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Environmental impacts of intensive beef fattening: a case study in the Veneto region, Italy

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Beef farming is associated with substantial environmental impacts, and the assessment of intensive fattening systems is increasingly critical, particularly in light of growing animal welfare concerns. This study evaluates the environmental impacts of specialised beef fattening farms in the Veneto region of Italy at both the farm and regional levels. The decline in the number of animals fattened in these systems has led to a corresponding reduction in regional beef production-related emissions. For the first time, we also quantify the environmental impacts linked to animal welfare outcomes. We find that animals raised on slatted floors, which are associated with higher mortality rates, contribute disproportionately to these welfare-related environmental impacts. These findings offer valuable insights for both farmers and policymakers, underscoring the importance of integrating environmental and animal welfare considerations in the development of future housing and management strategies.

Food systems are responsible for 26% of global anthropogenic greenhouse gas (GHG) emissions[1]. Beef production is associated with significantly higher levels of GHG emissions per unit of product than other foods[1]. Notably, the environmental impact of beef farming shows large variability, due to differences in methodological choices but also due to differences among existing production systems and geographies[2]. However, beef production plays a significant role in the economy, rural development, and culture[2,3]. Global beef production has almost doubled in the last 50 years (www.fao.org/faostat). Therefore, transitioning to more sustainable farming pathways is essential, and a clear understanding of the differences among existing production systems is critical to facilitate this transition.

Several studies have investigated wide-ranging pathways towards lower emission animal production systems[4–7]. When the concept of sustainability is applied to animal farming, it should encompass a broader view, considering not only the environmental pillar but also social implications, such as the welfare of farmed animals. Indeed, the growing public concern about animal welfare is increasingly pressuring current production systems toward transformation to improved welfare practices[8,9]. Some studies have investigated how these externalities trade off, for example, pig production with low land use has low GHG emissions but high antimicrobial use and poor animal welfare[10]. In the Brazilian beef sector, a positive association was observed between grazing land use and GHG emissions[11]. Further research is necessary to evaluate the environmental impacts and welfare outcomes of different farming practices.

Beef production was focused on here, as it accounts for approximately 48% of GHG emissions from animal products[1], but intensive beef farming systems are not homogeneous, and a deeper examination of how they vary is fundamental for understanding and improving their performance. To advance effective solutions, there is a need to understand the different production systems and outcomes at regional scales, grounded in local conditions to ensure relevance, yet broad enough to be generalisable for policy or funding interventions[12]. To address this challenge, we studied different types of fattening systems in which beef cattle are kept indoors for more than six months, with limited living space per animal on different flooring systems, a minimum allowance of 3.5 m^2 per animal in deep bedding floor systems and 2.9 m^2 per animal on fully slatted floor systems[13]. Besides GHG emissions, we investigated other important impacts, including acidification and eutrophication potentials, and resource use, such as freshwater withdrawals and land occupation.

This study focuses on the Veneto region in northeast Italy, as Italy is the fourth-largest beef producer in the European Union (11.3% of production)[14], and the Veneto has the highest beef stocking density among all Italian regions[15]. Nearly one-third of the beef cattle fattened in the EU by specialised fattening farms are produced in Italy14, with approximately two-thirds of the cattle reared mainly in the northern part of the country. The production in Veneto is highly intensive and commonly relies on the indoor fattening of specialised beef breeds, mainly Charolais and Limousin suckler weanlings imported from France[16]. The main difference in fattening

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practices in Veneto lies in the housing system adopted, specifically the flooring system, which is associated with different welfare status. Beef cattle are mainly housed on either deep-bedding systems or fully slatted floors. Nevertheless, the use of fully slatted concrete floors in beef cattle housing systems has raised concerns about animal health and welfare[13].

We quantified the Life Cycle environmental impacts and animal welfare burden of two representative farms with different flooring systems, which reflect the annual fattening population of young bulls and heifers imported from France (approximately 300,000 fattened cattle per year on Veneto farms).

Our paper presents regional-level environmental impacts that are valuable for informing agri-food stakeholders, particularly regarding housing systems. The paper examines the interaction between population dynamics during the decade (2020-2029) and environmental impacts.

We highlight the environmental costs associated with different welfare outcomes, specifically mortality and early culling, based on primary data and supported by sensitivity analysis using literature data. Animal mortality represents a significant environmental burden, as these animals consume resources but do not contribute to final production outputs. This issue is particularly relevant in the Veneto region, where fattening systems rely heavily on human-edible crops, such as maize, which is cultivated specifically for animal feed. To quantify the environmental impact of mortality, we estimated the emissions attributable to the additional animals required to replace each lost animal. Under this replacement scenario, a greater number of animals is required to achieve the same output, resulting in increased emissions and resource use. This substitution approach is essential for evaluating the true cost of mortality in systems aiming to maintain production levels. Early culling is both an emergency measure used to slaughter animals in the late stage of fattening due to health issues (which we assess here) but is also used to change the overall herd composition towards greater long-term productivity (which we do not assess here). From a production perspective, culled animals can represent a high-impact loss compared to those lost to early-phase mortality, as they have already consumed a greater quantity of resources. Therefore, we assessed the environmental costs of mortality and early culling separately, recognising their distinct contributions to the overall environmental cost of welfare outcomes.

