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Research article

Greenhouse gas emissions of an autochthonous Greek cattle breed under extensive mountain grazing: farm, meat, and product-level insights

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Abstract: Global demand for animal-derived foods, particularly beef, continues to rise, intensifying greenhouse gas (GHG) emissions and accelerating climate change. Robust carbon footprint assessments at system and product levels are therefore critical, especially in organic and extensive livestock systems that simultaneously contribute to biodiversity conservation. In this study, we quantified GHG emissions from an organic, extensive Brachycheros cattle farm and its associated beef products using a Tier 2 life cycle assessment (LCA) and a cradle-to-gate boundary. Total farm-level emissions were estimated at 325,821 kg CO_2-eq, with enteric methane representing the predominant source. Beef emissions' intensity reached 98.29 kg CO_2-eq per kilogram of produced meat, reflecting the lower carcass yields of locally adapted breeds under extensive systems. Product-level emissions were calculated at 20.19 kg CO_2-eq and 24.80 kg CO_2-eq when applying literature-based and study-specific beef intensity values, respectively. Overall, the findings underscored the strong influence of production system characteristics and indigenous breed performance on carbon footprints, highlighting the importance of farm-specific GHG assessments in traditional livestock systems.

Keywords: carbon footprint; life cycle analysis; indigenous breeds; Greek Brachycheros breed; GHG emissions; meat products

1. Introduction

Global population growth is projected to reach 33% by 2050, driving an estimated 70% increase in demand for agricultural and livestock products [1]. Livestock farming supports the livelihoods of more than 1.3 billion people and contributes approximately 40% of global agricultural GDP [2,3]. As a result, the livestock sector plays a pivotal role in meeting future food needs, particularly considering the sustained global demand for animal-derived foods. At present, livestock products supply 13–17% of global calorie intake and 28–33% of global protein consumption [1,4].

Despite its importance, the livestock sector is also a major contributor to greenhouse gas (GHG) emissions, accounting for an estimated 14.5% of global emissions [1], with reported ranges between 9% and 25% [4]. Emissions mostly originate from enteric fermentation, feed production, manure management, transportation of feed and animals, and processing activities [1,5]. Cattle production is responsible for approximately 62% of total livestock-related emissions [6]. Within the sector, beef production contributes 41% of emissions, followed by cow's milk (20%), buffalo's meat and milk (9%), small ruminants (6.5%), swine (9%), and poultry (8%) [7].

While global debates often focus on high-input, high-emission production systems, extensive and traditional systems play a critical role in conserving livestock biodiversity and maintaining genetic resources. These systems frequently rely on indigenous breeds that are well adapted to harsh environments, low-input diets, and climatic variability, which are traits increasingly valuable under climate change. Yet, despite their ecological and cultural importance, local breeds remain underrepresented in GHG research, with most emission estimates derived from high-productivity commercial breeds and intensive systems. This scarce information limits the ability to accurately assess the environmental impact of traditional systems and undervalues the role of indigenous genetic resources.

Beef production remains economically significant worldwide. Although the European Union ranks fourth in global beef production [8], following China, Brazil, and the United States, the Greek beef sector remains underdeveloped, achieving only 20–25% self-sufficiency [9]. Two major husbandry systems dominate: (i) Intensive calf-fattening operations using meat-type or crossbred animals, and (ii) reproduction–beef systems managed under (semi-) extensive conditions, where autochthonous breeds or their crosses are commonly used [9]. Greece hosts eleven (11) recognized indigenous cattle breeds [10], with the Brachycheros breed being the most numerous. These breeds contribute to landscape management, rural livelihoods, and agrobiodiversity, yet their environmental performance remains undocumented. Researchers overwhelmingly focus on high-productivity commercial breeds or mixed systems, resulting in an underrepresentation of traditional, low-input production systems. To date, scarce information exists for GHG emissions of the beef sector at the national level [9], and no researcher has assessed emissions from individual farms rearing indigenous breeds or examined the additional contribution of product processing. Accordingly, despite the presence of eleven recognized autochthonous cattle breeds, no researcher has quantified the carbon footprint of value-added meat products derived from these breeds. This absence of empirical data limits the ability to evaluate the environmental role of traditional livestock systems and undervalues the contribution of local genetic resources to sustainable food production. This knowledge gap is particularly important because emission intensities in extensive systems are strongly influenced by breed traits, including productivity, local resource use, and factors that differ substantially from those of commercial breeds.

