass-clover silage and compound feed until slaughter. Autumn lambs grazed after weaning until slaughter. The winter lambs also grazed after weaning but were housed and fed grass-clover silage and a small amount of compound feed until slaughter. During the indoor period, the ewes in all production systems were fed grass-clover silage complemented with some compound feed during late pregnancy and lactation. During the grazing season the ewes had no additional feed.

1.4. Housing and manure management

The beef suckler herd was assumed to be kept in loose housing with

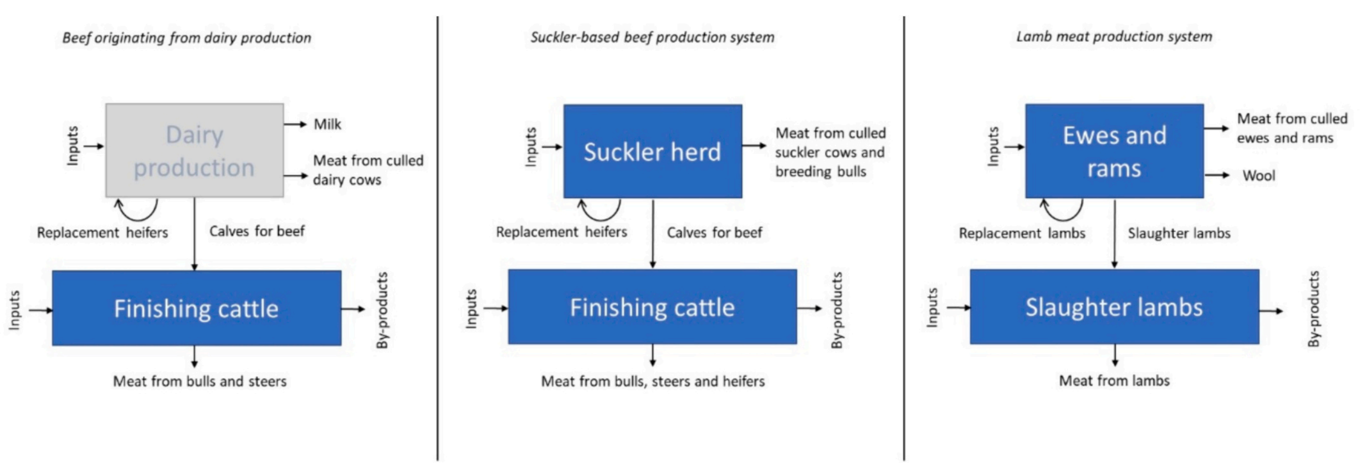

Fig. 1. Beef and lamb production systems studied, including dairy bulls and dairy steers from dairy production, bulls, steers and heifers from suckler-based beef production, and lamb from a meat-production system. The dairy system (gray box) was not modelled, but data from previous studies included in the calculations.

cubicles during the indoor period, resulting in the slurry being stored in an outdoor open tank with a floating crust. Steers and heifers were assumed to be kept on deep litter with scraped alleys, resulting in semi-liquid and farmyard manure stored together on a concrete pad outdoors until application on the fields. The slaughter bulls were, after a transition period on straw, assumed to be kept on fully slatted floor during the finishing period, resulting in the slurry being stored in an outdoor open tank with a floating crust. All sheep were assumed to be kept on deep litter during the indoor period, resulting in farmyard manure stored on a concrete pad outdoors until application on the fields.

1.5. Climate impact assessment

This is not a complete environmental impact assessment e.g. as specified by FAO (2016) The environmental impact categories included in the study were climate impact as CO_2-eq. (using the following characterization factors: fossil CO_2: 1; biogenic CH_4: 27; fossil CH_4: 29,8 and N_2O: 273 (IPCC, 2021)) and impact on biodiversity.

All animal feed, both purchased and home grown, was included in the environmental assessment. All roughages were assumed to be homegrown and complemented by purchased compound feed of Swedish origin, consisting of a mix of cereal and by-products (rapeseed meal, DDGS, molasses). Carbon footprint of by-products was based on modeling of main crops and allocation to by-products based on economic value.

Methane emissions from feed digestion were calculated as a fraction of feed gross energy intake. In contrast to most other studies, this fraction was not an exogenous constant, but an endogenous variable calculated as a function of feed quality, daily feed intake and animal liveweight. For cattle, the prediction equations from Moraes et al. (2014) was used (specifically, the "Animal" level equations) and for sheep the prediction equations from van Lingen et al. (2019). For more details, see Table SM6.