Our objectives were: 1) to estimate and compare the environmental impacts of beef cattle fattened under two different housing scenarios based on flooring systems, at a regional level; 2) to project future emission trends, and 3) to highlight the environmental costs associated with the differing welfare outcomes of these systems.

Results

Environmental impacts of modelled farms

Analysis of our data reveals substantial variability in environmental impacts across intensive beef production systems (Supplementary Table 1). The global warming potential (GWP) ranged from 6.34 to 9.96 kg CO_2-eq/kg body weight gain (BWG) (also called Live Weight Gain), with higher values observed in bulls raised on deep bedding. The main contributors to total farm-stage GWP are enteric fermentation and feed (Fig. 1). We broke down the diets' global warming potential to show the contribution of individual feed ingredients (Supplementary Fig. 1). Notably, system-level differences are most pronounced in emissions from manure management, where methane emissions contribute more substantially in slatted floor systems. In contrast, deep bedding systems are associated with higher direct nitrous oxide emissions. The eutrophication potential varied from 47.81 to 75.42 g PO_4^{3-}-eq/kg BWG, with higher potential in deep bedding systems. The acidification potential ranged from 91.42 to 153.57 g SO_2-eq/kg BWG, with higher values associated with slatted floor systems. Resource use was also quantified: freshwater withdrawals for input production ranged from 883 to 1,217 L/kg BWG, and land occupation ranged from 5.35 to 7.00 m² per year/kg BWG. In Supplementary Table 1, we report the environmental impact of early-culled animals.

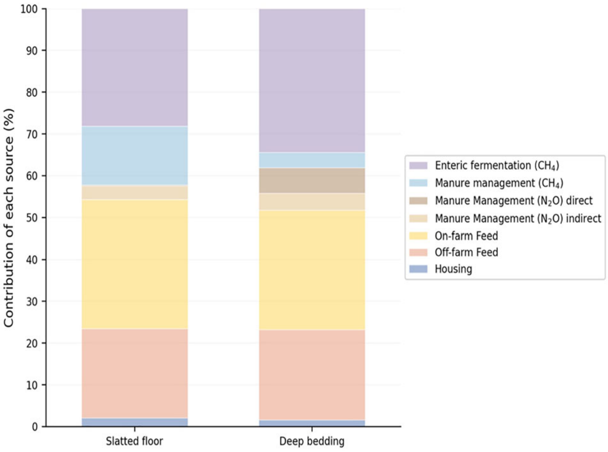

Fig. 1 | Contribution of various emission sources to global warming potential per kilogram of body weight gain, differentiated by housing system. Colours represent distinct sources: enteric fermentation, manure management, feed production, and housing. Differences in housing systems, especially in manure management, lead to notable variations in emission profiles. Methane emissions are significantly higher in slatted floor systems, while direct nitrous oxide emissions are more prominent in deep bedding systems.

Regional population trends

We estimated baseline trends for populations of 6-12-month-old bulls and heifers imported from France into the Veneto region and housed in different systems for the period 2020 to 2024, and population trends for the period until 2029 (Fig. 2). France is the most important source of weanlings for these beef fattening systems. Based on these trends, the number of bulls and heifers fattened on deep bedding is expected to show a significant annual decline of 15,120 heads ($p < 0.001$) between 2020 and 2029 in the business-as-usual scenario, while bulls and heifers fattened on a slatted floor system should have a lower annual decline of 8442 heads ($p < 0.001$). We also modelled another scenario in which the beef cattle population remains stable after 2024, based on the 2024 annual population situation (Fig. 2). Under this assumption, bulls and heifers fattened on deep bedding would remain the dominant system, with a decline of 4737 ($p = 0.03$) and 2,642 animals ($p = 0.03$) in animals produced on slatted floors.

Regional population environmental impacts

Population trends significantly affect the regional environmental impacts. From 2020 to 2029, all emissions decreased; however, significant and varying trends were observed across systems and scenarios. As the deep bedding population is proportionally larger, it contributes a greater share to the regional inventory across all indicators, ranging from 58.34% of total emissions for GWP to 68.45% for eutrophication potential.

Overall, the sum of regional population global warming potential across years is estimated at 5081 kilotonnes CO_2-eq in the business-as-usual population scenario, and 5991 kilotonnes CO_2-eq under the stabilised population scenario. The eutrophication potential is projected at 40,312 and 47,506 tonnes PO_4^{3-}-eq, while acidification potential is 80,457 and 94,745 tonnes SO_2-eq, respectively. The freshwater withdrawals are estimated at 765,758 and 905,025 megalitres, and land occupation at 399,002 and 470,590 hectares for the business-as-usual and stabilised scenarios, respectively. A decline in total inventory impacts is observed, with a more pronounced effect in the cattle reared on deep bedding systems, due to larger population reductions (Fig. 3).

If the business-as-usual population trend continues, a 59.42% reduction in GWP is projected between 2020 and 2029, compared to a 20.32% reduction under a stabilised population scenario. Similar patterns are observed across other environmental impact categories. Eutrophication potential is expected to decrease by 59.21% under a business-as-usual population scenario and by 19.97% under a stabilised population scenario.

