

Research Paper

Carbon neutrality and beef production in the marginal areas: A case study of Podolian cattle system[☆]

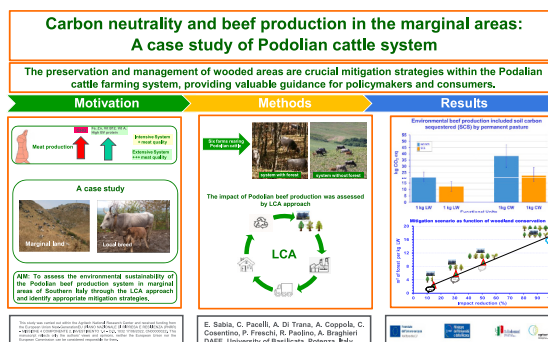
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HIGHLIGHTS

- Environmental impact of Podolian beef production in marginal areas has been analyzed
- Live weight (LW), carcass weight (CW) and hectare of land were the functional units
- Carbon sequestration from permanent pastures has been included in the accounting
- Eight impact categories were analyzed through the LCA methodology
- Carbon neutrality for 1 kg of Podolian beef needs 16.7 m² of woodland/kg LW and 30.8 m² of woodland/kg CW

GRAPHICAL ABSTRACT



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ABSTRACT

CONTEXT: The Sixth Assessment Report of the Intergovernmental Panel on Climate Change stated that human activities caused global warming, mainly through emissions of greenhouse gases (GHGs); livestock supply chains contribute 14.5 % of global anthropogenic GHG emissions, with cattle (beef, milk) accounting for about two-thirds of that total, mainly due to methane emissions resulting from enteric fermentation.

OBJECTIVE: This study aimed to assess the environmental sustainability of the Podolian beef production system in marginal areas of Southern Italy (specifically the Basilicata region) through the Life Cycle Assessment (LCA) approach and identify suitable mitigation strategies.

METHODS: The environmental impact of Podolian beef production was assessed using the following indicators: Global warming potential (GWP₁₀₀, kg CO₂ eq), Freshwater eutrophication (FEP, g P eq), Terrestrial acidification (TAP, g SO₂ eq), Marine eutrophication (MEP, g N eq), Land use (LOP, m² year crop eq), Fossil resource scarcity (FFP, g oil eq), Mineral resource scarcity (SOP, g Cu eq), and Fine particulate matter formation (PMFP, g PM 2.5 eq). The boundaries of the beef production systems encompassed a cradle-to-farm gate analysis. Three functional units (FU) were used: kg of live weight (LW) at slaughter, kg of carcass weight (CW) and hectare of land. Additionally, carbon sequestration from permanent pasture and woodland was calculated.

RESULTS AND CONCLUSIONS: Our case study evaluated the main impact categories of livestock farming for beef production. The results of GWP₁₀₀ were higher than the European average for the three functional units

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considered. As the overall outcome is the total deducted the 39 % due to grassland management. Achieving carbon neutrality would require $16.7 \pm 4.9 \text{ m}^2$ of woodland per kg of LW or $30.8 \pm 9.0 \text{ m}^2$ of woodland per kg of CW.

SIGNIFICANCE: Our study indicates that the environmental impact per kilogram of beef produced in marginal contexts is generally higher than in intensive livestock farming systems. However, delving deeper into the specific context and accounting for carbon sequestration from pastures used in this cattle farming allows to achieve environmental performance comparable to the most efficient intensive systems. Specifically, we identified the wooded area resource within the Podolian cattle farming system as an existing mitigation strategy which requires effective management and preservation. This study provides more explicit guidance to policy-makers and consumers on the environmental implications of different meat production practices, supporting more informed planning of regional, national, and European resources.

1. Introduction

The Sixth Assessment Report (AR6) of the Intergovernmental Panel on Climate Change (IPCC, 2023) clearly showed that human activity, primarily by emitting greenhouse gases (GHGs), led to the phenomenon of global warming with a global surface temperature rise of $1.1 \text{ }^\circ\text{C}$ above the 1850–1900 baseline during the period of 2011–2020. Global GHGs emissions continued to rise, driven by unsustainable energy practices, land use, lifestyle choices, and consumption and production patterns spanning regions, nations, and individual behaviours. In 2019, global net anthropogenic GHGs emissions were estimated at 59 ± 6.6 Gigatons of CO_2 eq, marking an increase of about 12 % (6.5 Gigatons of CO_2 eq) compared to 2010 and a significant 54 % (21 Gigatons of CO_2 eq) surge since 1990 (IPCC, 2023). Globally more, net anthropogenic GHG emissions from agriculture, forestry, and other land use (AFOLU) sectors are about 13 gigatons of CO_2 eq. (22 % of total emissions), with Europe directly contributing approximately to 3 %. The livestock sector, particularly ruminants, is directly involved in enteric methane emissions and manure management for about 26 % of all AFOLU sector emissions (Dhakal et al., 2022). Cattle (beef and dairy cattle) account for nearly two-thirds of the GHG emissions from the livestock sector (FAO, 2018). Many studies illustrated that beef production significantly contributes to the emission of GHGs, leading certain beef production systems to carry a substantial environmental burden (Berton et al., 2025; Kearney et al., 2023; Crosson et al., 2011). Despite this, red meat remains a high-quality source of protein and essential micronutrients such as iron, vitamin A, iodine, zinc, and vitamin B12, which are also naturally present in other animal-based foods (Rocchetti et al., 2023). Additionally, research highlights considerable variability in the environmental impact of beef cattle farming, with GHG emissions varying between 8.6 and 35.2 kg of CO_2 eq per kilogram of consumable beef (de Vries and de Boer, 2015). In several Western countries, including Italy, beef systems based on the fattening of confined specialised breeds are often combined with beef grazing systems which utilise both local and specialised breeds, creating a mixed production scenario. Moreover, the popularity of “grass-fed” beef and beef produced in silver-pastoral systems has grown as these are perceived to be healthier and produced with a focus on animal welfare and environmental sustainability, particularly when pasture-based systems are employed (Sabia et al., 2024a; Linder et al., 2022). While specialised beef breeds tend to outperform local breeds in productivity, they require extensive grazing during certain phases of their lifecycle—an option not available in all European regions, such as Italy. In contrast, some European meat production systems integrate woodlands, such as the Montado in Portugal and the Dehesa in Spain. In marginal areas, such as the Basilicata region (Italy), beef production typically relies on extensive systems which rear local breeds such as Podolian cattle, which is a native breed characterised by a high rusticity. These animals are well adapted to semiarid environments with poor vegetation and are raised on either open pasture or pasture with night shelter. Podolian cattle graze on natural pasture and in woodland year-round, supplemented with meadow hay and straw during summer (Napolitano et al., 2005). These animals can convert vast renewable resources from grassland and pasture into high-nutrient foods with