The emissions of methane from barns and during manure storage was calculated with the methane conversion factor (SM6) following methodology in IPCC (2019). Nitrogen oxide emission factors for barns with slurry handling were assumed to be 0.5% for barn and 0.5% for storage. For deep litter systems the emission factors were assumed to be 1.0% from the deep litter and 1.0% from storage of used deep litter (IPCC, 2019).

Nitrous oxide emissions from soils were calculated as a fraction (emission factor) of different inputs of nitrogen (SM7 and SM8). For emissions from artificial fertilizer application we used a factor of 1.6% for application on annual crops and 1.0% for application on grass-legume leys, based on Hergoualc'h et al. (2021).

Energy use for feed production and in barns were calculated using several different types of fuel use factors, see Table SM9. Carbon dioxide emission factors were 13 and 95 g CO_2 MJ^{-1} for electricity and diesel, respectively (Swedish Energy Agency, 2023).

As a measure of carbon storage in leys and cropland, soil carbon (SOC) from a recently published study, Henryson et al. (2022), was used. Henryson et al. (2022) found that the average carbon content increased by 140 kg C/ha and year on beef farms, based on data from the Swedish soil and crop monitoring programPastures also store carbon, but as Swedish permanent grasslands often are not fertilized, an estimate of 30 kg of stored carbon per hectare and year was used in this study (Karltun et al., 2010). 1 kg of C is the equivalent of 3.67 kg of CO_2.

Drained organic soil is a major emitter of greenhouse gases as a result of oxidation of organic matter (Grønlund et al., 2006; Maljanen et al., 2004). There is no statistical information as to what extent the cattle and lamb production in Sweden is located on this type of soil. Therefore, a general distribution of organic soils for all cropland (5%) and pasture (7%) was used (Lindahl and Lundblad, 2021). The IPCC's emission factor organic soil (Lindgren and Lundblad, 2014) was used.

Modeling and calculation of all emissions was performed in the ClimAg biophysical model described in Wirsenius et al. (2020).

1.6. Biodiversity impact assessment

To assess impacts of different animal rearing systems on biodiversity, a scoring system with a scale from 0 to 10,000 was developed. The score reflects the assessed contribution to biodiversity of different land use categories and is based on previously published methods to assess biodiversity scores on farmland (Emanuelsson et al. (2024), Kvarnbäck and Emanuelsson (2001), and SIS (2023), field inventory data from a monitoring program of biodiversity in permanent grasslands in Sweden (Glimskär et al., 2023a, 2023b; Lundin et al., 2016), and expert judgement.

Kvarnbäck and Emanuelsson (2001) carefully examined diversity among several species groups in eleven farms across Scandinavia. This work was taken further by Emanuelsson et al. (2024) who developed a biodiversity scoring system that incorporated both land use (e.g. arable land, semi-natural grasslands, forest), and field boundaries in the landscape (e.g. field-forest edges, water streams, roads). In addition, in the standardized system for inventories of nature values in Sweden (SIS, 2023) different land use categories are ranked according to their contribution to landscape biodiversity. In the present study, the scoring systems suggested in these previous studies were revised to fit the purpose to examine the contribution of different animal rearing systems to biodiversity. Field inventory data from plots distributed in different grassland types across Sweden was analyzed in this process (Glimskär et al., 2023a, 2023b) together with other published sources (see below). Expert judgments were necessary to adapt the scoring system to the purpose of the present study as previous methods were not suitable to use directly. The scoring system used in this study is shown in Table 2.

For semi-natural grasslands, the ranking was differentiated based on soil type and moisture gradient, both being environmental factors known to be important for species diversity (Dengler et al., 2014; Moeslund et al., 2013; Slabbert et al., 2022). For example, dry and thin soils with a high sand content are generally more species rich than wet clay soils (Glimskär et al., 2023a). Scoring points for semi-natural grasslands varied from 5000 to 10,000 reflecting variation among grassland types (Table 2), and this differentiation was based on data from inventories of vascular plants in field plots in many different grassland types throughout Sweden (Glimskär et al., 2023a; Glimskär et al., 2021; Lundin et al., 2016). This paper focused on the forest districts of Götaland, using an average score of 8000 points per hectare of semi-natural grasslands. Results for other regions in Sweden can be found in Ahlgren et al. (2022). Improved permanent grasslands are less rich in biodiversity than semi-natural grasslands and were therefore given a lower score (Diekmann et al., 2019; Glimskär et al., 2021), Table 1).