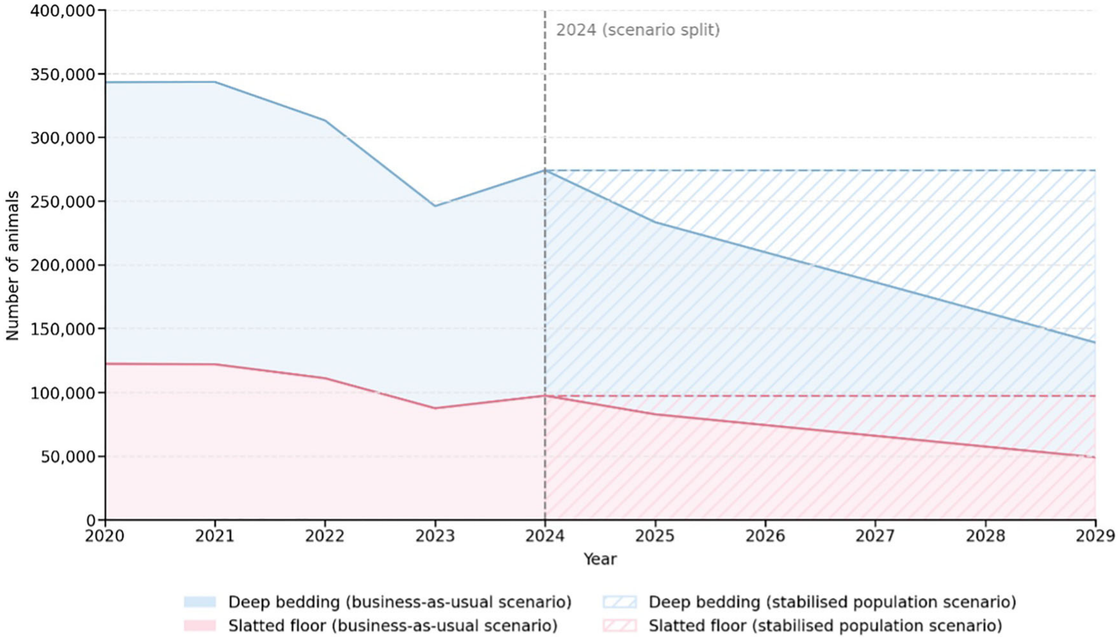

Fig. 2 | Estimated beef cattle population trends from 2020 to 2029 for deep bedding and slatted floor housing systems. From 2020 to 2024, both the 'business-as-usual' and stabilised population scenarios follow a declining trajectory. After 2024, the 'business-as-usual' scenario continues to decline at a similar rate, whereas the stabilised population scenario maintains animal numbers at 2024 levels through to 2029.

Acidification potential follows a similar trend, with reductions of 58.98% for business-as-usual populations and 19.83% under the stabilised scenario. In terms of water withdrawals, the business-as-usual population scenario sees a 60.14% reduction, while the stabilised population scenario sees a 20.83% reduction. Lastly, in the land occupation, reductions are projected at 59.48% for a business-as-usual population scenario and 20.21% in the stabilised scenario.

In response to welfare concerns regarding slatted flooring systems, it is plausible that there will be a shift away from slatted production systems. To examine the effects on environmental impacts, we modelled a scenario in which housing systems across the entire population shift to 80% deep bedding and 20% slatted floors, using the last available imported population from 2024 as a basis to illustrate the impact of such a transition. This distribution represents a plausible shift aligned with potential future policy developments. Under this scenario, annual population-level emissions are projected to change, with global warming potential decreasing by 27.6%, eutrophication potential decreasing by 2.3%, and land occupation decreasing by 0.8%. In contrast, acidification potential increases by 1.3%, and freshwater withdrawals rise by 0.7%.

Environmental impacts associated with different welfare outcomes

We used mortality and early culling rates as indicators of animal welfare outcomes across different fattening systems. Mortality was higher in the deep bedding system. In contrast, early culling rates were significantly higher in the slatted flooring system, averaging 4.61%, compared to just 0.3% in the deep bedding system (Supplementary Table 2). However, when combining mortality and early culling rates, the deep bedding system results in lower overall animal losses.

The cumulative global warming potential from mortality and early culling was substantial (see Fig. 4). Under the business-as-usual population scenario, the total global warming potential associated with mortality was estimated at 27,946,044 kg CO_2-eq, equivalent to the global warming potential of approximately 13,213 beef cattle fattened in Veneto production systems. The cumulative global warming potential due to early culling was higher, at 41,419,290 kg CO_2-eq (approximately 21,123 beef cattle). In contrast, under a stabilised population scenario, the GWP of mortality increased to 33,021,658 kg CO_2-eq, corresponding to about 15,613 beef cattle, while the impact from early culling reached 49,951,304 kg CO_2-eq (approximately 24,975 beef cattle).