In this study, we address this critical gap by quantifying GHG emissions from an organic, extensive Brachycheros cattle farm in a mountainous region of Greece as well as its associated meat products. Emissions are estimated at farm and product levels using a Tier 2 methodology and a cradle-to-gate approach, and results are compared with those from other production systems. We anticipate that farm-level emissions will exceed those of intensive systems and semi-extensive farms rearing non-indigenous breeds, while product-level emissions are expected to align with values reported for similar organic beef products. Thus, this study highlights the importance of farm-specific GHG assessments for indigenous breeds, which can support biodiversity conservation, inform sustainable livestock strategies, and enhance the value of traditional animal products.

2. Materials and methods

2.1. Area of study

The study was conducted on a farm in the mountainous region of Karditsa Prefecture, in the municipality of Argithea and the regional unit of Eastern Argithea (latitude 39.296; longitude 21.458). The livestock facilities covered 1,430 m^2, within a total fenced enclosure of 5,940 m^2. The farm is at an altitude of 1,060 m on the eastern slope of Mount Simeniko (Asimi) in southern Pindos Mountain. Consequently, the area can be characterized as mountainous, with rich flora consisting of fir trees, cedars, holm oaks, species of oak and maples.

The climatic conditions in Argithea are typical of a warm, temperate environment, with winters receiving more rainfall than summers. According to the Köppen–Geiger classification, the region falls within the Csb climate category. The mean annual temperature is 10.7°C (51.3°F), and yearly precipitation reaches approximately 1,144 mm (45.0 in). July is the warmest month, with an average temperature of 21.1°C (70.0°F), whereas January is the coldest, averaging 0.9°C (33.6°F). Precipitation varies considerably throughout the year, with a difference of about 125 mm (5 in) between the driest and wettest months. Annual temperature variation reaches 20.2°C (36.4°F). Relative humidity peaks in January (81.79%) and is lowest in August (55.13%). December is the wettest month (14.43 days of rainfall), while August is the driest (5.97 days of rainfall) [11].

2.2. Farm characteristics and data collection

This study was conducted during May to October 2025, with data collection referring to the previous productive year, defined as January to December 2024. According to the farmer and farm records, there were no changes in herd size or management practices during the preceding five consecutive years (2019–2024), enabling, therefore, the reference year to represent a stable production period.

Primary data used for estimating productive indices and greenhouse gas (GHG) emissions were obtained through an on-site field visit and an interview with the farmer based on a structured questionnaire. The interview focused on key indicators related to farm characteristics and management practices, including farm size and infrastructure, animal numbers by category, reproduction, and animal management strategies, feeding practices, and manure handling systems. The animals' number and the respective animal categories are presented in Table 1.

Table 1. Animal categories and respective number and average weight of animals.

Category	Number	Average live weight (kg)
Adult males	82	320
Adult females	75	220
Male calves for fattening	41	80
Female calves (>1 year old)	15	80
Replacement animals	23	180
Total	236	-

According to the farmer's records, 34 adult male animals were slaughtered during the study period, each yielding an average carcass weight of 97.5 kg. Total beef production for the examined period was therefore 3,315 kg (= 97.5 kg × 34).

The farm operates as a meat-producing unit under an extensive management system, where animals graze freely on local vegetation, primarily tree leaves and natural grass, across 10,000 acres of mountainous rangeland. During periods of harsh winter weather (up to three months), the farmer provides a limited amount of organically produced supplementary feed, consisting of alfalfa hay (21.8%), oat hay (27.3%), wheat hay (19.1%), grass (27.3%), and corn (4.5%). The farm is certified as organic, and consequently, all meat produced is also certified as organic.