excellent high human-edible protein conversion efficiency (Bragaglio et al., 2018). Calves are raised by their dams, suckling and grazing on pasture for 7 to 10 months. Upon reaching this age, they are transferred to a barn with straw bedding, concentrate supplements and an outdoor paddock where they are fattened until reaching slaughter age, typically around 14 months (Napolitano et al., 2005). The slaughter age of calves is relatively low, as the breed’s hardiness limits daily weight gains, making extended fattening economically disadvantageous. The farms avoid using synthetic fertilisers for forage production, relying solely on manure spread from barn accumulation during the winter. Several studies have shown that accounting for carbon sequestration by soil, particularly in permanent grasslands, can reduce the estimated environmental impact per kg of meat produced by 8 to 535 % (Sabia et al., 2024b; Alemu et al., 2017; Lupo et al., 2013). However, the dynamics of soil organic carbon accumulation remain controversial. Recent studies have observed that soil organic carbon can reach saturation levels influenced by ecological factors and constrained by the microbial population present in the soil. This process can also lead to CO_2 release into the atmosphere (Craig et al., 2021). Meanwhile, Wang et al. (2023) argue that relying exclusively on grassland carbon sequestration to offset greenhouse gas emissions from livestock systems is not feasible. Other studies, however, demonstrate a positive effect on reducing the environmental impact of beef cattle systems when soil carbon sequestration is also considered (Stanley et al., 2018). Nevertheless, no studies have investigated the integration of the beef production system with the forestry system, nor has there been an estimation of how forest conservation could contribute to achieving carbon neutrality in beef production. The Paris Agreement emphasises forest management as a strategy to mitigate climate change by reducing carbon dioxide emissions, and recognises forests among nature’s primary carbon storage and sequestration reservoirs (FAO, 2020; Luysaert et al., 2018). This study aims to estimate the environmental impact of the Podolian beef production system in marginal areas and explore potential mitigation strategies. Specifically, it evaluates the role of carbon sequestration by permanent pastures and forests integrated into the production system as a pathway to achieving net-zero carbon emissions.

2. Materials and methods

The Life Cycle Assessment (LCA) is defined by ISO14040 (2006) and ISO14044 (2006) standards. The principles and framework guiding LCA encompass four specific stages: 1) defining the goal and scope (which includes establishing the functional unit and system boundaries); 2) conducting the life cycle inventory (LCI) analysis (comprising the collection of input and output data for all processes); 3) performing the life cycle impact assessment (LCIA); and 4) interpreting the life cycle results.

2.1. Goal and scope

This study aimed to assess the environmental impact of the Podolian beef systems in marginal areas of Southern Italy, specifically in the Basilicata region, in terms of Global warming potential (GWP_{100} , kg CO_2

eq), Freshwater eutrophication (FEP, g P eq), Terrestrial acidification (TAP, g SO₂ eq), Marine eutrophication (MEP, g N eq), Land use (LOP, m² year crop eq), Fossil resource scarcity (FFP, g oil eq), Mineral resource scarcity (SOP, g Cu eq), and Fine particulate matter formation (PMFP, g PM 2.5 eq). Mid-Point impacts were assessed using the commercial software openLCA 2.0.1, employing the Agribalyse database v. 3.0.1 and the ReCiPe Midpoint (H) method (Huijbregts et al., 2017). ReCiPe Midpoint (H) offers characterisation factors designed to be representative globally rather than limited to the European context, while still allowing for implementing country- and continent-specific characterisation factors for several impact categories.

2.2. System boundary definition and functional units

The system boundaries of the beef production systems encompassed a cradle-to-farm gate analysis. Original data were gathered during on-site farm visits, employing a questionnaire administered between February and May 2023. Three functional units (FU) were used to comprehensively understand the environmental impact generated by the Podolian beef farming system: kg of live weight (LW) at slaughter, kg of carcass weight (CW) (LEAP, 2016), and hectare of land in agreement with recent developments to agricultural systems (Goglio et al., 2018; Nemecek et al., 2011).

2.3. Inventory analysis

Six farms rearing Podolian cattle, all registered in the Italian genetic herd book, which certifies their purity representative of the geographical area studied, were considered. Table 1 illustrates the main features of these farms. In the farms considered, calves are dam-reared, suckling and feeding on pasture for 7–10 months. At this age, they are moved to a straw-bedded barn with an outdoor paddock and fattened until slaughtering age (14 ± 2 mos. on average). All the on-farm activities (i. e., feed production, electricity, energy use, manure and animal management) were considered primary data. All beef cattle farms have a low stocking rate (0.5 ± 0.3 LU ha⁻¹) with continuous grazing rotation depending on the season and the availability of green biomass. The permanent pastures are characterised by a floristic composition that varies according to the season, with approximately 50 % grasses, 10 % legumes, 25 % composites and the remainder miscellaneous (Bragaglio et al., 2018; Braghieri et al., 2011).

2.4. Emission calculation

Total emissions for all the farms under study were calculated. Appendix Supplementary 1 provides all equations and methods for

Table 1
Main characteristics of six Podolian beef production farms involved in the study.

	Units	Farm 1	Farm 2	Farm 3	Farm 4	Farm 5	Farm 6	Mean	SD
Cows	no.	30	80	110	100	40	62	70	32
Heifers	no.	5	25	10	20	16	15	15	8
Bulls	no.	1	2	2	2	1	2	2	1
Calves	no.	15	35	66	70	40	55	47	21
Slaughtering weight	kg	500	500	415	431	440	490	463	38
Carcass weight	kg	275	280	228	240	250	285	260	24
Slaughtering age	mos.	15	16	14	12	15	14	14	2
Daily weight gain	kg	0.925	0.850	0.810	1.001	0.730	1.208	0.921	0.169
Total land	ha	52	220	200	800	250	500	337	269
Permanent pasture	ha	10	170	190	370	170	160	178	115
Woodland	ha	1	50	0	250	75	300	113	130
Stocking rate	LU ha ⁻¹	0.8	0.5	0.8	0.2	0.3	0.2	0.5	0.3
Meadow hay	t y ⁻¹	20	120	140	90	158	90	132	42
Wheat straw	t y ⁻¹	5	30	50	120	5	120	55	53
Concentrate	t y ⁻¹	4	60	70	96	5	168	67	62
Electricity	Kwh y ⁻¹	1500	2200	5400	5500	2500	3000	3350	1700
Diesel	t y ⁻¹	4	8	8	9	10	3	7	3