Arable land used for animal feed production are less diverse than grasslands and were therefore given lower biodiversity scores; 1000 to 3000 points depending on the crop. Flowering crops that offer nectar and pollen benefit pollinator biodiversity (Riggi et al., 2024; Westphal et al., 2003), and the present scoring scale reflects this notion. It further takes into account the value of perennial crops for a more functional habitat for biodiversity both above and below ground (Heinen et al., 2023). Leys were thus ranked lower than permanent grasslands, early mowing was ranked lower than late mowing, cropland was ranked lower than leys, and cropland with rapeseed or cereals were ranked lower than cropland with legumes (Table 2).

Consideration was also given to whether the production was organic or conventional following Tuck et al. (2014). An additional value of 1200 points per hectare were added to organic cultivation systems reflecting the notion that the expected overall biodiversity is in such systems compared to conventional systems (Bengtsson et al., 2005; Gabriel et al., 2010; Hole et al., 2005). Thus, a hectare of e.g. organically grown cereal received 2200 points compared to conventional cereal cultivation that received 1000 points per hectare. In the present study area, only a small share is organically grown, making the impact of this additional score limited.

Table 1
Scoring scale for different types of land use used in this study.

Type of land use	pointS/ha	Contribution to biodiversity
Permanent pasture		
Semi-natural grasslands	5000–10 000[a]	Grazing livestock. Ecosystems with a very high species diversity and important habitats for many threatened species
Improved permanent grasslands	4000	Grazing livestock. Less species rich than semi-natural grasslands but nevertheless important habitats in the agricultural landscape.
Arable land		
Grass-clover ley, late harvest (after midsummer)	3000	Nesting sites, flowering plants (nectar and pollen), soil fauna
Grass-clover ley with legumes, early harvest	2000	Flowering plants (nectar and pollen), soil fauna
Grass ley, grazed	2000	Grazing livestock, soil fauna
Grass-clover ley, grazed	2500	Grazing livestock, flowering plants (nectar and pollen), soil fauna
Cropland, field bean	2000	Flowering plants (nectar and pollen)
Cropland, peas	1500	Flowering plants (nectar and pollen)
Cropland, rapeseed	2000	Flowering plants (nectar and pollen), seeds for birds
Cropland, cereals	1000	Seeds and nesting sites for birds
Additional points for arable land		
Organic cropping	+ 1200	No herbicide use
Field size	+700 – +1400[b]	Small fields gives more landscape heterogenity

[a] Depending on soil type and moisture gradient.
[b] Relative value, studied farms compared to Swedish average.

Field size gives an indication of landscape heterogeneity that is crucial for biodiversity within the arable landscape. Small fields results in more forest-field edges and strips of grass, compared to landscapes dominated by large fields (Sirami et al., 2019). In this study typical arable field sizes in the studied production systems were compared to the average Swedish arable field size (Swedish Board of Agriculture, 2022). The fields in the forest districts of Götaland are smaller (1.6 ha) than the Swedish average field (3.6 ha), resulting in 2300 additional points per hectare arable land as previous studies have shown positive effects of small fields on biodiversity (e.g. Emanuelsson et al., 2024).

2. Results

2.1. Climate impact

The results (Fig. 2, Table SM10) for the beef case studies show that there was a large variation in climate impact among the different production systems, where dairy bulls had the lowest emissions (approx. 15 kg CO_2.eq. per kg carcass weight) and dairy steers and beef breeds had higher emissions, 24–38 kg CO_2.eq. per kg carcass weight. The beef breeds had higher impact than the dairy breeds as they have to carry all the emissions from the cow. Methane from enteric fermentation, emissions from manure storage and emissions from organic soils accounted for the largest emission sources in all systems.

The results (Fig. 3, Table SM12) for the lamb meat case studies show that emissions vary between production systems. Spring lambs (31 kg CO_2.eq. per kg carcass weight), closely followed by autumn lambs (35 kg CO_2.eq. per kg carcass weight), had the lowest emissions, while winter lambs (43 kg CO_2.eq. per kg carcass weight) had the highest emissions as they had a higher slaughter age and thus had time to release more climate gases but did not reach a higher carcass weight. All lamb production systems must also carry a large load from the ewe. Similar to the beef systems, methane from enteric fermentation, emissions from organic soils and emissions from manure storage accounted for the largest emissions.