Manure management practices reflect the extensive nature of the system. During snowy periods, manure is handled through solid storage, whereas for the remainder of the year, manure is directly deposited and naturally dispersed on pastures, contributing to the grazing ecosystem.

In line with the farmer's processing practices, part of the meat produced is used to produce value-added products, amongst them an organic beef burger. The burgers are sold in 320 g packages, each containing two 160 g patties. The product contains beef, water, seasoning, and olive extract as a natural preservative, with no synthetic additives or preservatives included.

2.3. Assessment of GHG emissions and carbon footprint

The system boundary included all on-farm processes related to animal production, feed provision, manure management, and energy use, while excluding capital goods such as buildings, machinery, and infrastructure due to lack of detailed data and their relatively minor contribution to annual emissions in extensive systems. For the product-level assessment, all ingredients, packaging materials, and processing steps were included.

2.3.1. Farm level

The latest version of the Global Livestock Environmental Assessment Model (GLEAM-i v3.0) [12] was used to estimate farm-level greenhouse gas emissions. GLEAM-i is a free web-based tool developed by the Food and Agriculture Organization of the United Nations (FAO) to quantify emissions from livestock systems and applies a Tier 2 methodology within a Life Cycle Assessment framework [12]. The model requires detailed data on animal type, production system, and production focus, as well as information on diet composition, manure management, herd size, animal productivity, and live weight. Energy and fuel consumption associated with farm operations are also incorporated into calculations based on the territory average values [12]. GLEAM-i comprises three integrated modules, which are herd, feed, and manure management. The herd module classifies animals into cohorts according to species, weight, production stage, and feeding situation. The feed module estimates feed intake for each cohort based on the nutritional characteristics of the ration and the animals' energy requirements, while the manure management module calculates emissions associated with the selected manure handling system [12]. GLEAM-i applies the 100-year global warming potential (GWP-100) values for non-CO_2 gases as specified in the Intergovernmental Panel on Climate Change's Sixth Assessment Report (AR6), thus CO_2 retains a GWP-100 of 1, fossil CH_4 29.8, biogenic CH_4 27.0, and N_2O 273 [12]. All parameters entered to GLEAM-i for this study are summarized in Table 2.

2.3.2. Meat Carbon Footprint (CF)

Based on the estimated farm-level emissions, the carbon footprint of meat was calculated by incorporating the number of slaughtered animals and the total quantity of meat produced (kg) during the study period, using following equation.

$$Emissions\ per\ kg\ of\ produced\ meat = \frac{Total\ farm\ emissions}{kg\ produced\ meat/year} \tag{1}$$

Table 2. Indices and parameters used in the Gleam-i software.

Index	Unit	Data
Number of animals (adult males)	-	82
Number of animals (adult females)	-	75
Weight at birth	kg	15
Live weight (adult males)	kg	320
Live weight (adult females)	kg	220
Live weight of animal at slaughter (Meat Males)	kg	320
Age at the first parturition	months	20
Replacement rate of adult females	%	31
Fertility rate (adult female)	%	86
Death rate of young females	%	3
Death rate of young males	%	3
Death rate of adult animals	%	1
Practice	Selected Option	
Manure management	Solid storage (25%); Pasture/Range/Paddock (75%)	
Grazing	Fresh grass, natural pasture (64%)	
Feed	Grass as hay or silage cultivated (34%); Grains from maize (2%)	

2.4. Product carbon footprint

The GHG emissions associated with the final processed product (packaged burger) were calculated by incorporating the emissions related to burger production, including those arising from the ingredients used, the energy required for the manufacturing process, and the materials involved in packaging. Each product package contained two burger patties weighing 160 g each, for a total of 320 g.

The burgers were packed using a two-part system consisting of a vacuum-sealed plastic pouch and an outer carton box. After production, the patties underwent flash freezing at −18°C, and the two patties were placed into the vacuum pouch and sealed. The sealed pouch was then inserted into the carton box, which was closed using its top flaps. The fully packaged product was subsequently returned to the freezer, where it remained stored until distribution. Emissions from transportation to processing and distribution were excluded because these stages are highly variable and not recorded with sufficient precision, making their inclusion unreliable for further estimation.