SD = Standard Deviation; LU = Livestock Unit.

determining on-farm and off-farm emissions. In detail, we utilised the methodology described by the Intergovernmental Panel on Climate Change (IPCC, 2019) to address the correlation between gross energy intake (GEI) and emissions from enteric fermentation. As detailed in the literature, GEI was determined following the equation (IPCC, 2019). Methane (CH₄) emissions from enteric fermentation, manure storage, and direct deposition on grassland were computed using the Tier 2 equation endorsed by the relevant authority (IPCC, 2019). The CH₄ conversion factor (Y_m) was 4 % for fattening cattle and 6.5 % for adult cows and bulls. The CH₄ emission from manure volatile solids (VS) was determined to be 3.9 kg/animal/day, with a maximum methane production capacity of 0.1 m³/kg VS. The methane conversion factor (MCF) was 27 for pit storage and 1.5 for pasture. Direct and indirect N₂O emissions occurring during grazing on pasture were estimated using the IPCC equation. The quantity of nitrous oxide emitted from manure was calculated based on total nitrogen excretion, and the country-specific emission factor of 0.02 kg of N-N₂O/kg of excreted N for Italy was applied (Romano et al., 2023). Considering direct nitrogen soil deposition, an emission factor of 0.0125 kg N-N₂O/kg N was utilised (Romano et al., 2023). This method and approach have the advantage of using standard approaches on an Italian national level without considering the specific environmental conditions of the geographical area under study. Indirect emissions of N₂O were estimated following the methodology recommended by IPCC (2019), which considers nitrate leaching runoff and the re-deposition of volatilised gases into soils and waters. Specifically, an emission factor of 0.01 kg N₂O-N/kg N was applied for indirect atmospheric deposition. In comparison, 0.025 kg N-N₂O/kg N was utilised for N leaching runoff, as suggested by an Italian country-specific emission factor (Romano et al., 2023). The estimation of carbon dioxide (CO₂) emissions resulting from energy consumption accounted for both direct emissions from the combustion of fossil fuels and indirect emissions from electricity usage. The calculation accounted for the volumes of diesel fuel consumed (in litres) and the electricity consumed in kilowatt-hours (kWh) during various farm operations. Following Romano et al. (2023), a standard value of 0.85 kg per litre for diesel density and a 3.14 kg CO₂ eq emission factor for estimating CO₂ release from the combustion of 1 kg of diesel were utilised. For electricity, an Italian-specific emission factor of 0.47 kg CO₂ eq per kWh was employed (Romano et al., 2023). In the LCA, the characterisation factors employed for GWP₁₀₀ were 1, 29.8, 27.0 and 273 CO₂ eq for CO₂, CH₄ - fossil, CH₄ - non fossil and N₂O, respectively. These values were recommended by Forster et al. (2023) and IPCC (2014).

2.5. Carbon sequestration from soil

The approach advocated by Petersen et al. (2013), which examines a

100-year timeframe and states that 10 % of the total carbon introduced into the soil will be sequestered, is recommended. However, while some models suggest that soil C stocks can increase over extended periods (Jones and Donnelly, 2004; Six et al., 2002), the prevailing consensus indicates that soil C dynamics tend to reach equilibrium following management changes (Paustian et al., 2016; Goglio et al., 2015; Oberholzer et al., 2014). Significant uncertainties exist regarding the extent of carbon stock alterations for land use and management changes, primarily due to variability in local conditions and the absence of dependable field data (Börjesson and Tuvesson, 2011). Substantial reductions in soil organic carbon have been frequently documented in cases where land use changes involve the transformation of forests and permanent grasslands into agricultural fields. In contrast, reversing such processes, such as restoring cultivated lands to forests or grasslands, generally leads to a rise in soil organic carbon levels (Shrestha et al., 2014; VandenBygaert et al., 2008). However, our approach is based on the assumption that the pastures and forests under consideration will experience no alterations in land use or soil management practices over the years. These researchers also emphasise the importance of the soil's capacity for carbon sequestration as an effective strategy for mitigating greenhouse gas emissions, as also suggested by Pelaracci et al. (2025). Furthermore, widely used models for grassland systems, such as Roth-C (Coleman and Jenkinson, 1996) and CENTURY (Shrestha et al., 2014), provide additional insights into soil C dynamics and could complement our approach. Currently, there is not universally accepted methodology for integrating soil carbon storage into agricultural LCA approach (Goglio et al., 2015; Arzoumanidis et al., 2014; Petersen et al., 2013); nevertheless, the method proposed by Petersen et al. (2013) is currently among those used in livestock systems (Lunesu et al., 2025; Quevedo-Cascante et al., 2024; Sabia et al., 2024b; Arca et al., 2021; Batalla et al., 2015). The geographic area under study is characterised by permanent pastures with a dynamic composition of different botanical families in other seasons of the year, with approximately 50 % grasses, 10 % legumes and 18 % composites (Braghieri et al., 2011). As proposed by Soussana et al. (2010) and Petersen et al. (2013), estimates of carbon changes are rooted in net carbon fluxes. The computation of yearly carbon inputs into grasslands encompasses herbage residues and manure, following the methodology delineated by Batalla et al. (2015). These authors considered 40 % and 16 % of the total yield as above-ground and below-ground residues, respectively, and assumed a 45 % carbon content on a dry matter basis. According to their findings, 10 % of the carbon added to the soil will be sequestered over a 100-year timeframe.

Eq. (1):

$$\text{Kg C/ha} = \{[(\text{D.M.} \times 40\%) + (\text{D.M.} \times 16\%) \times 45\%]\} \times 10\% \text{ (Petersen et al., 2013)}$$

Where:

D.M. = Dry Matter.

D.M. x 40 % = 40 % crop residue aboveground (Soussana et al., 2010)/total crop production.

D.M. x 16 % = 16 % crop residue belowground (Soussana et al., 2010)/total crop production.

The estimation of carbon sequestered from the soil was then deducted from the environmental impact associated with GWP_{100} , as outlined by Petersen et al. (2013). The carbon sequestered by permanent pastures was subsequently subtracted from the GWP_{100} impact category after being converted into CO_2 eq by multiplying it by the conversion coefficient 44/12.