A sensitivity analysis was conducted using average mortality and early culling rates reported in the literature for the same production systems in Veneto. Under the declining population scenario, the estimated GWP of mortality rose to 28,748,160 kg CO_2-eq, equivalent to approximately 13,593 beef cattle. In contrast, in the stable population scenario, the GWP reached 33,886,721 kg CO_2-eq (about 16,022 beef cattle). For early culled, given declining population trends, the total GWP over 10 years was estimated at 151,547,488 kg CO_2-eq, equivalent to approximately 77,320 beef cattle, whereas under a stable trend it increased to 178,720,040 kg CO_2-eq (about 91,184 beef cattle). Cumulative values of other environmental impacts follow similar patterns (see Fig. 4).

Discussion

Beef farming generates substantial GHG emissions and is resource-intensive. Besides that, intensive animal farming is under special scrutiny due to animal welfare concerns. Recent studies have shown that consumers oppose measures that would reduce GHG emissions while worsening animal welfare in dairy farming[17]. Therefore, strategies that address both environmental and animal welfare are essential, but studies rarely quantify welfare aspects and environmental impacts, and the methodologies used are rarely comparable.

Italian beef production is the fourth-largest in the European Union, and the Veneto region is one of the country's main production areas. Intensive indoor beef production systems are quite standardised across Europe; our study is therefore relevant, as it reflects fattening systems comparable to those found in other countries such as Austria, Germany and Slovenia. This highlights the relevance of Veneto fattening farms at the EU level. The remarkable similarity between cattle production systems operating in the Veneto region and in several other European countries has been confirmed by previous studies that applied the same welfare assessment protocol to beef farms in this region and in Austria and Germany[18].

Here, we estimated the environmental and animal welfare impacts of different intensive beef fattening systems. We found that deep bedding systems had better environmental performance in terms of GWP,

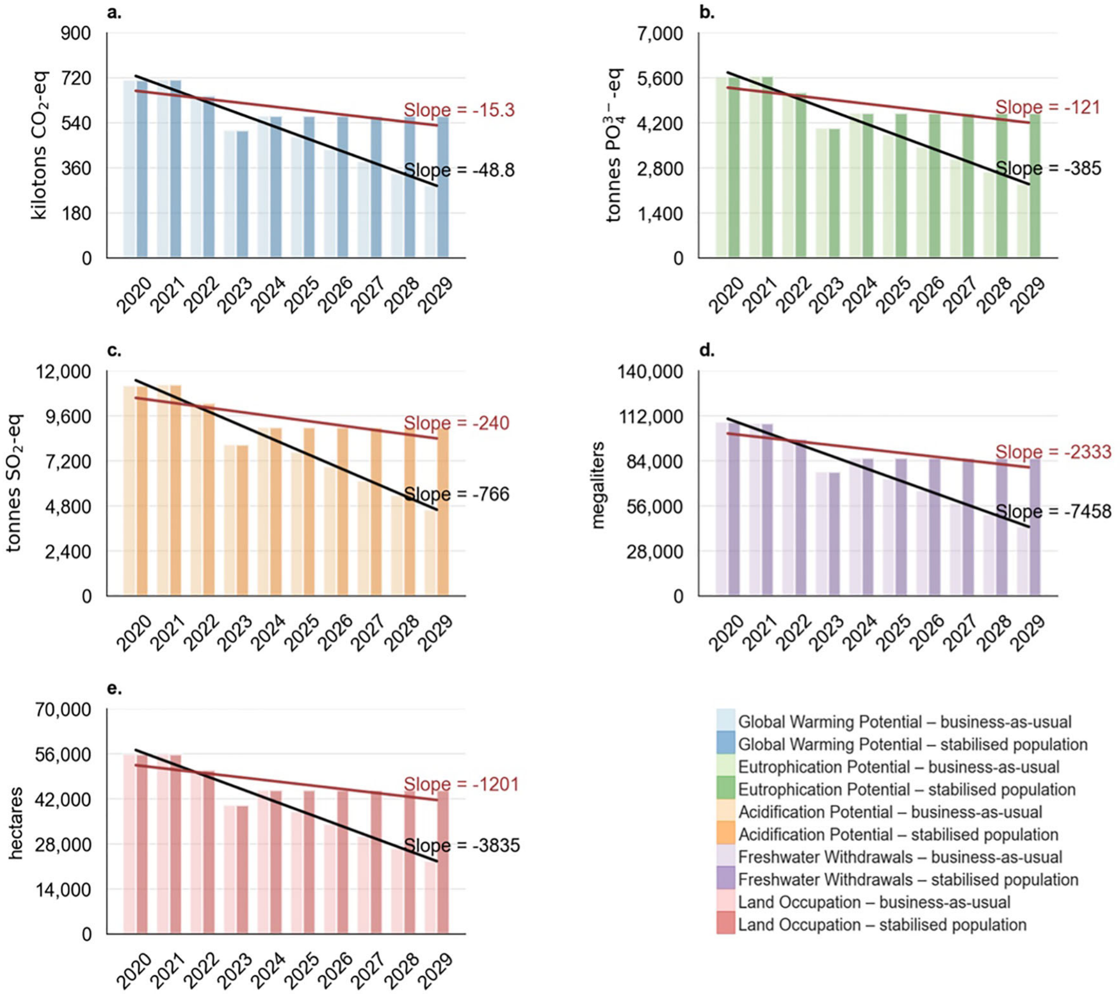

Fig. 3 | Comparison of total environmental impact between the 'business-as-usual' and stabilised population scenarios from 2020 to 2029. The black line represents the trend under the business-as-usual scenario, while the red line represents the trend under the stabilised scenario. Each line is annotated with the slope and significance level. **a** Annual comparison of global warming potential between population scenarios. **b** Annual comparison of eutrophication potential. **c** Annual comparison of acidification potential. **d** Annual comparison of freshwater withdrawals. **e** Annual comparison of land occupation.