2.4.1. Burger carbon footprint

To estimate the total carbon footprint of the product, the emissions associated with each individual component were calculated separately and subsequently summed to obtain the final value per package [13]. Ingredient-level emissions were derived using the equation:

$$\text{Ingredient emissions (kg CO2-eq)} = \text{Quantity of ingredient (kg)} \times \text{GHG emissions of each ingredient (kg CO2-eq /kg)} \tag{2}$$

The composition of the 320 g burger is presented in Table 3. Greenhouse gas emission factors for each ingredient were obtained from the literature [14,15] and are summarized in Table 3.

Table 3. Composition of the burgers (320g) and respective GHG emissions of ingredients based on the literature.

Ingredient	Quantity (kg)	GHGs emission intensities (kg CO2-eq/kg)
Beef	0.25177	80
Water	0.03777	0.0004
Seasoning	0.02021	1.3
Olive extract	0.000252	6

To this analysis, and in addition to using literature-based emission factors for beef (Table 3), product-level emissions were calculated using the beef emission intensity derived directly from the farm-level estimates obtained through Eq (1), enabling a comparison between literature-based and farm-specific values.

2.4.2. Product packaging GHG emissions

Packaging consisted of two components: A vacuum-sealed plastic pouch containing the product and an outer carton box with a thin plastic coating. The total packaging-related emissions were calculated by summing the emissions associated with the vacuum pouch and the carton box [16]. All data related to packaging and used in the calculations were provided directly by the respective manufacturers, as detailed below.

2.4.2.1. Vacuum-sealed bag GHG emissions

The vacuum-sealed bag had a surface density of 67 g/m² (0.067 kg/m²), a thickness of 70 μm, and dimensions of 15 × 27 cm, and was recyclable. It consisted of three material layers commonly used in food packaging: An outer polyethylene (PE) layer, a modified-polyethylene binding layer (Tie), and an inner polyamide (PA) layer. The composition of the bag was 75% PE, 5% Tie, and 20% PA [17]. The assessment of GHG emissions did not include energy use associated with production, transportation, or end-of-life treatment, as such data were not available. GHG emission factors (kg CO_2-eq/kg) for the materials were 1.79 for PE, 1.87 for Tie, and 6.4 for PA [18,19]. Total emissions from the vacuum bag were calculated using the equation:

$$\text{Material emissions (kg CO2-eq)} = \text{Percentage in bag composition (\%)} \times \text{Bag weight (kg)} \times \text{material GHG emissions (kg CO2-eq /kg)} \quad (3) \tag{3}$$

To express emissions per bag, the total surface area was first determined. The bag was two-sided, with each side measuring 15 × 27 cm, resulting in a total surface area of 810 cm^2, equivalent to 0.081 m^2.

2.4.2.2. Carton box GHG emissions

The recyclable carton box had external dimensions of 14 × 14 × 3.5 cm, weighed 30 g, and was laminated to enhance durability and moisture resistance. Its structure included two major panels (14 × 14 cm), four side walls (14 × 3.5 cm), and two top flaps that secured the closure of the packaging. The carbon footprint of the carton box was calculated following the Greenhouse Gas Protocol [13] using the following equation:

$$\text{Carton box emissions (kg } CO_2\text{-eq)} = \text{Box weight (kg)} \times \text{carton GHG emissions (kg } CO_2\text{-eq /kg)} \tag{4}$$

The GHG emissions applied for this type of carton packaging was 0.249 kg CO_2-eq per kilogram of material [20].

2.5. Sensitivity Analysis

To evaluate the robustness of the estimated greenhouse gas emissions and to assess the influence of key parameters on the final results, a sensitivity analysis was conducted on three variables known to substantially affect emission intensities in extensive beef systems: carcass weight, enteric methane emission, and replacement rate of adult females. Each parameter was varied by ±10% relative to the baseline values used in GLEAM-i, while all other inputs were held constant. The resulting changes in total farm emissions and emission intensity per kilogram of carcass meat were calculated to determine the sensitivity of the system to biological and management variability.