2.6. Carbon storage from woodland

The rearing of Podolian cattle for beef production is distinguished by the remarkable adaptability of these animals to graze throughout the year. This includes their ability to thrive in diverse and often challenging environments, such as the wooded areas and marginal lands of the Basilicata region. These cattle exhibit a natural resilience and foraging

instinct, allowing them to efficiently use the region's sparse vegetation and rugged terrain, which are often unsuitable for other types of livestock. This practice supports sustainable livestock management and contributes to preserving traditional agricultural methods and the biodiversity of these unique landscapes. Almost all Podolian farms retain woodlands, which they cyclically harvest approximately every twenty years for industrial purposes or heating local homes. The main tree species that characterise the woods of Basilicata region are Mediterranean oaks (*Quercus ilex* L.) and beeches (*Fagus* L.) (Gasparini et al., 2022), and at around twenty years of age have an average carbon storage of 90.94 ± 40.20 tons of C/ha above-ground and below-ground biomass (Luyssaert et al., 2007). A recent study on an Italian national scale showed that forests in the Basilicata region are, on average, capable of retaining 1.5 tons/C per hectare per year, equivalent to 5.5 tons of CO_2 -eq per hectare per year for above-ground (Di Cosmo et al., 2022; Gasparini et al., 2022). Luyssaert et al. (2007) indicated that 35 % of the detached carbon was added to this value for below-ground biomass. Using this assumption, the hectares of woodland, which should no longer be cut and sold as timber but managed and preserved to achieve carbon neutrality, were computed to neutralise the CO_2 eq emissions from Podolian farms to achieve carbon neutrality. Cattle grazing, a practice on which the Podolian system is based, at a moderate stocking rate may prevent shrub encroachment and the accumulation of dead inflammable herbaceous vegetation (Casasús et al., 2007); forest management was not considered within the system boundaries of the study for the reason that it was negligible at this stage of the case study, since the same Podolian cattle with their grazing and trampling activities keep the shrubs in the forest under control (Sabia et al., 2024a; Riedel et al., 2013). Scenarios were proposed to reduce the carbon footprint per kilogram of beef, LW, and CW by 50 %, 30 %, and 15 % to mitigate environmental impact.

3. Results

3.1. Farm level

Table 1 depicts the main characteristics of the Podolian farms under study. The Podolian farms show an average size of 337 ± 269 ha (mean \pm SD), with a wooded area of 113 ha. One farm does not include any forest within its system. The average number of animals slaughtered per year is 47 ± 21 , with an average age of 14 months and a LW at slaughter of 463 ± 38 kg, yielding a dressing percentage of 55 %. The average daily weight gain (DWG) is 0.921 ± 0.169 kg per head per day. The consumption of concentrated feed is limited to one farm (4 t y^{-1}), with an average value of $67 \pm 62 \text{ t y}^{-1}$.

3.2. Environmental performances

Tables 2–3–4–5 show the environmental results of the Podolian system, expressed in terms of the two productivity FU used, LW and CW, and also in terms of hectares of land and the respective percentages of pollutants. In terms of GWP_{100} , the impact was 20.7 ± 4.6 kg CO_2 eq per kg LW (mean \pm SD) and 38.2 ± 8.9 kg CO_2 eq per kg CW (mean \pm SD). The minimum values observed were 15.2 kg CO_2 eq per kg LW and 25.7 kg CO_2 eq per kg CW. Considering the impact in terms of hectares of land, an average value was 1603 ± 852 kg CO_2 eq per hectare of land, with a minimum value of 720 kg CO_2 eq and a maximum value of 2611 kg CO_2 eq per hectare, respectively. The primary pollutant was CH_4 (66.4 %), followed by N_2O (19.7 %) and CO_2 (12.3 %). Environmental toxicity indicators such as FEP, TAP, and MEP showed very low values for both functional units. Conversely, LOP had high values, amounting to $120.3 \pm 72.7 \text{ m}^2$ year crop eq per kg of LW and $224.9 \pm 138.9 \text{ m}^2$ crop year eq per kg of CW (mean \pm SD), where extensive pasture occupation accounts for 96.1 % and annual crop occupation for 3.3 %. In terms of non-renewable resources, FFP and SOP, the observed values were 385.0 ± 243.8 g oil eq per kg of LW, 824.0 ± 400.1 g oil eq per kg of CW, and

Table 2
Environmental impact category per 1 kg of LW at farm gate.

Impact category	Reference unit	Mean	SD	Min	Max
Global warming potential (GWP ₁₀₀)	kg CO ₂ eq	20.7	4.6	15.2	26.5
Freshwater eutrophication (FEP)	g P eq	2.0	0.9	0.5	3.1
Terrestrial acidification (TAP)	g SO ₂ eq	94.8	34.5	49.1	146.5
Marine eutrophication (MEP)	g N eq	69.6	43.5	13.5	119.4
Land use (LOP)	m ² year crop eq	120.3	72.7	27.6	203.2
Fossil resource scarcity (FFP)	g oil eq	385.0	243.8	130.2	812.3
Mineral resource scarcity (SOP)	g Cu eq	18.2	17.5	2.5	49.4
Fine particulate matter formation (PMFP)	g PM 2.5 eq	19.4	9.1	10.7	36.0

LW = Live Weight; SD = Standard Deviation.

Table 3
Environmental impact category per 1 kg of CW at farm gate.

Impact category	Reference unit	Mean	SD	Min	Max
Global warming potential (GWP ₁₀₀)	kg CO ₂ eq	38.2	8.9	25.7	47.7
Freshwater eutrophication (FEP)	g P eq	117.5	180.7	1.0	369.9
Terrestrial acidification (TAP)	g SO ₂ eq	181.1	62.3	94.8	262.8
Marine eutrophication (MEP)	g N eq	131.8	82.1	25.1	223.7
Land use (LOP)	m ² year crop eq	224.9	138.9	51.2	383.4
Fossil resource scarcity (FFP)	g oil eq	824.0	400.1	247.2	1375.1
Mineral resource scarcity (SOP)	g Cu eq	41.3	27.7	9.5	83.6
Fine particulate matter formation (PMFP)	g PM 2.5 eq	37.0	15.9	20.4	64.4

CW = Carcass Weight; SD = Standard Deviation.

18.2 ± 17.5 g Cu eq per kg of LW and 41.3 ± 27.7 g Cu eq per kg of CW, respectively. Regarding FFP, the primary pollutant was crude oil (68.1 ± 9.2 %), while for SOP, it was potash-salt crude (55.1 ± 31.4 %).

3.3. Carbon sequestration and sensitive analysis

Fig. 1 shows GWP₁₀₀ values with the reduction due to the carbon sequestered by the permanent pastures present within the Podolian farm. The impact reduction is about 39 %, with values being 12.3 ± 3.6 kg CO₂ eq per kg LW and 22.6 ± 6.6 kg CO₂ eq per kg CW (mean ± SD). The production of Podolian beef systems may achieve carbon neutrality by preserving 30.9 ± 14.1 ha of forest (mean ± SD), i.e. 16.7 ± 4.9 m² of forest per kg LW and 30.8 ± 9.0 m² of forest per kg CW (Table 6). To mitigate the environmental impact in terms of GWP₁₀₀ by 30 %, 9.3 ± 4.2 ha of forest have to be preserved, while to reduce it by 15 %, 4.6 ± 2.1 ha of woodland are required.