acidification potential, freshwater withdrawals, and animal welfare than those with slatted floors. Our environmental results per kilogram of body weight gain align with those of other studies that investigated intensive beef finishing[19–23]; for example, GWP for beef finishing in the same region ranges from 8.8 (1.6 kg CO2-eq)[23].

Notably, based on estimated population trends from 2020 to 2029, the number of specialised beef breed animals imported from France to Italy is declining. However, this number of animals will remain substantial, and we expect a change in the proportion of fattening systems. The use of fully slatted floors is not recommended due to their negative impact on animal welfare, as they fail to fully meet the behavioural and physical needs of animals during the finishing period[13,22]. Therefore, we can expect a more pronounced reduction in animals fattened in this system in the future. A transition to more animals on deep bedding is expected to reduce certain regional-level environmental impacts, while others are likely to remain unchanged. We projected the imported population and environmental impacts to 2029 to account for market changes driven by disruptions in French supply. According to communications with the farmers' association responsible for purchasing animals, there is currently a shortage of calves in the Veneto market. In addition, prices of French-origin calves have increased over recent years[24]. The association anticipates that farmers will increasingly turn to dairy-origin crossbred calves for fattening[25]. Accordingly, 2029 was selected as the final time point for the projections, as developments beyond this period remain highly uncertain.

We note that we did not include the effects of substitution and leakage in this study (e.g., farmers send their cattle elsewhere for fattening if these production systems decline), and this represents a limitation that should be addressed in future research. It would require an assessment of the environmental impacts of fattening systems in different geographies.

Our analysis of the environmental costs associated with welfare outcomes, based on comparisons between survey data and sensitivity analyses with literature sources, demonstrated the significant impact that changes in mortality rates have on environmental outcomes across all assessed parameters. We used mortality as an iceberg indicator of animal welfare. To assess the impact of mortality, we estimated the number of replacement animals required to maintain initial input levels and achieve equivalent production outputs. In these cases, mortality occurs during the early phase of the fattening period; thus, replacing animals is essential for farmers to utilise available housing capacity and mitigate economic losses efficiently.

In contrast, early culled animals pose a greater challenge, as they consume substantial resources and cannot be replaced early enough in the production cycle to offset the associated losses. In this case, replacement animals were not considered, as early culling is more common during the final phase of the fattening period due to health issues or accidental injuries[18], with affected animals continuing to occupy housing space until early culling. Our results show that their emissions are consistently higher per kilogram of body weight gain than those of animals that reach final weight, due to lower growth performance efficiency. As with mortality,