3. Results

3.1. Farm GHG emissions

The total farm-level emissions were estimated at 325,821 kg CO_2-eq. The relative contribution of each greenhouse gas (CH_4, CO_2 and N_2O) is illustrated in Figure 1a. Methane (CH_4) was the dominant source, accounting for 75% of total emissions, followed by nitrous oxide (N_2O) at 17.90% and carbon dioxide (CO_2) at 7.10%.

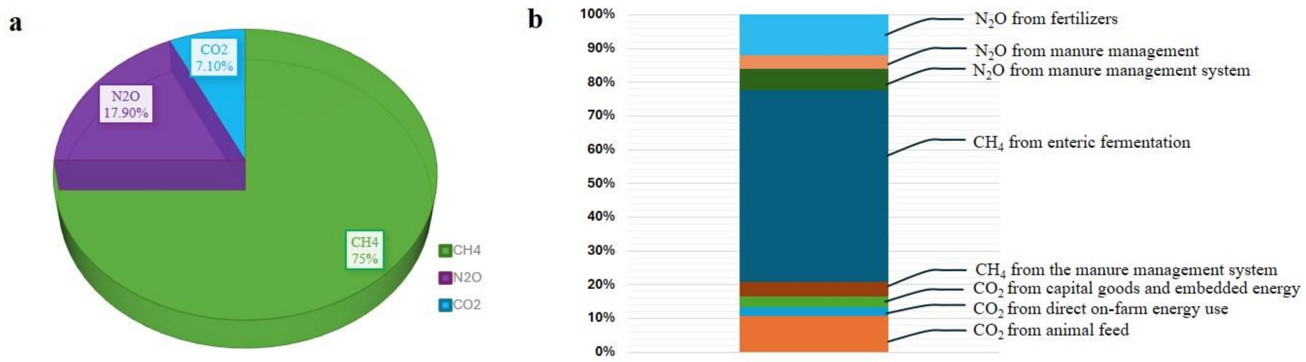

Figure 1. Contributions of greenhouse gas (GHG) emissions from livestock production related to the farm level. (a) Proportional distribution of methane (CH_4), nitrous oxide (N_2O), and carbon dioxide (CO_2) to total emissions, highlighting CH_4 as the dominant source. (b) Breakdown of emission sources (%) across the production system.

Figure 1b illustrates the distribution of GHG emissions across the farm sources. Methane (CH_4) from enteric fermentation represented the largest share, accounting for 56.7% of total emissions. This was followed by nitrous oxide (N_2O) from fertilizer residues, contributing approximately 12%, and carbon dioxide (CO_2) associated with feed production, which accounted for 10.7%. Emissions from manure management systems, nitrous oxide (N_2O) and methane (CH_4), together contributed 12% of total GHGs. Energy use on and off the farm (CO_2) represented 10% of emissions, while the nitrous oxide (N_2O) included in the aggregated manure management category contributed an additional 4%.

3.2. *Meat GHG intensities*

Based on the total carcass production (kg) and the estimated farm-level emissions, the emission intensity of produced meat by the farm was calculated at 98.29 kg CO_2-eq per kilogram of carcass meat. Accordingly, the corresponding burger (raw meat of 251.77 g) emissions estimated by equation 2 were 24.75 CO_2-eq.

3.3. *Burger carbon footprint*

The estimated emissions associated with each ingredient of the burger were calculated using the estimated beef emission intensity derived from the examined farm and average beef emissions from the literature. Using the literature-based emission intensities of each ingredient of the burger (section 2.4.1, Table 3), beef contributed 20.14 kg CO_2-eq, water 0.000015 kg CO_2-eq, seasoning 0.026 kg CO_2-eq, and olive extract 0.0015 kg CO_2-eq. Summing the emissions of all ingredients resulted in a total product footprint (CF_L) of 20.17 kg CO_2-eq per 320 g package. The burger's GHG emissions were also calculated using the beef emission intensity derived from the examined farm (section 3.2), resulting in a total product footprint (CF_T) of 24.78 kg CO_2.

