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Effect of slaughter age on environmental efficiency on beef cattle in marginal area including soil carbon sequestration: A case of study in Italian Alpine area

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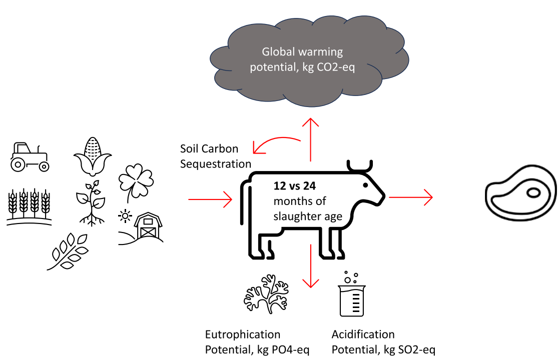
HIGHLIGHTS

- The breeding of beef cattle in marginal areas in the Alpine plays an important role.
- The slaughter age influences the environmental impact generated by the production of 1 kg of beef.
- Carbon sequestration by pastures showed to incorporate a relevant role in mitigating GHG.
- Two functional units was used: kg of live weight (LW) and kg of carcass weight (CW).
- Sensitivity analysis included the woodland to achieve Net Zero carbon neutrality.

GRAPHICAL ABSTRACT



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ABSTRACT

The production of beef carries significant environmental repercussions on a worldwide level. Considering that the production of beef in Alpine mountainous regions, such as South Tyrol (Italy), constitutes a modest yet progressively growing segment within the local agricultural sector focus must be put on minimizing the environmental impact of producing one kilogram of meat, while also accounting for the carbon sequestered by Alpine pastures in such marginal areas. To this end 20 beef farms distributed in the South Tyrolean region (Italy) were divided based on the age at slaughter of the beef cattle: 10 farms with a slaughter age of 12 months (SA12) and 10 farms with a slaughter age of 24 months (SA24). Live cycle assessment (LCA) approach was used, and the impact was estimated using two functional units (FU): 1 kg of live weight (LW) and 1 kg of carcass weight (CW). Global warming potential (GWP_{100}, kg CO_2-eq), acidification potential (AP, g SO_2-eq), and eutrophication potential (EP, g PO_4-eq) were investigated. Furthermore, within the account, the carbon sequestered by pastures and permanent grassland has been included for estimated the overall carbon footprint. In terms of GWP_{100}, the SA12 system proved to be significantly lower for both two functional units under studies, with reductions of 8.5 % and 7.4 % in terms of LW and CW, respectively, compared to the SA24 system, specifically, the SA12 system showed an environmental impact in terms of GWP_{100} of 19.5 ± 1.1 kg CO_2-eq/kg LW, which was significantly

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lower than the SA24 system that exhibited a value of 22.9 ± 1.1 kg CO_2-eq/kg LW ($P < 0.05$). When accounting for the carbon sequestered within the system, the observed values in terms of GWP_{100} are significantly lower for SA12 compared to SA24, 17.6 ± 1.5 vs. 20.9 ± 1.5 kg CO_2-eq/Kg LW ($P < 0.05$), and 29.2 ± 2.5 vs. 38.7 ± 2.5 kg CO_2-eq/Kg CW ($P < 0.01$). These differences are due to less purchase of concentrated feed and greater use of natural resources such as pastures and permanent grasslands. The research indicated that the production of beef in the Alpine region of South Tyrol predominantly occurs within extensive parameters, leading to a satisfactory environmental profile, also including the C sequestration.