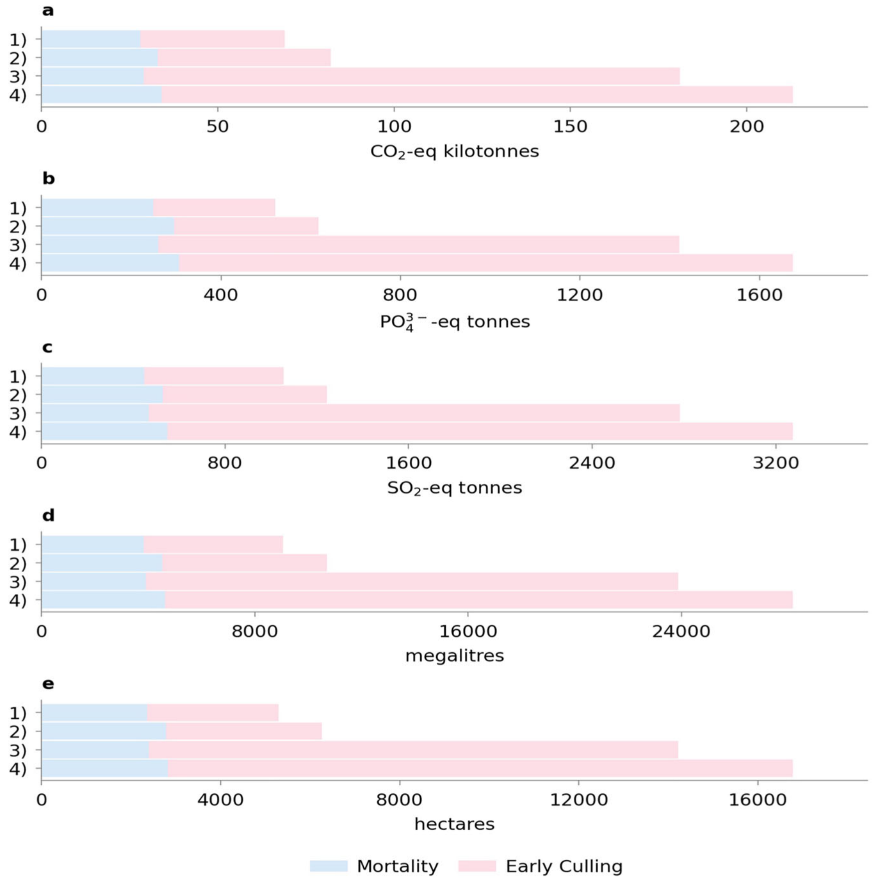

Fig. 4 | Contribution of mortality and early culling of animals to environmental impacts with primary and literature data in 'business-as-usual' (BAU) and stabilised population scenario. 1) BAU primary data, 2) stabilised population scenario primary data, 3) BAU literature data, 4) stabilised population scenario literature data. **a** Contribution and difference between scenarios in global warming potential. **b** Contribution and difference between scenarios in eutrophication potential. **c** Contribution and difference between scenarios in acidification potential. **d** Contribution and difference between scenarios in freshwater withdrawals. **e** Contribution and difference between scenarios in land occupation.

survey data and sensitivity analyses with literature sources indicate that changes in early culling rates have a significant impact on environmental outcomes across all evaluated indicators.

Given that our analysis is based on two farms, we assessed the robustness of the welfare outcome data with literature data. While animal performance data were consistent with values reported in previous studies, welfare-related parameters are less consistently documented and often show greater variability. Acknowledging that mortality may vary across multiple factors and differ substantially between production years, we conducted sensitivity analyses. As animals are sourced from different farms and transported from France to Italy, diverse pathological conditions may be observed. To address this uncertainty, we conducted a targeted literature review and performed sensitivity analyses using region- and breed-specific mortality and early culling rates from the literature.

Mortality and early culling significantly influence environmental burdens, as affected animals consume resources without contributing to final production outputs. Moreover, this issue is particularly critical and warrants attention in the Veneto region, where fattening systems rely heavily on human-edible crops specifically grown for animal feed, rather than pasture-based systems. In animal production, mortality and early culling are more pronounced during the rearing phase; therefore, each loss in the finishing phase is especially problematic.

Economic data to quantify the shift from slatted floor to deep bedding were not available; nevertheless, a deep-bedding system would be expected to increase production costs owing to the additional requirements for bedding material and bedding management, as well as the higher space allowance per animal[26]. It was not a primary focus of our paper to address the economic implications of the shift; nevertheless, they are an important aspect and represent a limitation of our study that future research should assess.

In summary, among the systems evaluated, deep bedding exhibited lower environmental performance at both the farm and population levels. A further reduction in emissions is anticipated as the beef fattening population continues to decline. If this trend continues, a substantial decrease in regional emissions from this production system can be expected. Moreover, this study highlighted how variations in animal welfare outcomes influence the environmental impact of beef production systems, with animal losses contributing significantly to the environmental burden at the regional scale. Due to the uniformity of the production system and its centralised management by a farmers' association, implementing new mitigation strategies should be relatively straightforward.

Methods

Data source and systems boundaries

A region is the first-level administrative division of Italy, with political, administrative and legislative powers. The Veneto region is located in the eastern part of the Po Valley. It is Italy's leading producer of beef (20% of the total domestic share), with around 450,000 head of total cattle in its fattening farms[24]. All beef cattle in Veneto are fattened indoors in slatted floor or deep-bedded pens. Scenarios for two specialised finishing beef systems in the Veneto region were created using data from questionnaire-based interviews with farm managers conducted in 2019. We selected two representative farms because they provided the most comprehensive input data for conducting an environmental impact analysis. This data represents real production data on the farm. Our representative farm inputs align with those of other studies[23]. A simplified workflow diagram of the Life Cycle Assessment (LCA) is provided in the Supplementary Material (Supplementary Fig. 2).

The calculations were conducted for the period from the arrival of purchased animals at farms in the Veneto region until they reached the target weight and left the farm for slaughter, excluding the breeding and rearing phases in France (the animals' origin country), as well as transport and processing beyond the farm gate in Italy. The animals are housed indoors in uniformly sized pens and are grouped by sex and age class. Typically, the Charolais cattle are raised on a deep bedding system, while Limousin cattle are raised on a slatted flooring system.

Data were collected on a commercial real farm as part of routine management, and no experimental procedures were performed. All procedures and methods used in this study were non-invasive and complied with the ethical guidelines established by the International Society for Applied Ethology Ethics Committee[27]. None of the animals underwent painful procedures or mutilations, and no additional handling or interventions were performed specifically for data collection that would require approval from an ethical review board. Transport to the slaughterhouse and slaughter procedures were carried out in accordance with European legislation on animal welfare during transport and at the time of killing[28,29]. Slaughter was performed at a commercial slaughterhouse and was outside the study's system boundaries. Early culling was performed in a typical slaughter procedure without specific reagents.

Environmental impacts assessment

For the environmental evaluation of farms, the LCA methodology was employed. Since only the Italian production stage was considered, the functional unit for the LCA was one kilogram of body weight gain on the fattening farm.