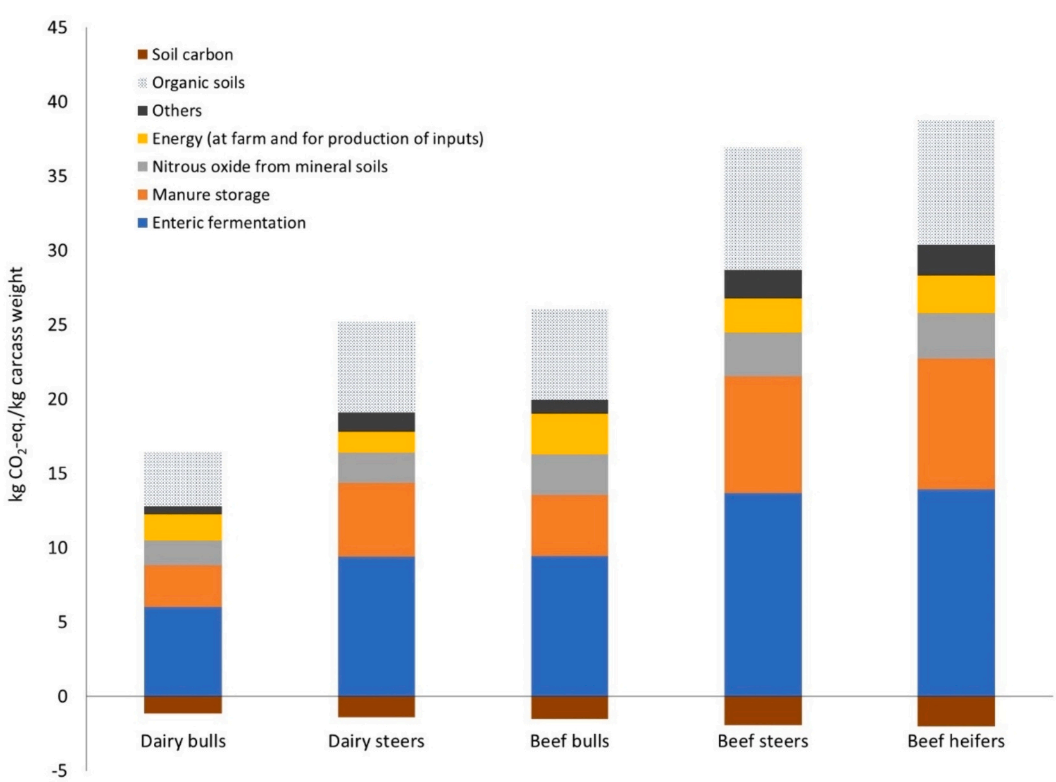

Fig. 2. Climate impact results for five beef production systems with cattle of dairy and beef breed. Negative values mean that carbon is sequestered from the atmosphere, i.e. has a cooling effect on the climate. "Others" include smaller emission posts e.g. transports, methane from pasture, indirect nitrous oxide emissions. Note that emissions from organic soils are not always included in LCA-studies, see discussion section 4.1.