1. Introduction

In recent decades, there has been much focus on the sustainability of food production, with livestock products typically having a greater environmental impact than plant-based foods. The study compared the environmental impacts of various livestock products and found that beef production had the highest land and energy usage and the greatest potential for global warming (GWP) (De Vries et al., 2015). According to the Intergovernmental Panel on Climate Change (IPCC) special report released in 2019, the Agriculture, Forestry, and Other Land Use (AFOLU) sectors are responsible for nearly 15 % of anthropogenic greenhouse gas (GHGs) emissions. Ruminants, in particular, play a significant role in GHG emissions as they are producing methane because of anaerobic fermentation in their polygastric digestive system (Zanon et al., 2023a). Cattle alone and hereby in particular beef cattle contribute to almost two-thirds of the emissions form the livestock sector according to FAO (2018). Despite this, red meat a food remains a high-quality source of protein, as well as an abundant source of essential micronutrients like iron, vitamin A, iodine, zinc, and vitamin B12, which are naturally present also in other animal-based foods (Rocchetti et al., 2023). Furthermore, when produced through pasture-based systems, 'grass-fed' beef has gained popularity, as it is perceived to be healthier and produced in an animal welfare and environmentally friendly manner (Monahan et al., 2012; Henchion et al., 2017; Linder et al., 2022). Moreover, pastoral systems have the advantage of utilizing land that is not suitable for crop production, converting non-human edible forage into high-value, human-edible products and therefore contributing to global food security (Zanon et al., 2022). In addition, grass-fed beef systems provide ecosystem services such as preserving and enhancing biodiversity, conserving cultural landscapes, and contributing to socio-economic activity in rural areas, particularly in marginal regions such as the Alps (Bragaglio et al., 2018; Angerer et al., 2021). The latter is crucial for enhancing the appeal of a region for tourism purposes (Tasser et al., 2005; Bernués et al., 2011). Irrespective of this, pastures could also be part of the solution for reducing GHG emissions from livestock production as several authors have shown that optimal management of livestock grazing practices can maximize soil carbon sequestration, a vital ecosystem service of grasslands (Wang et al., 2015; Griscom et al., 2017). The European Union (EU) has adopted a widely accepted approach known as Life Cycle Assessment (LCA) to evaluate the environmental impacts of a functional unit of a product throughout its entire life cycle (Sala et al., 2021). LCA has been applied in several studies to investigate the impacts of livestock enterprises. These studies have examined dairy cattle (Mazzetto et al., 2020; Sabia et al., 2020a), beef cattle (Hietala et al., 2021), dairy buffaloes (Sabia et al., 2018; Chirone et al., 2022), dairy sheep (Vagnoni et al., 2017; Sabia et al., 2020b) and organic produced eggs (Costantini et al., 2020). However, in recent studies the LCA approach has been focused mainly also on three impact categories to have a more specific focus also depending on the specific geographic area, such as GWP, acidification potential (AP), and eutrophication potential (EP) (Pirlo and Lolli, 2019; Wang et al., 2019). One of the current issues related to alpine environments is the phenomenon of eutrophication of alpine lakes (Ren et al., 2022), where grazing animals are cited as the major contributors (FAO, 2018), conversely, the nitrogen supply in the alpine environment turns out to be important for the proper sustenance of plant species in the alpine environment (Zhang et al., 2020). In the study province of South Tyrol (northern Italy) ruminant livestock farming and hereby especially dairy cattle farming has a long tradition and is the second most important pillar for the agricultural sector besides apple production. In contrast, beef production plays a minor role (Zanon et al., 2023b). Various studies have demonstrated that beef production is a significant contributor to the emission of naturally occurring GHGs, resulting in certain beef production systems bearing a heavy environmental burden (Nguyen et al., 2010). Nevertheless, research has unveiled a significant range in the environmental impact of beef cattle farming, the emissions of GHGs can fluctuate between 8.6 and 35.2 kg CO_2 equivalents per kg of consumable beef (de Vries and de Boer, 2010). In mountainous regions beef production, like the South Tyrol study marginal area, typically relies on extensive production systems because of limited arable land. The study province of South Tyrol is in the northernmost part of Italy and is distinguished by its Alpine terrain, with 86 % of the total area located 1000 m asl. In South Tyrol ruminant livestock farming and hereby especially dairy cattle farming has a long tradition as it is the second most important pillar within the agricultural sector besides apple production. In contrast, beef production plays a minor role (Zanon et al., 2023b). As for 2022, there were approximately 8000 livestock farms present in the region, which primarily focused on breeding cattle and maintained a total of 128,000 cattle. Of these, 66,600 were dairy cows, according to Autonome Provinz Bozen-Südtirol in 2022. In 2022, 54 beef cattle farms were present in the region (vetinfo.it). Although there is limited data available on beef cattle farming, in 2022, the 42 slaughterhouses in South Tyrol processed roughly 11,000 cattle (Zanon et al., 2023c). In terms of farm structure, beef cattle farms within the research area are relatively small, encompassing approximately seven hectares of agricultural land and maintaining an average herd size of 16 cattle per farm with different age of slaughter and changing environmental implications Zanon et al. (2023b). Since of their relatively small size, over half (56.9 %) of the livestock farms operate as a secondary activity. Beef cattle farming is less labour-intensive than dairy farming, affording farmers greater flexibility in terms of work-time management (Zanon et al., 2023c). In the region of South Tyrol two beef production systems are commonly present, namely the suckler to beef system with a slaughter age of 12 months and the calf to beef system in form of heifer and/or steer fattening with an average slaughter age of 24 months (Zanon et al., 2023b). South Tyrolean livestock farms frequently utilize Alpine pastures for cattle grazing during the summer months (Holighaus et al., 2023). Pasture management is usually performed in form of paddock grazing as well as free ranging grazing on the traditional alpine pastures (Malga) during summer transhumance. Hereby the livestock unit per ha varies from 0.5 to 1.5. Furthermore, Alpine pasturing has been shown to provide several ecosystem services, while enhancing the appeal of a region for tourism purposes (Bernués et al., 2011; Tasser et al., 2005; Wild et al., 2023). Limited research has been conducted on LCA studies that investigate the difference in slaughter age as a factor in reducing the carbon footprint (Herron et al., 2021). McAuliffe et al. (2018) have noted that enhancing the daily weight gain and subsequently reducing the age at which cattle are finished can help mitigate GHG emissions and pollutants in pasture-based beef systems. In regions with temperate climates, such as Ireland, the recommended production systems often emphasize the finishing of steers at 24 months of age, utilizing a grass forage diet, and incorporating concentrate supplements during periods of housing (Drennan and McGee, 2009). Previous studies have shown the potential for decreasing GHGs by 24–535 % in pasture-based beef production systems in the US (Pelletier et al., 2010; Lupo et al., 2013; Stanley et al., 2018) and tropical and subtropical regions (Mazzetto et al., 2020; Ribeiro-Filho et al., 2020). The European Commission has recently issued a proposal for a regulation for voluntary certification for carbon storage in order to contribute to the net reduction of GHGs emissions with a balance of net anthropogenic emissions of zero carbon by 2050 (European Union, 2021). Among the proposals included within the regulation is the dissemination of agricultural practices with the use of pasture and permanent grassland and land use change and silviculture. However, to the best of our knowledge, few studies take into account the carbon sequestered by pastures for a proper evaluation of environmental impact of beef production systems (Stanley et al., 2018; O'Brien et al., 2020; Escribano et al., 2022; Mazzetto et al., 2023). There is no universally accepted approach for incorporating soil organic carbon into LCA methodologies (Goglio et al., 2015). Previous investigations in the context of beef production systems that have accounted for soil organic carbon have either utilized fixed values derived from literature sources (Pelletier et al., 2010) or have relied on measured data collected over a limited time frame. Especially for beef farms in mountain area, which largely differ in structure and management, to the best of our knowledge no similar study is available. Therefore, the objective of this study is to assess the environmental impact of two types of livestock beef production system with different slaughter ages, considering the carbon sequestered from Alpine pasture grasslands in marginal area.

2. Material and methods

2.1. Definition of goal and scope

The boundaries of the LCA model used to evaluate the environmental impact of beef production in South Tyrol were established as follows: the cradle-to-farm gate approach was employed for all two systems under investigation. Mid-point impact assessment considered global warming potential (GWP_{100}, kg CO_2-eq), acidification potential (AC, g SO_2-eq), and eutrophication potential (EP, g PO_4-eq). The mid-point impact assessment was conducted utilizing the commercial software SimaPro 8.01, employing the EPD 1.04 (2018) method from the Ecoinvent 3.3 database.

2.2. Soil carbon sequestration

The approach proposed by Petersen et al. (2013), considering a 100-year timeframe where 10 % of the total carbon added to the soil will be sequestered, is recommended. These researchers also emphasize the importance of soil's potential for carbon sequestration as an effective strategy for reducing GHGs emissions. Carbon change estimates, as suggested by (Soussana et al., 2010; Petersen et al., 2013) are based on net carbon fluxes. The calculation of annual carbon inputs into grassland includes herbage residues and manure, following the methodology outlined in (Batalla et al., 2015). The authors of (Batalla et al., 2015), considered 40 % and 16 % of total yield as above-ground and below ground residues, respectively, and assumed a 45 % carbon content on a dry matter basis content, 10 % of C added to soil will be sequestered in a 100 years perspective (Eq. (1)). The estimate of carbon sequestered from the soil was then subtracted from the environmental impact related to GWP_{100} (Petersen et al., 2013).

$$\text{Kg C/ha} = \{[(\text{D.M.} \times 40\%) + (\text{D.M.} \times 16\%) \times 45\%]\} \times 10\% \tag{1}$$