Dataset used

Input data were collected through surveys of real farms and used to calculate the environmental impacts of animals (Supplementary Table 2). Feed was offered *ad libitum* as a total mixed ration, and drinking water was available without restriction. The composition of diets was documented during the survey (see Supplementary Table 3).

Beef cattle on slatted floors used a two-phase feeding strategy based on growth stages, while those on the deep bedding farm used a four-phase strategy evenly distributed over the fattening period. Most of the feed ingredients (82% on the slatted floor farm and 55% on the deep bedding farm) were produced on the same farms where the cattle were fattened. For each on-farm crop, data were gathered on land use, irrigation water use, fuel, lubricants and motor oil for agricultural machinery, seed, organic and mineral fertilisers, crop protection chemicals, and yield. The impacts for purchased feed (off-farm feed) were taken from an environmental impact database for animal feed ECOALIM[30]. The database is primarily based on French data, which we consider representative of Italian production. Land-use change was considered for purchased off-farm feed ingredients, as it is already incorporated into the values reported in the ECOLIAM database[30] from which environmental impact data were obtained. For on-farm crop production, land-use change was also considered, as the LCA platform used for calculating environmental impacts includes models to account for land-use change through gap-filling procedures. However, cropland in the studied Italian region has been under continuous cultivation with no recent land conversion; therefore, the land-use change value was assumed to be zero. Energy use for the on-farm operations was recorded for each farm. Cereal straw was used as a bedding material in the deep bedding system and was included in calculations. The production of excreta, both solid and liquid, was modelled in terms of total matter and volatile solids (VS) using a mass balance model[1]. Nitrogen excreta are based on the difference between N in inputs and N out in products[1]. Manure management was accounted for, assuming that all processed excreta were used on the farm as organic fertiliser, a common practice. On the slatted floor system, slurry was collected in a pit below the animals, then continuously transferred to external storage and removed for use in an anaerobic digester. In both systems, manure was used as input to an anaerobic digester, and the processed excreta were periodically spread on fields in accordance with the legislation. Biogas production was excluded from the calculation due to a lack of input and output data. Therefore, manure was considered up to biogas. For off-farm feed transport, based on communication with the farmers, the feed was sourced from a storage facility in the Veneto region and transported by lorry. The animal welfare indicators used in this study, mortality rate and early culling rate, were collected through farm interviews. In our model, early culling refers to the slaughter of animals on farms before the planned finishing period due to health-related issues. This typically occurs during the last part of the fattening period, which we assumed to be 30 days before the remaining animals on the farm, which remain in the fattening phase until their predicted slaughter date. In contrast, mortality primarily occurs at the start of the fattening period; therefore, we assumed it occurred 60 days after the start of fattening. To test the robustness of our welfare-consequences scenarios on farms, we conducted sensitivity analyses using literature data[31–39] for mortality and early culling from the same region and breeds. This analysis used literature values to evaluate how changes in these key input parameters affected the model outputs, while all other performance data remained unchanged. Mortality has been suggested as an iceberg indicator for animal welfare. However, a limitation of the using indicator is its inability to reflect the broader explanation of animal welfare outcomes. The culling rate in this study does not include the culling of underperforming animals. Animals with lower growth performance are retained until the end of the production cycle and are slaughtered in the normal production flow. Consequently, the culling rate includes only animals removed for health reasons that prevent them from being kept on the farm, requiring transfer to a slaughterhouse and, subsequently, to a rendering plant. Early culling is an emergency measure.

Emission estimations

The LCA was performed using the Harmonised Environmental Storage and Tracking of the Impacts of Agriculture (HESTI[40] open-access platform, which is designed to estimate environmental impacts in the agriculture and food sectors, following the LCA methodology, and to provide a data format to harmonise how agri-environmental data are shared between researchers and in supply chains. In addition to quantifying farm resource use, emissions, and environmental indicators, HESTIA provides climate and soil datasets and other data to fill gaps in farm activity data (such as crop residue) and models to fill gaps in land-use change.

Input data are imported into the platform (www.hestia.earth) from an Excel file structured according to the HESTIA schema, which standardises data organisation. In the platform, each Cycle, equivalent to a unit process in LCA, represents a distinct production system (e.g., crop production, animal housing, or diet phases). Each Cycle includes "blank nodes" specifying site measurements, inputs (e.g., electricity, diesel, animal types), and outputs (e.g., live animals, excreta). Before upload, data undergo validation to detect missing or inconsistent values. HESTIA's model library coordinates the execution of LCA models in sequence across cycles. In our study, emissions are first estimated for on-farm crop production, then for complete diets (including off-farm inputs), and finally for animal housing, which integrates animal performance, resource use, and diet emissions, providing a full assessment of farm-level environmental impacts.