3.4. *Carbon footprint of packaging.*

3.4.1. Vacuum-sealed bag and carton box

The GHG emissions associated with the vacuum-sealed bag were calculated as part of the overall packaging footprint. Emissions per square meter were estimated at 0.089 kg CO_2-eq/m^2 for PE, 0.0062 kg CO_2-eq/m^2 for Tie, and 0.085 kg CO_2-eq/m^2 for PA. Summing the contributions of all materials resulted in a total emission value of 0.18 kg CO_2-eq/m^2 for the vacuum bag. When expressed in accordance with the total surface area used for the packaging (0.081 m^2, section 2.4.2.1), the respective emissions were 0.0072 kg CO_2-eq for PE, 0.0005 kg CO_2-eq for Tie, and 0.0069 kg CO_2-eq for PA, while total emissions of the vacuum-sealed bag amounted to 0.01458 kg CO_2-eq. Regarding carton box, its total GHG emissions were estimated at 0.0075 kg CO_2-eq.

3.4.2. Total emission intensities of packaged product

Table 4 presents the total GHG emissions of the packaged product, which were calculated using literature-based beef emission intensities and farm-specific beef emission intensities derived from the targeted farm. The former approach resulted in a carbon footprint ($CF_{P\text{-}L}$) of 20.19 kg CO2-eq per packaged product, while the latter approach resulted in a carbon footprint ($CF_{P\text{-}L}$) 24.80 kg CO2-eq per packaged product.

Table 4. Summary of the carbon footprint (kg CO_2-eq / packaged product) for the packaged product based on literature beef emissions ($CF_{P\text{-}L}$) and on beef emissions estimated on the targeted farm ($CF_{P\text{-}T}$).

Packaged product	$CF_{P\text{-}L}$	$CF_{P\text{-}T}$
Vacuum bag	0.01458	0.01458
Carton box	0.0075	0.0075
Burger	20.17	24.78
Total	20.19	24.80

3.5. *Sensitivity results for GHG emissions*

According to the sensitivity analysis results, increasing the carcass weight by 10% reduced emission intensity from 98.29 CO_2-eq/kg to 89.36 kg CO_2-eq/kg, whereas a 10% reduction in carcass weight increased intensity to 109.21 kg CO_2-eq/kg. Total farm emissions remained unchanged, confirming that productivity was the dominant driver of per-unit emissions. Enteric methane accounted for 56.7% of total emissions; therefore, modifying the methane emission factor had a substantial effect. A 10% increase in enteric methane emissions raised total farm emissions from 325,821 to 351,015 kg CO_2-eq, increasing emission intensity to 105.86 kg CO_2-eq/kg. Conversely, a 10% reduction lowered total emissions to 300,627 kg CO_2-eq and reduced emission intensity to 92.72 kg CO_2-eq/kg. Moreover, increasing the replacement rate from 31% to 34.1% increased total emissions by approximately 3.2%, raising emission intensity to 101.43 kg CO_2-eq/kg. A 10% reduction (27.9%) decreased total emissions by 3.0%, lowering emission intensity to 95.42 kg CO_2-eq/kg.

4. Discussion

In this study, we estimated the annual GHG emissions of an extensive cattle farm rearing an autochthonous Greek breed (Brachycheros). Additional emission intensities were produced for beef meat (per produced kg) and for a processed burger product (per package) derived from the same farm. While most researchers focus on high-productivity commercial breeds or mixed systems, we address a critical gap by quantifying emissions from a low-input, heritage breed that is central to regional biodiversity and cultural heritage but absent from global emission inventories.