Where:

D.M. = Dry Matter

D.M. × 40 % = 40 % crop residue above ground (Soussana et al., 2010)/total crop production

D.M. × 16 % = 16 % crop residue below ground (Soussana et al., 2010)/total crop production

2.3. Systems boundary and functional units

The study involved 20 beef farms distributed in the South Tyrolean region (Italy). The system-boundaries are shown in Fig. 1. The farms were divided based on the age at slaughter of the beef cattle: 10 farms with a slaughter age of 12 months (SA12) and 10 farms with a slaughter age of 24 months (SA24). The main characteristics of the farms under study are depicted in Table 1. In detail description SA12 farms engage in breeding their own calves, resulting in the development of their exclusive herd of beef cows. Prior to reaching the slaughter age, these calves are nurtured by their mothers and are kept together as a group. The SA24 farms acquire calves for further fattening from dairy farms when they are between three to four weeks old. The three-four weeks period spent with the mothers was not included within the system. These young calves are nourished with milk substitutes until they reach the age of four months. Subsequent to this nursing period, the animals are provided with a diet consisting of hay, concentrates, and pasture grass until they reach the age suitable for slaughter at 24 months. It's worth noting that all participating farms share a common commitment to refraining from using any organic or inorganic synthetic fertilizers and pesticides. In detail, the SA12 farms breed their own calves and therefore have an own herd of beef cows, before the slaughter age, the calves are nursed by their mothers and kept together in a herd. The SA24 farms buy the calves they use for further fattening from dairy farms at the age of three to four weeks and feed them with milk replacers up to an age of four months. After this nursing period, the animals are fed hay, concentrates and grass on pasture up to a slaughter age of 24 months. However, all participating farms are characterized by the total absence of the use of organic and inorganic synthetic fertilizers and pesticides. In all farms the breed was Simmental, Tyrolian Grey and cross breeds. Primary data were collected directly during farms visits using a questionnaire between February and May 2018, which gathered all the information regarding the production cycle of beef cattle in South Tyrol. Both systems involve the use of permanent grazing, but there is a difference in the number of grazing days between the two production systems. All the animals were slaughtered at the municipal slaughterhouse of the city of Bolzano, where the live weights and subsequently of the carcasses were measured at the end of the slaughter. The slaughterhouse processes are not included in the system. The SA24 system involves a higher use of concentrated feed. The impact was estimated using two functional units (FU): kg of CO_{2-}eq per kg of live weight (LW) at slaughter, and kg of CO_2-eq per kg of carcass weight (CW) (LEAP, 2016).

2.4. Calculation process of emissions

Emission estimation for each system included total on-farm emissions, encompassing enteric emissions, management of manure (storage, handling, and application to fields), fuel combustion, electricity consumptions, and the deposition of urine and faeces during grazing. In both studied systems, no organic or inorganic fertilizers were used. Detailed methods and emission factors can be found in the provided documentation Appendix S1. We employed the methodology outlined by the Intergovernmental Panel on Climate Change (IPCC, 2006a) to account for the association between gross energy intake and emissions. The calculation of gross energy was conducted based on Equation of Gross Energy (GE) (IPCC, 2006a), as specified in the literature. Methane (CH_4) emissions derived from enteric fermentation, manure storage, and direct deposition on grassland were calculated using the Tier 2 equation recommended by the appropriate source (IPCC, 2006a). The methane (CH_4) conversion factor (Ym) was 4 % for SA12 system, whereas it was 6.5 % for SA24 systems (Appendix S1). The manure methane emission volatile solid (VS) was measured at 3.9 kg/animal/day (IPCC, 2006a), with a maximum CH_4 production capacity of 0.1 m^3/kg VS. The

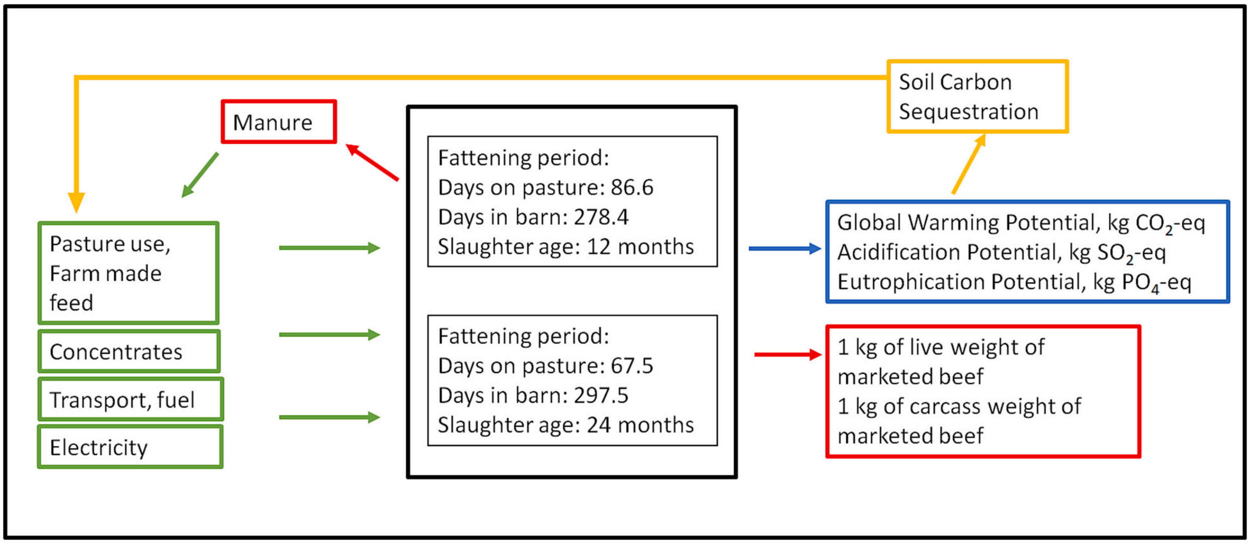

Fig. 1. System boundaries of the two beef production systems.

Table 1
Characteristics of the beef cattle farms located in the South Tyrolean Alpine region (mean ± S.D.).