4. Discussions

4.1. Farm systems

The Podolian system is widespread in many regions of Southern Italy, particularly in the Basilicata region. It is characterised by extensive pastures, permanent meadows, and woodlands (Bragaglio et al., 2018; Napolitano et al., 2005). In our case study, two farms do not have forests within their land use (farm 1 and farm 3, Table 1), confirming that not all farms can manage Podolian cattle for beef production with the presence of woodlands. However, at the European level, extensive beef production systems primarily involve using permanent pastures. This is due to the large expanses of land and favourable weather conditions that allow for year-round grazing of beef cattle with high feed biomass availability, but without wooded areas (Porto Costa et al., 2023; Nguyen et al., 2010). The farms considered in this study are all family-run and raise an average of 70 adult heads and fatten an average of 47 ± 21 calves. In a recent survey conducted in a marginal Alpine area, beef cattle farming is characterised by a very low number of animals slaughtered annually, approximately 12 head (Angerer et al., 2021). In contrast, the average number of cows per farm in the Swiss Alpine area is 24 (Gazzarin and Jan, 2024). Conversely, farms in Northern Europe, such as in Sweden, slaughter around 99 beef cattle per year using the suckler cow system (Hammar et al., 2022). On average, in the large expanses of Central Europe, around 120 beef cattle are slaughtered per year in the cow-calf system (Herron et al., 2021). The low number of animals slaughtered per year in the extensive Podolian system is most likely due to the limited local market demand for this kind of beef and its sensory characteristics, which do not align with the pressing needs of the market and consumers. However, applying an adequate ageing period significantly improved the tenderness of Podolian beef (Braghieri et al.,

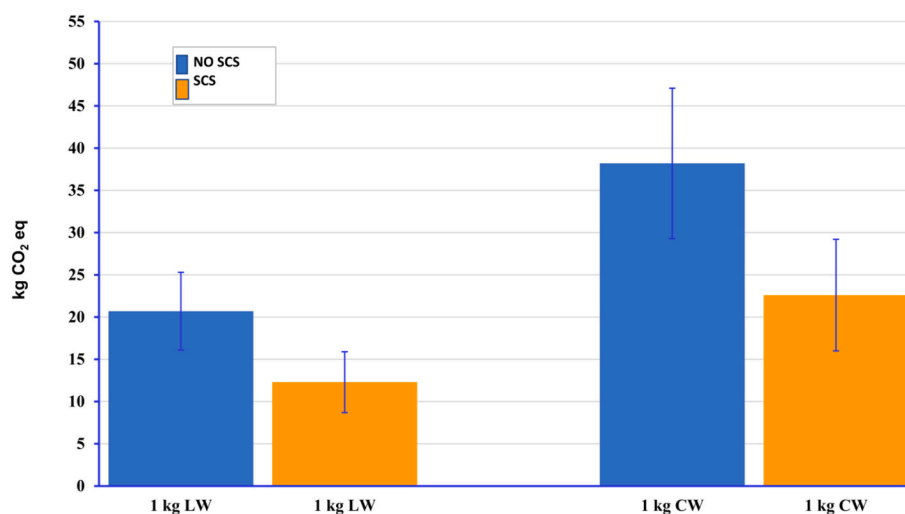


Fig. 1. GWP₁₀₀ of Podolian beef production including soil carbon sequestered by permanent pasture (Mean ± SD).

GWP₁₀₀ = Global Warming Potential horizontal time 100y; SD = Standard Deviation; LW = Live weight; CW = Carcass weight; SCS = Soil carbon sequestration.

2013). Owing to a farming system where animals graze on green forages directly from pasture, Podolian beef is characterised by a favourable content of polyunsaturated fatty acids (Cifuni et al., 2004; Braghieri et al., 2005), considering a moderate consumption of red meat at all times. The average DWG are generally satisfactory at 0.921 ± 0.169 kg/head/day (mean \pm SD), with a maximum value observed in Farm 6, reaching 1.208 kg/head/day. Specialised breeds exhibit higher DWG values than local breeds, with a low genetic selection index for growth traits (Fernandes et al., 2024; Vanbergue et al., 2024). However, extensive systems in marginal areas show low use of concentrated feeds, such as soybean and corn, and a reduced competition with human nutrition (Bragaglio et al., 2018). Energy consumption is notably low concerning electricity and fossil fuels, including diesel. In contrast, most European food and meat production systems demand substantial energy inputs. This high energy requirement contributes significantly to GHGs emissions, exacerbating their environmental impact. Consequently, the intensive energy inputs related to these production systems represent a substantial challenge to sustainable agricultural practices and climate change mitigation efforts (Clark and Tilman, 2017). The low energy inputs characterising the farms involved in Podolian systems may be due to their limited mechanisation degree, as in the marginal areas, it is difficult for agricultural machinery to access.

4.2. Environmental implications

In our case study, the main impact categories of livestock farming for beef production were evaluated following the FAO, LEAP (2016) guidelines. The results observed in terms of GWP₁₀₀ were higher than the European average for the three functional units considered (de Vries and de Boer, 2015; Nguyen et al., 2010). Local breeds exhibit lower DWG and slaughter yields than specialised beef breeds (Vanbergue et al., 2024). The current structure for assessing environmental impact based on the LCA approach relies solely on the ratio between total CO₂ equivalent emissions and the absolute output value of the production system over its entire life cycle. That represents a limiting factor for a more comprehensive environmental evaluation, encompassing a production system's multiple intrinsic and extrinsic factors. It reduces the complexity of environmental impacts to a single metric, potentially overlooking the multifaceted nature of ecological consequences. Environmental impact is a multidimensional construct influenced by various intrinsic factors, such as biodiversity loss, soil degradation, and water usage, as well as extrinsic factors, including socio-economic and geographical variables. Recent studies have observed that approaches for accurate environmental impact assessment must be conducted and compared on a territorial scale to ensure proper evaluation and planning at the local level. This localised approach allows for considering specific regional characteristics, environmental conditions, and socioeconomic factors that can influence the outcomes of environmental assessments (Lulovicova and Bouissou, 2024; Loiseau et al., 2018). However, our results are similar to previous studies on the same cattle breed without considering the carbon sequestered by permanent pastures (Bragaglio et al., 2018, 2020). Specifically, the average value observed in our case study is slightly lower than that reported by Bragaglio et al. (2018). This difference is likely due to the improved production performance of the Podolian cattle in recent years, with farmers placing greater emphasis on feed management. Notably, one farm showed GWP₁₀₀ values comparable to specialised breeds (15.2 kg CO₂ eq/kg LW and 25.7 kg CO₂ eq/kg CW Farm 6), most probably attributed to a higher use of concentrated feed and better DWG performance. This finding confirms that with appropriate management, the Podolian beef cattle may achieve environmental performance similar to that of specialised breeds in the Italian context (Berton et al., 2017; Buratti et al., 2017); however, recent European studies have observed approximately 50 % lower environmental performance, with absolute values expressed in terms of LW amounting to 10.2 kg CO₂ eq and in terms of CW amounting to 18.6 kg CO₂ eq (McGee et al., 2024). These differences in environmental