Total farm emissions were calculated at 325,821 kg CO_2-eq/year, with methane as the dominant contributor, primarily from enteric fermentation. Nitrous oxide emissions were approximately three times lower, while carbon dioxide contributed the least. The results confirmed that methane emissions are the main contributor to the total farm emissions, as expected. This distribution aligns with findings from comparable studies across production systems (Figure 2a). Ogino et al. [21] reported that enteric fermentation accounts for the largest share of emissions (48%), followed by feed production (27%), transport (14%), and manure management (8%). Similarly, an eight-year Canadian study assessing different grazing scenarios revealed that heavy continuous grazing results in 813,175 Mg CO_2-eq/year [22], which is substantially higher than the emissions estimated in this study. Another long-term Canadian assessment using the same herd structure (120 cows, four bulls, and progeny) reported annual emissions of 859,40 kg CO_2-eq/year (in average), more than double the emissions estimated here [23]. Extensive hill-country systems have commonly been reported to fall between 400,000–900,000 kg CO_2-eq/year depending on herd size and productivity [24], while grass-based UK beef farms often exceed 500,000 kg CO_2-eq/year, especially low-productivity systems [25].

Differences in reported GHG emissions across studies can be attributed to a combination of herd size, slaughter weights, vegetation type, and, critically, the system boundaries applied in each assessment. Variations in animal numbers, feeding regimes, and productivity levels further influence total and per-unit emissions, leading to substantial divergence between extensive, mixed, and intensive systems. As highlighted by Poore and Nemecek [15], methodological choices, particularly boundary definitions and allocation methods, can significantly alter emission outcomes. Large comparative LCAs also demonstrate that breed productivity, growth rates, and diet composition are major determinants of emission intensity [21,23,26]. Similarly, long-term grazing studies show that stocking density, pasture quality, and regional ecological conditions shape methane and nitrous oxide emissions [22,25]. Collectively, these factors explain why emission estimates differ across countries and production systems, even when similar methodological frameworks are used.

The emission intensity of beef in this study was estimated at 98.29 kg CO_2-eq/kg carcass weight, substantially exceeding national estimates for Greece (6.45–21.79 kg CO_2-eq/kg) [9] and values reported in other countries (Figure 2b) like Japan (maximum 32 kg CO_2-eq/kg) [6], Ireland (28–32 kg CO_2-eq/kg) [26], New Zealand (21–27 kg CO_2-eq/kg) [27], Australia (19–25 kg CO_2-eq/kg for grass-fed and 12–16 CO_2-eq/kg for feed lot) [28], Brazil (27–40 kg CO_2-eq/kg) [29,30], United Kingdom (22–30 kg CO_2-eq/kg) [31], and South Africa (27–34 kg CO_2-eq/kg for extensive grazing) [32]. The lower emission intensities are typically reported for intensive production systems, where higher carcass yields reduce total GHG emissions per kilogram of product.

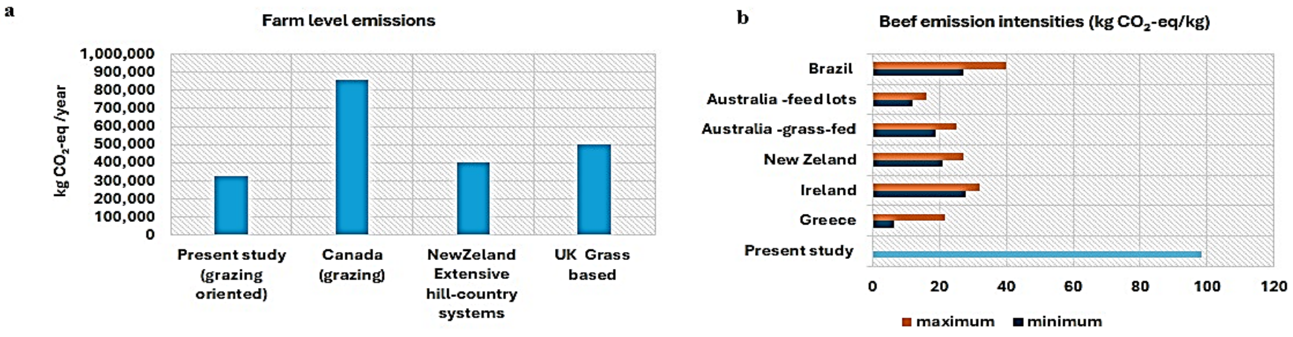

Figure 2. Comparison of beef-production GHG outcomes across systems and countries. (a) Total farm-level emissions (kg CO_2-eq/year) for this study and grazing-based systems [22,23,24,25]. (b) Emission intensities (kg CO_2-eq/kg carcass) across global beef systems [9,26,27,29,30], showing minimum–maximum ranges and the value from this study (light blue bar).