	SA12 (*n* = 10)	SA24 (n = 10)	P-value
Beef calves (n)	5.8 ± 1.2	14.9 ± 4.2	***
Cows (n)	7.2 ± 2.3	7.6 ± 4.2	ns
Live weight fattening (kg)	396.4 ± 34.4	585.3 ± 55.7	***
Carcass weight fattening (kg)	238.7 ± 16.9	304.0 ± 25.9	*
Permanent grassland (ha)	10.9 ± 9.1	6.6 ± 5.8	*
Days on pasture	86.6 ± 48.1	67.5 ± 43.2	*
Permanent Grasland (kg/DM/y)	76,020 ± 63,449	46,410 ± 40,448	*
Altitude of farms (m.l.s)	1150 ± 86	1100 ± 88	ns
Feed concentrate (kg/farm/y)	710 ± 802	3395 ± 928	***
Electricity (KWh/y)	3148 ± 439	3351 ± 217	*
Diesel (L/y)	752 ± 41	1038 ± 92	**

SA12: slaughter age 12 months; SA24: slaughter age 24 months; S.D. = standard deviation; DM = dray matter.
ns = not significant; * P < 0.05; **, P < 0.01; *** P < 0.001.

methane conversion factor (MCF) for pit storage was 27, whereas it was 1.5 for pasture-based systems. Estimates were made for direct and indirect N_2O emissions during grazing on pasture using the applicable IPCC equation. Nitrous oxide emissions from manure, based on total N excretion, were also estimated, utilizing the country-specific emission factor of 0.02 kg of N-N_2O/kg of excreted N for Italy (Còndor, 2011). Indirect emissions of N_2O were estimated using the approach recommended by (IPCC, 2006b), which considers nitrate leaching-runoff and the re-deposition of volatilized gases into soils and waters. Specifically, an emission factor of 0.01 kg N_2O/kg N was applied for indirect deposition from the atmosphere, while a country-specific emission factor of 0.025 N-N_2O/kg N, as suggested by Cóndor et al. (2011), was used for N leaching-runoff. The estimation of carbon dioxide (CO_2) emissions resulting from energy consumption considered both direct emissions from the combustion of fossil fuels and indirect emissions from electricity usage. The calculation considered the quantities of diesel fuel consumed in litres and the electricity consumed in kWh during various farm operations. As suggested by ENAMA (2005), a standard value of 0.85 kg per litre as diesel density and a 3.13 kg CO_2-eq. emission factor to estimate CO_2 release from the combustion of 1 kg of diesel were used, whereas for electricity an Italian-specific emission factor of 0.47 kg CO_2-eq. 1 kWh was considered (Condor, 2011). Within the life cycle assessment framework, the characterization factors employed to quantify global warming potential (GWP_{100}) were 1, 25, and 298 CO_2-eq for CO_2, CH_4, and N_2O, respectively (O'Brien et al., 2020).

2.5. *Sensitivity analysis*

A sensitivity analysis was conducted to evaluate the potential impact of hypothesis regarding on-farm strategies for carbon storage, specifically focusing on the integration of woodlands into on-farm livestock systems for beef production. Forests are recognized as some of the largest carbon reservoirs globally (FAO, 2020), with the capacity to sequester between 71.49 and 143.14 t of carbon per hectare per year (Luyssaert et al., 2007). These sequestration rates are influenced by various factors including latitude, climatic conditions, soil composition, and vegetation type. Luyssaert et al. (2007) reported an average carbon storage from woodlands, encompassing both above and below-ground components, of 91.9 ± 40.2 t of carbon per hectare, based on an average plant density of 2136 ± 2818 plants per hectare (mean ± SD). The study area, located at 46° north latitude, features alpine climatic conditions, and is dominated by tree species such as Swiss stone pine (*Pinus cembra* L), Norway spruce (*Picea abies* Karst.), silver fir (*Abies alba* Mill.), beech (*Fagus sylvatica* L.), and larch (*Larix decidua* Mill.) (Notarangelo et al., 2023). Notarangelo et al. (2023) observed an average plant density of 626 ± 241 plants per hectare (mean ± SD) in the South Tyrol region. When adjusted proportionally according to Luyssaert et al. (2007), this corresponds to an average carbon storage of 26.9 ± 3.4 t of carbon per hectare (mean ± SD), converted to CO2-equivalents.

2.6. *Statistical analysis*

The data at the level of individual farms, including GWP, AP, EP, main processes, and main pollutants, were examined using a one-way ANOVA (general linear model procedure). The farming systems were considered as a factor in the analysis. The dataset exhibited a normal distribution and was analyzed using SAS software (SAS Institute Inc., Cary, NC). All significance levels were determined based on a threshold of $P \leq 0.05$ to assess statistical significance.

3. Results and discussion

3.1. *Farms systems analysis*

The results of performance for the two studied livestock systems are shown in Table 1. The two systems are found to be significantly different across multiple parameters. Both systems exhibit a relatively low number of animals slaughtered per year. In general, beef farms in the Alpine region are characterized by a relatively low number of animals per farm, partly due to the specific topographical conditions of the soil and environment which allow only small-scale farming (Zanon et al., 2023b). Therefore, many farmers in South Tyrolean are also engaged in other economic and productive sectors of the region, unable to solely rely on meat sales to meet their financial needs (Kühl et al., 2020). The live weight at slaughter and carcass weight are significantly higher in the SA24 system compared to the SA12 system (Table 1). The observed differences are due to the different slaughter ages and also due to different feeding practices, as a greater and significant use of concentrated feed can be observed in the SA24 system compared to the SA12 system ($P < 0.001$). Pasture use is more common in the SA12 system (Table 1), where extensive grazing of beef cattle is more pronounced compared to the typical practices of intensive beef cattle farming, where grazing is limited (Pulina et al., 2021). In terms of energy resource usage, it can be observed that the SA12 system utilizes fewer fossil fuels in terms of diesel ($P < 0.01$) and has lower electricity consumption per year ($P < 0.05$) compared to the SA24 system. This is primarily due to the shorter production cycle, as well as the higher utilization of grazing and permanent pastures in the SA12 system compared to the SA24 system ($P < 0.05$) in order to compensate for the lower use of external feed sources on farm. In the realm of agricultural practices, pasture-based systems have emerged as a particularly advantageous approach. One noteworthy advantage is their demonstrated ability to significantly curtail expenditures, encompassing both the costs of sourcing animal feed and the expenses tied to the operation and maintenance of machinery used for forage harvesting and the management of manure. This economic benefit was empirically substantiated in a study conducted by White et al. (2001). Their findings underline the potential of pasture-based systems to offer a more cost-effective alternative within the agricultural sector, thus paving the way for enhanced sustainability, reduced resource consumption, and improved overall efficiency in livestock management. Both production systems do not utilize mineral fertilizers during their production cycle, but solely rely on the manure produced by the farm animals. This is mainly due to the fact that in the alpine agricultural system, there is not a high level of mechanization, and industrial agricultural crops (e.g., maize silage) that require high energy and agronomic inputs.