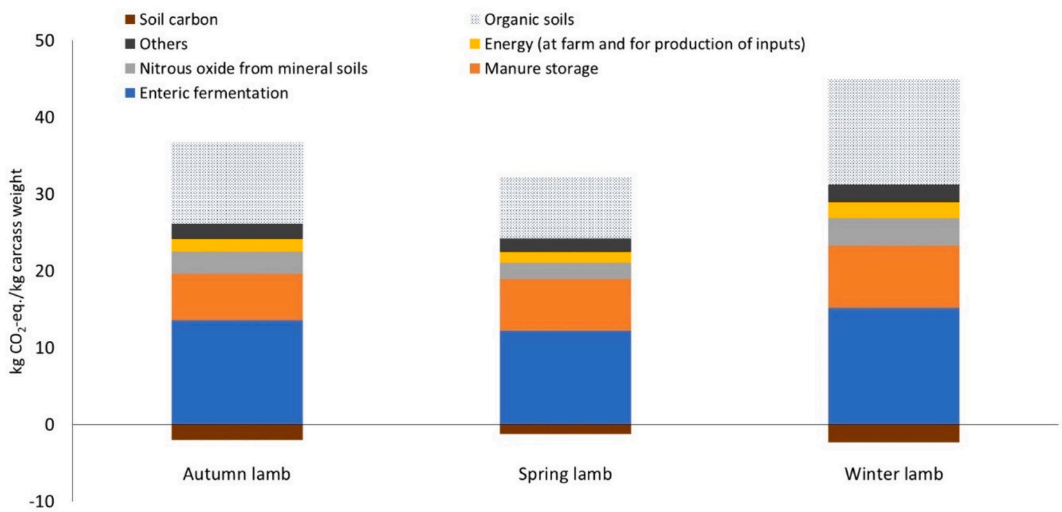

Fig. 3. Climate impact results for three production systems of lamb meat with various time of the year for slaughter. Negative values mean that carbon is sequestered from the atmosphere, i.e. has a cooling effect on the climate. "Others" include smaller emission posts e.g. transports, methane from pasture, indirect nitrous oxide emissions. Note that emissions from organic soils are not always included in LCA-studies, see discussion section 4.1.

2.2. Biodiversity impact

The results (Fig. 4, SM11) show that dairy bulls have a much smaller positive contribution to biodiversity than other beef rearing systems, since they do not graze. In the other beef and lamb rearing systems in this study, grazing on semi-natural grasslands creates the largest positive effect on biodiversity, followed by grazing on agriculturally improved permanent grasslands (i.e. intensively managed or modified grasslands that have been reseeded or fertilized). Winter lambs graze relatively large areas of semi-natural grasslands and therefore obtain high biodiversity scores (Fig. 5, SM13).

3. Discussion

3.1. Climate impact

Meat originating from culled dairy cows compose a large proportion of the beef consumed in Sweden. By complementing the results for the studied beef systems with a general climate footprint for dairy cows, a Swedish average can be obtained, provided the studied region is representative for all of Sweden. The estimated climate impact for Swedish beef production is then approx. 22 kg CO_2-eq. per kg carcass

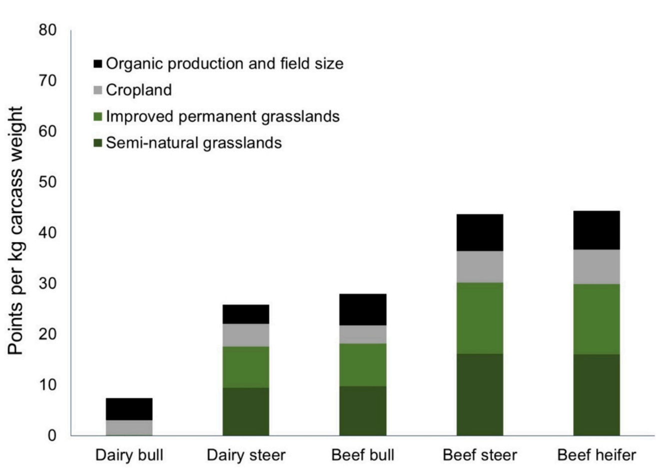

Fig. 4. Biodiversity impact for five beef production systems with cattle of dairy and beef breed. High values are positive for biodiversity.

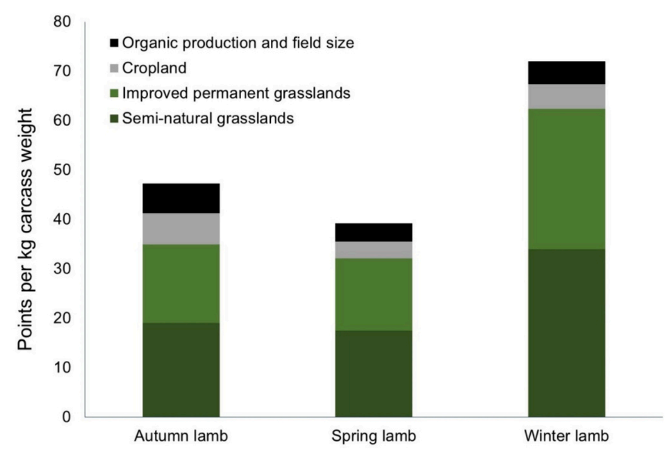

Fig. 5. Biodiversity impact for three production system of lamb meat with various time of the year for slaughter. High values are positive for biodiversity.

weight of beef when including soil carbon sequestration and emissions from organic soils and approx. 19 kg CO_2-eq. per kg carcass weight when excluding soil carbon sequestration and emissions from organic soils. This is well in line with other studies, see e.g. reviews of beef LCA studies by (de Vries et al., 2015; Pishgar-Komleh and Beldman, 2022).