Emissions are estimated according to widely used standardised models. We used emission factors associated with slatted floor systems and solid manure storage, as they best correspond to the characteristics of deep bedding systems currently implemented in the Veneto region and have already been used in this way in the literature[23]. Methane (CH_4) emissions from enteric fermentation and manure management were calculated according to the Ref. 41. Similarly, nitrous oxide (N_2O) emissions to air from manure management were also estimated following the Ref. 41. Ammonia (NH_3) emissions to air from manure management were calculated following Ref. 42. Nitrous oxide emissions from soils were calculated as a fraction of different inputs of nitrogen. N_2 to air is estimated as three times nitrogen oxide[43]. Direct N_2O emissions to air from inorganic and organic fertilisation were calculated based on Ref. 44. In contrast, indirect emissions were calculated according to Ref. 42. Nitrate (NO_3^-) leaching to groundwater from fertilisers was modelled using the approach by Ref. 1. Phosphorus (P) and nitrogen (N) losses from soil erosion and runoff to surface water were calculated using the method developed from Ref. 45. NH_3 emissions to air from fertilisation were estimated using emissions factors from Ref. 42.

Background environmental impact data related to electricity production were sourced from Ref. 46. Emissions related to CO_2 from fuel combustion are calculated according to Ref. 42. Background data to produce mineral fertilisers, plastic packaging waste, lubricants, and motor oils were also obtained from Ref. 46. All background data were managed through the HESTIA platform.

Environmental impacts assessment

After emissions were calculated, they were characterised based on impact indicators considered important for the agri-food sector: global warming potential, acidification potential, eutrophication potential, freshwater withdrawals, and land occupation for input production. The GWP, which measures the impact of mixed greenhouse gases on the climate over a 100-year time horizon and is expressed in CO_2 equivalents, was assessed according to Ref. 47. Greenhouse gases were converted to CO_2 equivalents from Ref. 48. Acidification potential, expressed in SO_2 equivalents, reflects changes in soil chemistry caused by the deposition of nitrogen and sulphur in acidifying forms. Eutrophication potential, expressed in kg PO_4^{3-} equivalents, estimates the potential for nutrient emissions to cause excessive aquatic plant and algae growth in freshwater ecosystems. Both acidification and eutrophication were characterised using Ref. 48. Additionally, freshwater withdrawals and land occupation to produce inputs in Italy were assessed. Freshwater withdrawals, also referred to as freshwater use or blue water, are the volumes of water withdrawn to produce inputs, measured at the point of use and expressed in litres withdrawn from freshwater lakes, rivers, and aquifers. Land occupation is the amount of land required to produce the inputs used multiplied by the time (in years) that the land was occupied, including fallow periods and expressed as the total amount of land used, of the type specified in each Site (e.g., cropland), multiplied by the number of years occupied. Input data for freshwater withdrawals and land occupation related to on-farm feed ingredients were calculated using information obtained from farmer interviews, whereas data for purchased off-farm feed ingredients were sourced from the ECOLIAM database[30]. The GWP, acidification potential and eutrophication potential are among the most commonly reported midpoint impact categories in the agri-food sector and are particularly relevant when comparing agri-food systems with other food production systems[1].

Regional annual environmental impacts estimations

We calculated the environmental impact inventory at the regional level in the Veneto region for the period 2020-2029. The analysis was based on data regarding the import of 6- to 12-month-old bulls and heifers from France to the Veneto region, obtained from the National Veterinary Information System[15]. This age range was selected as it corresponds to the typical age at which these breeds are imported from France into the finishing units located in the Veneto region[18], other age categories were excluded from the analysis. To examine historical trends, we applied a simple linear regression model to real-world data on the annual population of imported animals from 2020 to 2024 to obtain a baseline scenario. The downloaded data have the number of imported animals by breed, but not by sex simultaneously. To address this limitation, we assumed that the total proportion of male and female animals in the Veneto region during the same period was the same across breeds. We assumed that the observed trends in the baseline period would continue through 2025–2029. The farm association provided data on the proportion of animals kept on deep-bedding and slatted floors. Among all bulls, 62% are kept on deep bedding and 38% on slatted floors. In contrast, 28% of all heifers are kept on deep bedding, while 32% are housed on slatted floors. Since the data are provided in terms of heads and the environmental impacts were calculated in kg of BWG, we converted the population to kg of body weight raised in Italy. Then we multiplied the total population body weight by each impact indicator, generating annual estimates for each breed and sex. According to communications with farmers, husbandry practices and diet composition did not change significantly between 2020 and 2024. Therefore, we assumed that the body weight data from our modelled farms provides a reliable basis for projecting future emission trends. The environmental impact of mortality in the population was calculated as the number of animals that died during the first 60 days, under a stable and declining scenario. For early culled animals, we calculated the number of animals slaughtered in the last 30 days of the fattening period. Transport to the slaughterhouse and slaughter procedures were carried out in accordance with European legislation on animal welfare.

Statistical analysis

Regression analysis between time and population, and time and population emission annual inventory was calculated using PROC REG SAS (Copyright (c) 2023 by SAS Institute Inc., Cary, NC, USA). Slope and standard error were calculated.

Data availability

All data generated or analysed during this study are included in this published article (and its supplementary information files). The data are available on HESTIA at https://www.hestia.earth; HESTIA ID of study: qbgaqjwj78da.

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Author contributions

O.M. conceptualized the study, conducted the analyses, and wrote the original draft; L.M. collected the data and contributed to review and editing; J.P., V.C., and G.C. participated in reviewing and editing the manuscript; B.C. contributed to data analysis; F.G. and H.B. were involved in reviewing, editing, and supervising the project. All authors read and approved the final manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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