3.1.1. *Global Worming Potential (GWP_{100})*

In terms of GWP_{100}, the SA12 system proved to be significantly lower for both two functional units under studies, with reductions of 8.5 % and 7.4 % in terms of LW and CW, respectively, compared to the SA24 system (Table 2–3). Specifically, the SA12 system showed an environmental impact in terms of GWP_{100} of 19.5 ± 1.1 kg CO_2-eq/kg LW, which was significantly lower than the SA24 system that exhibited a value of 22.9 ± 1.1 kg CO_2-eq/kg LW ($P < 0.05$). When considering the functional unit of CW, the results obtained were 32.3 ± 2.5 kg CO_2-eq/kg of CW for the SA12 system, compared to 43.5 ± 2.5 kg CO_2-eq/kg CW for SA24 system. In our study, a longer animal rearing time resulting in a significant higher productive performance was not able to compensate the increased energy inputs required to maintain the animals until the age of 24 months for both functional units LW and CW. The observed variations in greenhouse gas emissions and environmental impacts between the two systems, SA12 and SA24, can be primarily attributed to from the general management of the herd (Table 1). Our analysis reveals that the SA24 system necessitates higher consumption of diesel, electricity, and concentrated feed compared to the SA12 system, resulting in significant disparities in the overall environmental performance. The increased reliance on diesel and electricity in the SA24 system may be related to various factors, such as larger-scale operations, longer fattening period and mechanized processes, which collectively contribute to higher energy demands. Moreover, the utilization of concentrated feed in the SA24 system might entail resource-intensive agricultural practices, including feed production and/or also purchase and transportation, leading to amplified carbon footprints. However, for both systems, the primary process responsible for greenhouse gas emissions, in terms of GWP_{100}, was enteric fermentation followed by permanent grassland, both which were significantly higher ($P < 0.001$) in the SA24 system compared to the SA12 system. Conversely, no significant differences were found in terms of concentrate, manure management and general consumption between the two systems (Fig. 2). The absence of significant differences in concentrate, manure management and general consumption between the two systems shown in Fig. 2 indicates that both SA12 and SA24 may employ similar management practices and have comparable overall resource usage efficiency. For both systems, the primary pollutant was methane, followed by carbon dioxide, and finally nitrous oxide (Fig. 3). There is a significant difference between the two systems in terms of methane emissions ($P < 0.001$) and carbon dioxide emissions ($P < 0.01$), while no significant differences were observed in terms of nitrous oxide emissions (Fig. 3). The differences in methane emissions are likely attributed to the fact that the animals in the SA24 system are heavier, even though the SA12 system uses a higher proportion of pasture-based grazing for feeding. Nerveless feeding during the winter period, with a greater intake of meadow hay together with the greater weight of the animals of the SA24 system compared to the SA12 animals and a lower digestibility, may be factors that influence the greater methane emissions observed in our study. In agreement with previous studies Hammar et al. (2022) observed in a study conducted in Sweden on beef cattle farms, that methane emissions increased when the animals were fed with fodder and concentrate compared to when they were fed with fodder only, due to the greater gross energy intake. Furthermore, the fermentation process in the rumen, which is responsible for methane production, is influenced by various factors, including diet composition, feeding frequency, and feeding management (Saunois et al., 2020). Methane is a potent greenhouse gas with GWP of approximately 28–36 times higher than carbon dioxide over a 100-year time horizon, however, methane has a shorter atmospheric lifetime of 9.8 years, compared to carbon dioxide (Voulgarakis et al., 2013), which remains in the atmosphere for much longer, with an average lifetime of over 200 years. Therefore, reducing methane emissions can provide more immediate benefits in

Table 2
Parameters of the environmental impact considered expressed per kg of LW (mean ± S.D.)

	SA12 (n = 10)	SA24 (n = 10)	P-value
GWP_{100} (kg CO_2-eq)	19.5 ± 1.1	22.9 ± 1.1	*
GWP_{100} SCS (kg CO_2-eq)	17.6 ± 1.5	20.9 ± 1.5	*
AP (g SO_2-eq)	11.9 ± 2.8	9.3 ± 2.8	ns
EP (g PO_4-eq)	4.8 ± 1.1	3.3 ± 1.1	ns

SA12: slaughter age 12 months; SA24: slaughter age 24 months; LW = Live weight; S.D. = standard deviation; S.C.S.: soil carbon sequestration; GWP = Global warming potential; AP = Acidification potential;
EP = Eutrophication potential. ns = not significant; * $P < 0.05$; **, $P < 0.01$; *** $P < 0.001$.

Table 3
Parameters of the environmental impact considered expressed per kg of CW (mean ± S.D.).

	SA12 (n = 10)	SA24 (n = 10)	*P*-value
GWP_{100} (kg CO_2-eq)	32.3 ± 2.5	43.5 ± 2.5	**
GWP_{100} SCS (kg CO_2-eq)	29.2 ± 2.5	38.7 ± 2.5	**
AP (g SO_2-eq)	19.6 ± 4.3	22.2 ± 4.3	ns
EP (g PO_4-eq)	8.0 ± 2.7	6.2 ± 2.7	ns

SA12: slaughter age 12 months; SA24: slaughter age 24 months; CW = Carcass weight; S.D. = standard deviation; S.C.S.: soil carbon sequestration; GWP = Global warming potential; AP = Acidification potential; EP = Eutrophication potential; ns = not significant; * $P < 0.05$; **, $P < 0.01$; *** $P < 0.001$.