Regarding Swedish lamb, it is estimated that autumn lamb makes up 52% of all Swedish lamb production, spring lamb 28% and winter lamb 20%. If the lamb production systems studied are representative for the whole country, a Swedish average climate impact for lamb meat can be obtained. It is 34 kg CO_2-eq. per kg carcass weight of lamb including soil carbon sequestration and emissions from organic soils and 26 kg CO_2-eq. per kg carcass weight excluding soil carbon sequestration and emissions from organic soils. This is well in line with other LCA studies of lamb production in Great Britain (Jones et al., 2014; Wiedemann et al., 2015) and Ireland (O'Brien et al., 2016).

In many previous LCAs, emissions from organic soils are not included. In this study, we have chosen to include these emissions and they proved to have a large impact on the climate impact results. If emissions from organic soils and sequestration of soil carbon is excluded from the calculations the climate impact is reduced by 16–20% for beef and 22–27% for lamb. Including or excluding organic soil emissions is in other words a vital choice in carbon footprint calculations of animal products.

3.2. Biodiversity impact

The method to assess how variation in land use impacts biodiversity used in this study, presumes that all land use contributes somewhat positively to biodiversity, compared to a reference state corresponding to a hardened urban surface, such as tarmac. There are alternative ways of reasoning about the reference situation. In LCA biodiversity methods, an ideal natural state (i.e. no human impact) with high biodiversity is often used as a reference state, with the assumption that all types of anthropogenic land use will have a negative impact on biodiversity (Vrasdonk et al., 2019). It is the potential risk of deteriorating this natural state that is assessed as biodiversity damage potential, alternatively preventing the land to return to its natural state.

This approach is however less relevant for grasslands in a European context, where semi-natural grasslands are among the most diverse terrestrial ecosystems and provide habitats for a large proportion of the continent's endangered species. For the Swedish region used in this study, the most likely alternative land use category to semi-natural grasslands and other farmland, would be spontaneously grown bush or spruce forest plantations. An alternative reference state could therefore have been production forests. However, as production forests are typically considered to be degraded ecosystems low in biodiversity (Felton et al., 2010), such a reference state would also have been given low biodiversity scores with the present method.

The method used in this study provides a novel approach, where the effect of land use is ranked on a positive scale. This is because we want to reflect the positive contribution semi-natural grasslands maintained by grazing animals have to biodiversity. Semi-natural grasslands are essential for the conservation of biodiversity in Europe but the amount of such grasslands have declined sharply over several decades (Auffret et al., 2018; Cousins et al., 2015; European Environment Agency, 2020). Similar reasoning is presented in Torres-Miralles et al. (2022), where the proportion of semi-natural grasslands of the total land use, on meat producing case study farms in Finland, was used as a biodiversity indicator.

In the present study, the total land use area in the production systems was included in the biodiversity scoring, resulting in all land used for feed production contributing, to a varying degree, positively to biodiversity, also rather barren cropland. This approach results in increasing biodiversity scores with increasing land use, and is most likely best suited for studies in forest-dominated regions, such as Sweden, where 68% of the terrestrial area is forests and only 7% is agricultural land (Statistics Sweden, 2024). In this type of regions, all open land contributes to a varied mosaic landscape and hence increases biodiversity. In countries dominated by agricultural land, forests and set-aside land provides landscape heterogeneity, and increased areas of agricultural land may not be beneficial for landscape biodiversity, but rather the opposite. In such regions, proportions of various land use, similar to Torres-Miralles et al. (2022) could be more relevant for biodiversity assessments. The method used in the present study was at a later stage modified to combine the scores of various land use with proportions of land in a recent pan-European study on livestock farms (Diaz Vicuna et al., 2024).