performance are attributed to different genetic types of beef cattle and variations in geographical and environmental contexts. The primary pollutant was CH₄ from enteric emissions, N₂O from manure and fossil fuels, and CO₂. These findings in the context of ruminant livestock farming are supported by multiple studies, with slight differences in the significance of methane within the GWP₁₀₀ impact category. The variations range from minimum values of 13.8 % (Berton et al., 2017) to high values of 83–85 % in local breeds (Clariget et al., 2024; Costantini et al., 2021; Bragaglio et al., 2018). These differences are likely due to varying dietary rations with different energy digestibility values and different farming systems (intensive vs. extensive). However, our results fluctuate within the average values reported in the literature, between 50 and 60 % of enteric methane emissions (FAO, 2018). Few studies in the field of beef production account for the carbon sequestered by permanent pastures (Pereyra-Goday et al., 2024; McDonald et al., 2023; Hammar et al., 2022; Alemu et al., 2017; Pelletier et al., 2010). The observed reduction in terms of GWP₁₀₀ extends between 24 and 535 % in pasture-based beef production systems in the US (Lupo et al., 2013). Extensive permanent pastures for forage supply have traditionally characterised the Podolian system. These grazing areas, widespread in the internal marginal area in Basilicata regions, do not compete with food production for direct human nutrition. When considering the carbon sequestered by permanent pastures, the reduction in terms of environmental impact observed is approximately 39 % for both functional units considered, achieving values close to those in European regions with higher productivity for beef cattle (12.3 ± 3.6 kg CO₂ eq per kg LW and 22.6 ± 6.6 kg CO₂ eq per kg CW, mean \pm SD, Fig. 1) (Bonnin et al., 2022; Casey and Holden, 2006). A recent study conducted in South America observed that including organic carbon stored in the soil could reduce the environmental impact in different rotational grazing systems by 22.4 to 42.1 % (Pereyra-Goday et al., 2024). In contrast, in a study conducted in Sweden, the estimated reduction considering the carbon sequestered in the soil was 15–22 % (Hammar et al., 2022), and in a study by Alemu et al. (2017) emissions were reduced by 12–25 % in a beef system in western Canada. Although Deng et al. (2023) observed that the carbon stored in plants and soil is a function of livestock density, not all studies that involve permanent pastures include the carbon sequestered in the soil. However, significant uncertainties exist in modelling SOC changes, particularly for perennial grasses growing on pastureland. A recent study conducted at the European and UK levels observed that in 2009–2018, continuous grasslands showed a steady increase in carbon sink in all European geographical areas (De Rosa et al., 2023). In particular, the capacity of plants to store carbon is also a function of other macro- and micronutrients, such as nitrogen and phosphorus, which in a grazing system with livestock can be distributed directly to the grazed soil via urine and manure. Estimating the annual carbon input is more complex for perennial grasses than annual crops, as only a portion of the root biomass is replaced yearly (Poehlau, 2016). The environmental impact, expressed per unit of land area (hectares per year), was found to be relatively low. In a study conducted in Ireland by Casey and Holden (2006) on organic beef cattle systems, reported emissions were 2302 kg CO₂ eq ha⁻¹ yr⁻¹, approximately 30 % higher than the values observed in the present study. Similar results were found in a recent study conducted in Spain, with a value of 1434.7 kg of CO₂ eq ha⁻¹ (Horrillo et al., 2020). In contrast, conventional Irish beef systems showed substantially higher emissions, reaching 5346 kg CO₂ eq ha⁻¹ yr⁻¹ (Casey and Holden, 2006). The notably favourable outcomes observed in the current study are likely due to the extensive use of permanent pasture and woodland in the Podolian farming system (Table 1), which differs from the Irish systems that typically utilise an average of about 110 ha for beef production (Casey and Holden, 2006). Although the Podolian farms examined are not officially certified as organic under current legislation, they have all the fundamental characteristics of organic beef farming systems. This is further supported by a recent study, which indicates that organic systems emit less CO₂ equivalents per unit area compared to conventional

systems (Hashemi et al., 2024). One the Podolian farm considered showed a remarkably low emission level of 720 kg CO₂ eq ha⁻¹ yr⁻¹ (Table 4). Nonetheless, our study highlights a marked variability in the environmental impact when expressed per unit of land area, with values ranging from a maximum of 2611 kg CO₂ eq ha⁻¹ yr⁻¹ to a minimum of 720 kg CO₂ eq ha⁻¹ yr⁻¹. This pronounced variability, as interpreted through the lens of current methodologies for assessing environmental impact per FU, can be primarily attributed to the heterogeneous structure and characteristics of Podolian cattle farming systems. These systems are typically small-scale, family operated enterprises situated in internal and marginal rural areas, where agricultural conditions and resource availability are often less than ideal. As a result, meat productivity per hectare differs significantly across the sampled farms. Additionally, the extent and composition of the land used for livestock production vary considerably among holdings, reflecting a high degree of heterogeneity in both land use patterns and farming practices. Such structural differences contribute substantially to the observed discrepancies in environmental performance, underscoring the complexity of applying uniform impact assessment models to diverse and regionally adapted production systems. Nevertheless, similarly low environmental impacts per unit area are also observed in plant-based production systems, which generally impose lower ecological impacts compared to systems based on animal-derived products (Hashemi et al., 2024; Nemecek et al., 2011). Results for impact categories, FEP, TAP and MEP directly involving soil and inland and marine waters are shown in Tables 2–3–4. In extensive systems with low energy inputs, generally, low levels of environmental impact are observed in terms of acidification, eutrophication of inland and marine waters (Angerer et al., 2021; Dick et al., 2015). The low diesel consumption due to the limited mechanisation of marginal internal agricultural areas and the complete absence of organic and inorganic fertiliser use results in these production systems exhibiting very low levels of pollutants. Conversely, in the majority of intensive systems, both for beef and milk production, very high environmental impacts in terms of acidification and eutrophication are generally observed (Bonnin et al., 2022; Berton et al., 2017; Chen and Corson, 2014). However, our results align with previous studies conducted in extensive grazing systems (Costantini et al., 2021; Bragaglio et al., 2018). Evaluating the impact generated in terms of LO, the observed results are higher compared to intensive meat production systems, where values can be lower than 30 m² of LO per kg of BW (Nguyen et al., 2010), while in LCA studies on beef production systems conducted in the USA and Canada report land occupation values ranging from 33 m² per year per kg of body weight (Capper, 2012) to 56 m² per year per kg of body weight (Beauchemin et al., 2011). However, beef production systems in marginal areas offer significant advantages by utilising agricultural lands which are poorly mechanised and not in

Table 4
Environmental impact category per hectare per year at farm gate.