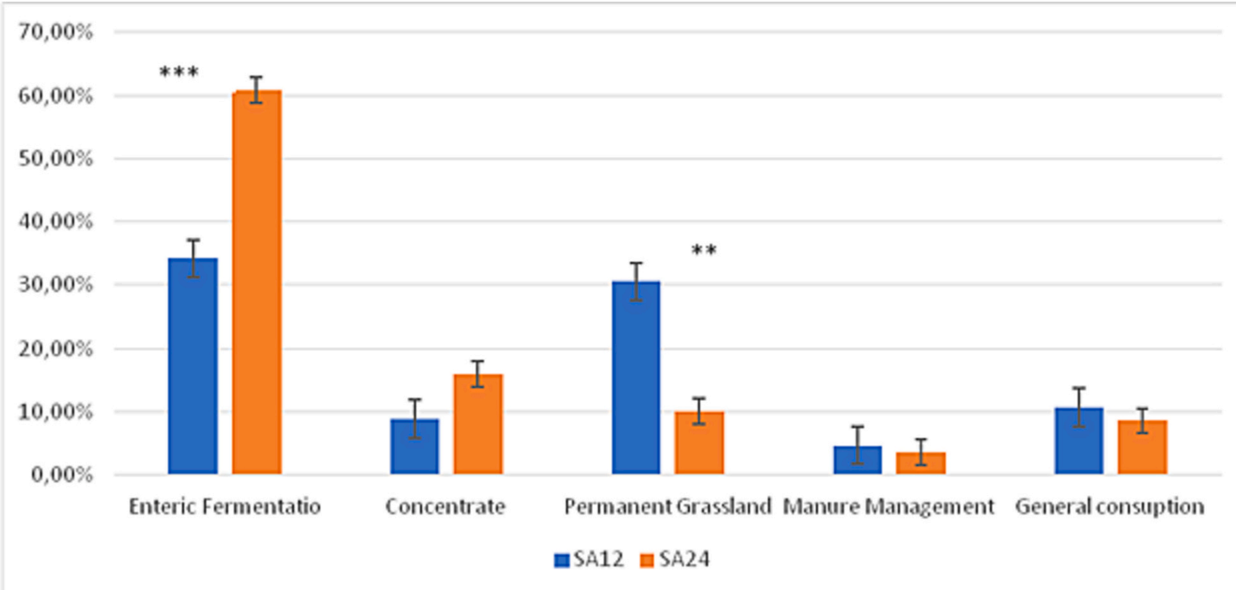

Fig. 2. Percentage of the main processes involved for the GWP_{100} impact category.
SA12: slaughter age 12 months; SA24: slaughter age 24 months; GWP = Global warming potential; **, $P < 0.01$; *** $P < 0.001$.

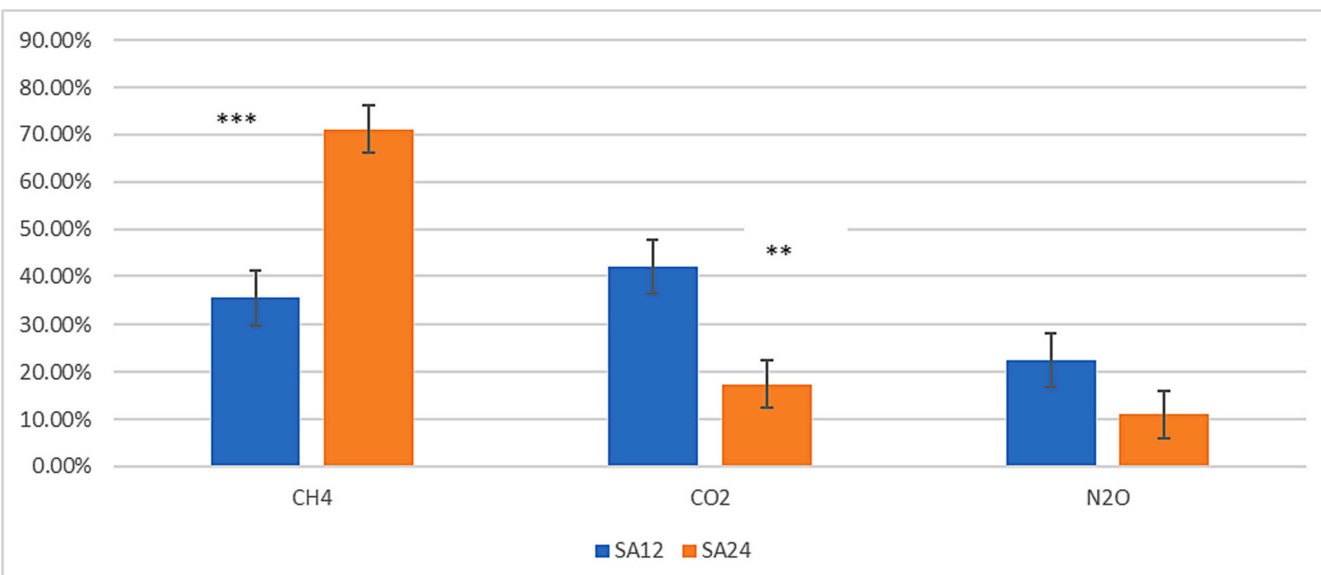

Fig. 3. Percentage of the main pollutants involved for the GWP_{100} impact category.
SA12: slaughter age 12 months; SA24: slaughter age 24 months; GWP = Global warming potential, ** $P < 0.01$; *** $P < 0.001$.

terms of slowing down the rate of warming, while reducing carbon dioxide emissions is crucial for addressing the long-term and cumulative impact on the Earth's climate. The specific nutritional content of the feed in both systems could also play a role in affecting methane production rates. In a European-level study conducted by Nguyen et al. (2010) it was observed that in various production systems, the average values ranged from 16.0 to 27.3 kg CO_2-eq/kg for beef, and these variations were attributed to different rearing systems. In another study conducted on beef cattle raised in Irish beef systems much lower values were observed compared to our study, with results ranging from 6.6 to 10.6 kg CO_2-eq per kg of LW per year (Kearney et al., 2022). Similar results were observed in a recent study conducted in Spain within an extensive system, where values of 20 ± 5.96 kg CO_2-eq/kg LW were found (Reyes-Palomo et al., 2022). Furthermore, a study conducted in Paraguay within an extensive system, observed values of 22.0 ± 3.9 kg CO_2 eq kg LW^{-1} (Costantini et al., 2021), while in a recent study where two different fertilization practices were taken into consideration in beef producing farms in northern Italy, observed values were between 14.86 and 15.74 kg CO_2-eq/kg LW (Costantini et al., 2023). Considering CW, Alemu et al. (2017) reported significantly lower values compared to our study, ranging from 24.1 to 26.6 kg CO_2-eq/kg CW. Similarly, Beauchemin et al. (2010) observed even lower values at 21.7 kg CO_2-eq/kg CW. These differences could be mainly attributed to the varying rearing techniques, different environmental conditions, and diverse topography and genotype breed in Alpine area (Angerer et al., 2021). Table 4 summarizes the results obtained in different environmental conditions at a global level, the differences with our study, in particular in terms of CW, are most likely due to the different genetic types and to the fact that in the Alpine environment under study they are used local crossbreeds and not specialized beef breeds with low production performance,

Table 4
Comparison in terms of GWP_{100} between different beef production systems.