3.3. Uncertainty analysis

Life cycle assessment models contain a lot of data, and many assumptions are made. In an uncertainty analysis, we tested how the results for climate and biodiversity were affected by some of the main assumptions (SM14 and SM15) for a selection of the studied systems. For climate, especially the methane from feed digestion and the emission factors for organic soils had a large impact on the results. The impact on the absolute values were large in the uncertainty analysis, however, the ranking between the different production systems did not change. For biodiversity, some assumptions on grazing were tested, revealing that the share of semi-natural grassland has a large impact on the results. The scoring for organic production proved to have little influence, while the scoring for field size had a large impact on the biodiversity score.

3.4. Trade-offs between biodiversity and climate

There was a positive relationship between calculated GHG emissions and biodiversity score among the production systems studied (Graphical abstract), suggesting that systems promoting biodiversity have a larger climate impact. Comparing the biodiversity score:climate score quota (B:C) among the systems can indicate which system contributes most to biodiversity in relation to climate impact. The B:C of the dairy bulls was 0.5 (7/15; Graphical abstract), whereas B:C of dairy steers was 1.1 (26/24; Graphical abstract). The result implies that dairy steers contribute more to biodiversity than bulls per unit climate impact. The differences in B:C was less among the beef breed cattle, since all animals were grazing. The 30-month-old steer had somewhat higher B:C (1.3) compared to heifers (1.2) and bulls (1.1). Among lambs, extensively reared lambs slaughtered in winter were superior (B:C 1.7) to autumn lambs and spring lambs (both 1.3), which is due to a high proportion of pasture and forage in their feed.

Comparing the results of the two livestock species involved (Graphical abstract, Figs. 2–5) might give the impression that sheep better promote biodiversity than cattle. In the present model, this is an effect of both an assumed lower herbage yield and a longer grazing period for sheep production in the chosen region, creating a larger proportion of grazing land-use for sheep than for cattle. Anecdotal evidence, however, suggests that cattle grazing may be better than sheep grazing for the maintenance of endangered grassland biodiversity. Other studies (Karlsson, 2009; Krahulec et al., 2001; Öckinger et al., 2006) support this notion, as they found sheep grazing less favorable than cattle grazing for herbaceous plants and butterfly species, primarily due to sheep having a preference for low herbs driving the vegetation composition towards a more grass-dominated state. A correction factor for livestock species could therefore have been included in our method. It should also be noted that several other factors are important for maintaining grassland biodiversity, including the timing and intensity of grazing, and that different species assemblages may be favored by different grazing regimes.

4. Conclusions

The results showed large differences in both climate and biodiversity impact between the beef and lamb production systems studied, mainly connected to the level of intensity and grazing on semi-natural grasslands and other permanent grasslands. Extensive rearing systems, including large areas of this type of grazing per kg of carcass weight, resulted in a higher positive contribution to biodiversity but also a higher climate impact.

Regarding beef, the results show that the dairy bulls had the lowest emissions of greenhouse gases (15 kg CO_2-eq. per kg carcass weight, but at the same time also the smallest contribution to biodiversity (7 points), producing the least biodiversity in relation to climate impact. Beef breed steers and heifers had higher emissions of greenhouse gases (35 and 37 kg CO_2-eq. per kg carcass weight) but a significantly greater contribution to biodiversity (44 points).

Likewise, the results for lamb meat show that greenhouse gas emissions varied among production systems. Winter born intensively fed lambs slaughtered in the spring, closely followed by spring born lambs slaughtered in the autumn, produced on average the lowest emissions (31 and 35 kg CO_2-eq. per kg carcass weight), while extensively reared spring born lambs slaughtered in the winter had the highest emissions (43 kg CO_2-eq. per kg carcass weight). These winter lambs, on the other hand, provided a significantly greater contribution to biodiversity (72 points), both in total and in relation to their climate impact.

CRediT authorship contribution statement

Serina Ahlgren: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Data curation, Conceptualization. **Stefan Wirsenius:** Writing – original draft, Software, Methodology, Data curation. **Per Toräng:** Writing – original draft, Methodology, Conceptualization. **Annelie Carlsson:** Writing – original draft, Investigation, Data curation. **Anett Seeman:** Writing – original draft, Data curation. **Danira Behaderovic:** Writing – original draft, Validation, Methodology, Data curation. **Olle Kvarnbäck:** Writing – original draft, Methodology. **Nargish Parvin:** Writing – original draft, Data curation. **Anna Hessle:** Writing – original draft, Validation, Methodology, Funding acquisition, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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