Impact category	Reference unit	Mean	SD	Min	Max
Global warming potential (GWP ₁₀₀)	Kg CO ₂ eq	1603	852	720	2611
Freshwater eutrophication (FEP)	Kg P eq	0.16	0.11	0.02	0.44
Terrestrial acidification (TAP)	Kg SO ₂ eq	7.5	4.4	2.9	13.8
Marine eutrophication (MEP)	Kg N eq	5.8	5.1	0.5	16.1
Land use (LOP)	m ² year crop eq	10,477	9822	1216	27,937
Fossil resource scarcity (FFP)	Kg oil eq	30.7	16.0	14.5	52.6
Mineral resource scarcity (SOP)	Kg Cu eq	1.6	1.1	0.3	3.2
Fine particulate matter formation (PMFP)	Kg PM 2.5 eq	1.5	0.9	0.6	2.9

SD = Standard Deviation.

direct competition with the production of food for human nutrition. These regions often feature challenging terrain and low soil fertility, making them unsuitable for intensive crop farming. The presence of livestock, such as the Podolian cattle, plays a crucial role in maintaining the viability of these areas. Without livestock and farmers, these marginal lands would likely be abandoned, resulting in severe ecological consequences (Oggioni et al., 2020; MacDonald et al., 2000). Abandonment would lead to increased soil erosion, as there would be no grazing animals to maintain vegetation cover (Donovan and Monaghan, 2021). Additionally, the risk of wildfires would rise due to the accumulation of dry, unmanaged vegetation (Pillar and Overbeck, 2025; Colantoni et al., 2020). Therefore, integrating and maintaining livestock in these systems is essential for sustaining agricultural productivity, preventing environmental degradation and promoting the ecological health of these vulnerable landscapes (Zhen et al., 2025; Díaz-Pereira et al., 2020). However, different studies suggested that enhancing efficiency and intensifying agricultural production could contribute to biodiversity conservation by reducing the need for land dedicated to production (Salles et al., 2017; Grau et al., 2013). Nevertheless, our results are similar to previous studies conducted in extensive systems at the European and national levels (Angerer et al., 2021; Bragaglio et al., 2018; de Vries and de Boer, 2015). When examining the environmental impact of non-renewable resources, specifically Fossil Fuel Depletion (FFP) and Resource Scarcity (SOP), relatively low values are observed. That is likely attributable to minimal reliance on energy inputs like diesel and electricity. In many of these extensive systems, the infrastructure for electricity is often non-existent, and the use of diesel for mechanisation is minimal due to the low level of mechanisation in these areas. As a result, these systems have a significantly lower demand for non-renewable resources compared to more intensive farming practices (Dick et al., 2015). The limited reliance on such inputs reduces dependency on finite resources, making these systems more sustainable in the long term. Few studies analyzed these impact categories in extensive systems. However, our results align with previous studies conducted in other contexts (Costantini et al., 2021). (See Table 5.)

Table 5
Principal pollutants (%) for different impact categories.

Impact category and Pollutants	Mean	SD	Min	Max
Global warming potential (GWP ₁₀₀)				
Methane biogenic (CH ₄)	62.5	10.1	47.6	74.3
Dinitrogen monoxide (N ₂ O)	19.6	7.8	9.6	31.8
Carbon dioxide (CO ₂)	16.8	6.5	10.7	27.8
Freshwater eutrophication (FEP)				
Phosphate (PO ₄ ³⁻)	74.5	5.6	66.9	84.1
Phosphorus (P)	19.9	5.1	11.7	26.5
Terrestrial acidification (TAP)				
Ammonia (NH ₃)	79.4	5.9	70.8	85.2
Nitrogen Oxide (NO)	15.5	6.1	10.2	25.1
Sulfur Dioxide (SO ₂)	2.9	2.4	1.3	7.7
Marine eutrophication (MEP)				
Nitrate (NO ₃)	99.2	0.6	98.6	100.0
Land use (LOP)				
Occupation pasture extensive	96.1	3.7	89.4	100.0
Occupation annual crop	3.3	3.7	0.0	10.0
Fossil resource scarcity (FFP)				
Oil Crude	68.1	9.2	52.0	76.3
Gas Natural	20.3	7.6	12.8	33.4
Coal Hard	10.2	1.6	8.0	12.6
Coal Brow	1.1	0.6	0.0	2.0
Mineral resource scarcity (SOP)				
Potash salt crude (K ₂ O)	55.1	31.4	0.0	80.0
Iron (Fe)	12.9	16.5	7.8	50.0
Nikel (Ni)	9.2	6.8	3.8	20.4
Fine particulate matter formation (PMFP)				
Ammonia (NH ₃)	50.7	9.9	36.1	62.9
Nitrogen oxide (NO)	24.0	5.6	16.9	32.2
Particulate < 2,5	18.6	5.7	11.4	26.9

Cut – off 1 %; SD = Standard Deviation.