	SA12 (n = 10) (Italy, Alpine area)	SA24 (n = 10) (Italy, Alpine area)	Costantini et al. (2023) (Italy)	Reyes-Palomo et al. (2022) (Spain)	Costantini et al. (2021) (Paraguay)	Nguyen et al. (2010) (EU)	Kearney et al. (2022) (Irish)	Putman et al. (2023) (USA)	Tsutsumi et al. (2018) (Japan)	Alemu et al. (2017) (Canada)	(Mazzetto et al., 2015) (Brazil)
GWP_{100} (kg CO_2-eq/ kg LW)	19.5 ± 1.1	22.9 ± 1.1	14.86–15.74	20.0 ± 5.96	22.0 ± 3.9	16.0–27.3	6.6–10.6	–	–	–	–
GWP_{100} SCS (kg CO_2-eq/Kg LW)	17.6 ± 1.5	20.9 ± 1.5	–	–	–	–	–	–	–	–	–
GWP_{100} (kg CO_2-eq/ kg CW)	32.3 ± 2.5	43.5 ± 2.5	–	–	–	–	11.0–20.0	33.5	35.1–28.9	24.1–26.6	41.3
GWP_{100} SCS (kg CO_2-eq/Kg CW)	29.2 ± 2.5	38.7 ± 2.5	–	–	–	–	–	–	–	–	–

SA12: slaughter age 12 months; SA24: slaughter age 24 months; LW = Live weight; CW = Carcass weight; S.D. = standard deviation; S.C.S.: soil carbon sequestration; GWP_{100} = Global warming potential.

crossing with specialized breeds could be improve production performance and reduce environmental impact.

3.1.2. Global worming potential with soil carbon sequestration and sensitive analysis

Considering the carbon sequestered by permanent pastures and grasslands, according to the methodology suggested by Petersen et al. (2013), the reduction of the GWP_{100} impact was 9.7 % and 8.7 % for the SA12 system and SA24 system, respectively, with absolute values of 17.6 ± 1.5 vs. 20.9 ± 1.5 kg CO_2-eq/Kg LW ($P < 0.05$), and 29.2 ± 2.5 vs. 38.7 ± 2.5 kg CO_2-eq/Kg CW ($P < 0.01$) (Tables 2–3-4). Our results appear to be lower compared to those observed in a recent study conducted in Spain (Reyes-Palomo et al., 2022), where carbon sequestration reduced carbon footprint by approximately 60 %, while Batalla et al. (2015) using the same model (Petersen et al., 2013) observed a reduction between 3 and 41 %. The difference from our study is most likely due to the fact that the system studied in Spain had a very low average livestock stocking rate with about 0.50 LU per hectare, and some farms had extensive areas of woodland and corporate forests, significantly increasing the carbon sequestered by the entire farm system. In the United States, Stanley et al. (2018) observed a reduction in impact, including the carbon sequestered from the soil, of approximately 3 kg CO_2-eq/kg CW, while in a study conducted in Italy, comparing conventional and organic meat production systems, the estimated reduction attributed to carbon sequestered from the soil was found to be approximately 1.3 kg CO_2-eq/kg LW (Buratti et al., 2017). These findings suggest that both conventional and organic systems contribute to mitigating greenhouse gas emissions through soil carbon sequestration, albeit to varying degrees. The observed difference in carbon sequestration between the two systems in our study may be influenced by factors such as management practices, feed composition, and land use. The greater use of permanent pastures by the SA12 system compared to the SA24 system can also determine a different bacterial microflora in the soil capable of storing a greater quantity of organic carbon (Jia et al., 2017), while recent studies have shown that the reduction of tillage, the carbon sequestered by the soil increases and improving the presence of fungi and bacteria biomass (Sae-Tun et al., 2022). However, in a study conducted globally it was observed that incorrect management of permanent pastures can reduce the carbon content stored by the soil (Chang et al., 2021). Irrespective of this, our study highlights the significance of considering soil carbon sequestration as an essential component in assessing the environmental impact of meat production and underscores the potential for sustainable agriculture practices to contribute to climate change mitigation. Moreover, this observation highlights the variability of results across different geographical locations and farming systems. Therefore, it is crucial to consider the local context and land management strategies while assessing the environmental sustainability of livestock systems. Currently, the soil carbon sequestered is also included in ecosystem services (Robertson, 2011), where it also plays a crucial role within livestock farming sustainability (Bernués et al., 2019; Sabia et al., 2023). For the sustainability of livestock farming and in particular for the breeding of beef cattle, it will be increasingly crucial to identify strategies and methods to support carbon sequestration. In this regard, potential a mitigation strategy in term of CO_2-emissions applicable to beef cattle production systems in South Tyrol are underscored by the outcomes of the sensitivity analysis (see Table 5). Notably, the SA12 system exhibits an approximately 78 % lower impact compared to the SA24 system, with emissions totaling 44,772 ± 2526 versus 199,607 ± 9588 kg CO_2-equivalents, respectively (Table 5). Achieving Net Zero carbon in the SA12 system necessitates 4518 ± 255 m^2 of woodland, contrasting with 20,144 ± 968 m^2 required for the SA24 system (Table 5). These figures represent approximately 4 % and 30 % of the total permanent grassland for each respective system under examination. Recent research conducted in the United Kingdom indicates that the proposed scenario for achieving Net Zero carbon involves dedicating between 8 % and 85 % of farm area to woodlands, with an average of 38 % (McNicol et al., 2024). Considering the two functional units (FUs) used, approximately 1.9 to 2.3 m^2 of woodland per kilogram of live weight (LW) and roughly 3.3 to 4.4 m^2 of woodland per kilogram of carcass weight (CW) are needed to attain Net Zero carbon for the SA12 and SA24 systems, respectively (Table 5). This highlights how smaller beef farms can achieve carbon neutrality with comparatively less

Table 5
Sensitivity analysis results of woodland scenarios in tow different beef production systems for Net Zero carbon emissions (mean ± S.D.)

	Total amount of CO_2-eq	Net Zero Carbon (m^2 of woodland)	m^2 of woodland / kg of LW	m^2 of woodland / kg of CW
SA 12 (n = 10)	44,772 ± 2526	4518 ± 255	1.9 ± 0.1	3.3 ± 0.1
SA 24 (n = 10)	199,607 ± 9588	20,144 ± 968	2.3 ± 0.1	4.4 ± 0.1

SA12: slaughter age 12 months; SA24: slaughter age 24 months; LW = Live weight; CW = Carcass weight.

investment in terms of arable land and economic resources. However, further investigations are necessary to comprehend the specific mechanisms underlying soil carbon sequestration in different livestock production systems and to develop targeted strategies for enhancing carbon sequestration potential across agricultural landscapes.

To sum up, as environmental certifications and carbon credit policies evolve, beef cattle farms and other livestock operations will increasingly need to adopt mitigation strategies to align with the European goal of carbon neutrality by 2050.

3.1.3. Acidification potential

Tables 2–3 show the results of the impact in terms of Acidification potential for both considered functional units. No significant differences were observed ($P > 0.05$), between the two studied systems, which showed values of 11.9 ± 2.8 g SO_2-eq/kg LW and 9.3 ± 2.8 g SO_2-eq/kg LW for SA12 and SA24, respectively. In contrast to our results significantly higher outcomes concerning AP were observed across various beef production systems. For instance, Bragaglio et al. (2018) reported AP values ranging from 200 to 300 g SO_2-eq per kg live weight, while Nguyen et al. (2010) identified AP results ranging between 101 and 210 g SO_2-eq per kg slaughter weight (equivalent to an estimated range of 116–333 g SO_2-eq per kg live weight). In addition, Berton et al. (2017) showed a measurement of 193 g SO_2-eq for an intensive beef production system in Italy. Lower values were observed by Ogino et al. (2016), in extensive and intensive systems in the Asian region of Thailand (47.4 vs. 61.8 g SO_2-eq/kg LW), while similar results to ours were observed in an Alpine environment by Angerer et al. (2021). The exceptionally low AP values observed in analyzed production systems could primarily be attributed to the complete absence of artificial fertilizer utilization, as none of the farms acquired or employed such inputs. In this regard Clark and Tilman (2017) emphasized the substantial impact of reduced fertilizer application on acidification potential in livestock production systems. However, the differences observed compared to other studies may also be due to approach methodologies within the software currently in use and on the market, which take different methodologies and parameters into consideration. One of the problems that emerged in the sixth report (IPCC, 2023) was precisely the high variability in the methodologies used globally for estimating environmental impacts. Additionally, the infrequent procurement of forage and the in-house feed production carried out by the farms in question are key factors in upholding the low levels of ammonia production (AP). In fact, the limited reliance on external forage sources contributes to a reduced input of nitrogen compounds, which are known contributors to acidification potential (Xu et al., 2022). The observed mitigation of acidification in these two systems SA12 and SA24, underscores the importance of sustainable and localized agricultural practices in minimizing environmental impacts. The adoption of similar strategies in different geographical contexts could serve as a valuable approach to promote more ecologically responsible livestock production systems. Of the primary pollutants, nitrogen oxide emerged as the dominant contributor, succeeded by ammonia and sulfur dioxide. The distribution of sulfur dioxide was consistently comparable across two systems, comprising approximately 20 % of the overall impact.

3.1.4. Eutrophication potential

The generated impact in terms of EP is shown in Tables 2–3 for both considered functional units. No significant differences were observed between the two systems for both functional units ($P > 0.05$). However, the EP of both systems was lower in comparison to previous values in the literature. For instance, Pelletier et al., 2010 documented EP values spanning from 104 g PO_4-eq/kg live weight (in the case of the feedlot system) to 142 g PO_4-eq/kg live weight (for the pasture-based system). Conversely, approximately 50 g PO_4-eq/kg LW were recorded by Zonderland-Thomassen et al. (2014) and Berton et al. (2017). Nevertheless, Dick et al. (2015) identified elevated EP values within intensive systems when contrasted with extensive ones. It is highly plausible that the diminished outcomes observed with regard to EP stemmed from the complete absence of mineral fertilizers, encompassing N-P-K. Specifically, the absence of crucial elements such as nitrogen, phosphorus, and potassium, which conventionally play a pivotal role in driving eutrophication phenomena in both inland and coastal water ecosystems, emerges as a salient factor to consider (Huang et al., 2017). This element of inquiry beckons for further investigation to unravel the intricate dynamics that underpin the observed trends in eutrophication potential. Nguyen et al. (2010) demonstrated that the dominant driver of EP stems from emissions attributed to feeding inputs during the fattening phase. Contrarily, the influence of manure management exhibited marginal significance across all three scrutinized systems. Alig et al. (2012), reported a 36 % elevation in EP for organic farming systems when juxtaposed with their conventional counterparts. Similarly, Presumido et al. (2018) showed, wherein an extensive farming system showcased lower EP values compared to a semi-intensive configuration. These observed disparities can be reasonably ascribed to the divergent paradigms inherent in beef cattle farming across European countries. The variances in agricultural methodologies and intensities likely play a pivotal role in shaping the nuanced eutrophication potential across these systems. Nonetheless, it is imperative to acknowledge the limited scope of investigations focused on this subject, thereby warranting a measured interpretation of the outcomes. Additionally, the significance of contextual factors cannot be understated. Several researchers (e.g. de Vries et al., 2015; Dick et al., 2015) have emphasized the pronounced influence of regional climatic conditions and soil characteristics on both acidification potential (AP) and eutrophication potential (EP) values. Consequently, attempts to draw comparisons between various studies are inherently intricate owing to the inherent diversity in these local determinants.

4. Conclusion

The breeding of beef cattle in marginal areas in the Alpine environment plays an important environmental and social role. For both systems studied, the environmental performances are in line with previous research conducted at a European level, despite the low production performances. This is attributed to the restricted employment of concentrated feeds, forage production on-site as well as the abstention from artificial fertilizers and herbicides, factors that contribute to the promotion of sustainable practices. Slaughtering beef cattle at the age of 12 months improves environmental performance by reducing the environmental impact in terms of global warming potential for both considered functional units. Furthermore, carbon sequestration by pastures and permanent grassland were shown to incorporate a relevant role in mitigating greenhouse gas emissions and should therefore be considered within the assessment for a comprehensive evaluation of environmental impact of beef cattle farming in alpine environment. In the future of environmental certification and carbon credit policy, beef cattle farms and other livestock farms will increasingly have to adapt to mitigation strategies in order to achieve the carbon neutrality set at European level for 2050. Including the woodland in the system could be one possibility to drive beef farms to Net Zero carbon neutrality as shown by the sensitivity analysis in our study.

CRediT authorship contribution statement

Emilio Sabia: Writing – review & editing, Writing – original draft, Visualization, Supervision, Methodology, Investigation, Formal analysis, Conceptualization. **Thomas Zanon:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Methodology, Investigation, Formal analysis, Conceptualization. **Ada Braghieri:** Writing – review & editing, Investigation. **Corrado Pacelli:** Writing – review & editing, Investigation. **Verena Angerer:** Writing – review & editing, Investigation. **Matthias Gauly:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Project

administration, Methodology, Investigation, Conceptualization.

Declaration of competing interest

The authors affirm that they possess no identifiable conflicting financial involvements or personal affiliations that might have seemed to impact the research presented in this manuscript.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2024.170798.

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