4.3. Sensitive analysis and woodland conservation

Our study considers the conservation of forest areas within the Podolian system. It evaluates and estimates the amount of m^2 required to achieve carbon neutrality in producing one kilo of beef. By incorporating forest conservation into our analysis, we provide a more comprehensive assessment of the environmental impact and sustainability of Podolian beef production. This approach highlights the role of forested areas in offsetting carbon emissions and emphasises the importance of integrated land-use strategies in achieving carbon neutrality. Forests are crucial for planetary ecology, playing a key role in climate regulation and offering various essential ecosystem services within their local environments (Bernués et al., 2014). Additionally, forests are integral to the livelihoods of millions of people globally. They contribute approximately 0.6 % to global food consumption and supply valuable resources, including timber and a range of non-timber forest products (FAO, 2014). Agroforestry is often cited as an effective strategy for adapting to and mitigating climate change and addressing food security. Evidence shows that agroforestry systems yield positive biophysical and socioeconomic outcomes in smallholder and large-scale mechanised production contexts (Quandt et al., 2017). These systems can also help mitigate climate risks. However, agroforestry systems are not immune to the impacts of climate change, which may diminish their benefits. Despite this, there is limited empirical evidence on the specific effects of climate change on agroforestry, and modelling these impacts is generally more complex than single cropping systems (Luedeling et al., 2014). Our study highlights that the Podolian system requires, on average, 30.9 ± 14.1 ha of forest. That translates to 16.7 ± 4.9 square meters of forest per kilogram of LW and 30.8 ± 9.0 square meters per kilogram of CW (mean \pm SD, see Table 6). A recent study conducted in the UK observed that achieving carbon neutrality for producing one kilogram of CW would require between 10.5 and 35.5 square meters of forest per year, with some scenarios demanding up to 231.7 square meters per year per kilogram of CW (McNicol et al., 2024). This approach, however, assumes that part of the land within agricultural farms would be converted into forest. In contrast, our case study scenario involves preserving and managing existing natural forests within the Podolian system to achieve carbon neutrality for producing 1 kg of beef (LW and CW). This distinction underscores the inherent advantage of utilising naturally occurring forests in sustainable beef production systems, as it avoids the need for land conversion and instead relies on the careful stewardship of existing natural resources. Forest management must be precise and tailored to the specific geographic area and the types of vegetation present. This type of activity cannot disregard the economic aspect of its management, as maintaining the forest means renouncing income from the timber sale. Indeed, there is a trade-off between environmental and economic goals, and policymakers should

Table 6
Means \pm SD of mitigation scenario as a function of woodland conservation.

Mitigation Scenarios	Hectares of Woodland	m^2 per kg of LW	m^2 per kg of CW	kg CO ₂ eq kg LW ⁻¹	kg CO ₂ eq kg CW ⁻¹
Impact reduction of 100 %*	30.9 ± 14.1	16.7 ± 4.9	30.8 ± 9.0	0	0
Impact reduction of 50 %	15.4 ± 7.1	8.4 ± 2.4	15.4 ± 4.5	6.1 ± 1.8	11.3 ± 3.3
Impact reduction of 30 %	9.3 ± 4.2	5.0 ± 1.5	9.2 ± 2.7	8.6 ± 2.5	15.8 ± 4.6
Impact reduction of 15 %	4.6 ± 2.1	2.5 ± 0.7	4.6 ± 1.3	10.4 ± 3.0	19.2 ± 5.6

LW = Live weight; CW = Carcass weight. * Zero Net Carbon Neutrality for Podolian System.

consider it when defining interventions to keep a vital socio-economic fabric in marginal areas. That means analysing the environmental performance of activities carried out by farmers within the agroforestry system from an economic perspective as well. In this context, the presence of large ruminants, such as the Podolian cattle, within forested areas plays a crucial role in maintaining forest health. These cattle help prevent potential wildfires through grazing activities and controlling the underbrush, reducing the fuel load for fires. Additionally, the presence of human shepherds and caretakers contributes to preserving the forest as they engage in active management and oversight of the land. This combined approach of using livestock for ecological management and maintaining human stewardship is essential for sustaining the health and stability of forest ecosystems. Several studies have highlighted that enhancing the carbon sequestration capacity of forests requires nutrients such as nitrogen (N), which is naturally fixed in the soil by legumes. Gundersen et al. (2021) have observed that optimal carbon storage in forests requires an input of 47 kg of N per hectare per year. In marginal and rugged areas, this nutrient requirement can be met through the deposition and dispersion of manure by Podolian cattle in the forested area. The manure of these cattle is a natural source of nitrogen, contributing to the forest ecosystem's nutrient cycling and overall health. Thus, integrating Podolian cattle into forest management not only aids in maintaining the forest but also supports its ability to sequester carbon effectively. The availability of macro and micro-nutrients from the soil to plant roots is also a function of the microbial populations active in the topsoil (Moreno-Galván et al., 2023). Studies have observed that spreading slurry and cattle manure on agricultural soils increases the microbial and fungal biomass present (D'Hose et al., 2016), which enhances nutrient availability for plants and, by extension, for trees. Recently, consumer attention to environmental issues has been growing (Li, 2025). However, one of the phenomena of greatest concern in the agricultural and forestry sectors is greenwashing, a misleading practice where industrial sectors unrelated to forestry or agricultural systems attempt to adopt green methods superficially, often undermining primary and food production (Dreist et al., 2025; Santos et al., 2024). This practice must be distinguished from production systems, such as meat production, where woodlands are directly integrated into the system and actively contribute to offsetting the direct and indirect CO₂-equivalent emissions.

4.4. Limitations and conclusions

The approach we have observed presents limitations in the context of the currently uncertain estimation of SOC. While existing scientific evidence demonstrates a tangible effect, current methods exhibit significant levels of uncertainty. This limitation cannot be overlooked; however, it is also necessary to consider the fundamental role of agriculture, particularly in marginal land areas, in strategies aimed at mitigating environmental impacts overall, and specifically within the context of primary production. Our study indicates that in marginal contexts, the environmental impact is generally higher than that of intensive livestock farming systems for beef production per kilogram. However, by delving deeper into the specific context and case study and incorporating the calculation of carbon sequestration from pastures used in this farming system, it is possible to achieve environmental performance comparable to the most efficient intensive systems. Specifically, we have shown that an existing mitigation strategy within the Podolian system uses wooded area resources, which need to be managed and preserved. This approach enables the potential to achieve carbon neutrality in Podolian beef production in the marginal areas of the Basilicata region, both now and in the foreseeable future. This provides more explicit guidance to policymakers and consumers regarding different beef production practices, allowing for more informed planning of future regional, national, and European resources. Further research is needed to better identify and manage various systems within the framework of agroforestry, ensuring effective integration and

sustainability.

CRedit authorship contribution statement

Emilio Sabia: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Corrado Pacelli:** Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Investigation, Data curation, Conceptualization. **Adriana Di Trana:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Investigation, Conceptualization. **Adele Coppola:** Writing – review & editing, Visualization, Supervision, Conceptualization. **Carlo Cosentino:** Writing – review & editing, Visualization. **Pierangelo Freschi:** Writing – original draft, Visualization. **Rosanna Paolino:** Writing – review & editing, Visualization. **Ada Braghieri:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Funding acquisition, Conceptualization.

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Declaration of competing interest

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

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Appendix A. Supplementary data

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Data availability

Data will be made available on request.

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