Extensive grazing systems typically show higher emissions per kilogram of meat because animals grow more slowly, remain on the farm longer, and consume high-fiber forage that increases enteric methane production [22,25]. In contrast, intensive or feedlot systems achieve lower intensities due to higher feed efficiency, shorter finishing periods, and greater carcass yields [28,33]. In our case, the high estimated emission intensities were expected given the extensive system and the use of an autochthonous breed with lower productivity. Greek local breeds produce on average 224 kg carcass weight, compared to commercial breeds that produce greater than 400 kg carcass weight [34]. Lower productivity increases emission intensity, as is widely recognized [9]. U.S. findings further support that grazing-based systems exhibit higher emissions due to slower growth rates, lower-energy diets, and reduced carbon sequestration potential [35,36]. Furthermore, methodological choices, such as whether land-use change is considered, manure management, or upstream feed production are included etc., strongly influence reported values, often explaining cross-country discrepancies [15]. Regional factors such as pasture quality, climate, and breed type as well as the reliance on high-fiber forage typical of mountainous rangelands further shape emission outcomes, with beef farming systems showing higher methane yields per unit of feed [29].

The processed burger produced from the farm's meat exhibited emissions of 20.19 kg CO_2-eq per 320 g packaged burger (literature-based beef intensity-$CF_{P\text{-}L}$) and 24.80 kg CO_2-eq per packaged burger (farm-specific intensities-$CF_{P\text{-}T}$). The discrepancy between the literature-based estimate ($CF_{P\text{-}L}$) and the target-farm estimate ($CF_{P\text{-}T}$) arises because $CF_{P\text{-}L}$ relies on average emission intensities derived from broader, often more efficient production systems, whereas $CF_{P\text{-}T}$ reflects the actual performance, productivity, and management conditions of the specific farm. As a result, the farm-specific calculation incorporates the farm's own emission profile and production efficiency, leading to a higher carbon footprint per packaged burger compared with the literature-based approach. Normalized to 100 g of product, the resulting footprint ($CF_{P\text{-}L}$) of 6.30 kg CO_2-eq/100 g aligns with values reported in other studies. For example, UK assessments reported 4.5–6.6 kg CO_2-eq per 113 g for burgers made from Irish and Brazilian beef [37], while Dominguez-Lacueva et al. [38] estimated 2.09 kg CO_2-eq per 150 g for a beef burger under different system boundaries. A UK cradle-to-fork study similarly reported 6.67 kg CO_2-eq/100 g [39], and comparable studies in Australia and Canada have reported 5.0–7.5 kg CO_2-eq/100 g depending on feedlot versus pasture finishing [23,28]. Importantly, systems relying on local or indigenous breeds, such as Criollo cattle in Latin America, Nguni cattle in South Africa, or certain Iberian breeds, tend to exhibit higher emission intensities due to slower growth rates, lower carcass yields, and forage-based diets, despite offering resilience and biodiversity benefits [32,40]. These patterns mirror the performance of the Greek Brachycheros breed, where long finishing periods and low productivity elevate product-level emissions even when total farm emissions remain moderate. As highlighted by Poore and Nemecek [15], such variability across studies reflects differences in system boundaries, breed characteristics, feeding regimes, and regional production practices, underscoring the need to interpret product footprints within their agro-ecological and genetic contexts.

The sensitivity analysis demonstrated that emission intensity in extensive beef systems based on local breeds is highly responsive to changes in parameters influencing productivity and enteric methane output (section 3.5; Figure 3). Therefore, GHG emission intensity in the studied beef system is highly dependent on productivity-related parameters, such as carcass weight and replacement rates, confirming that low growth rates and small carcass yields are central drivers of the high emission intensity observed in the Brachycheros breed. A 10% increase in carcass weight substantially reduced emission intensity, whereas a corresponding decrease led to markedly higher values, despite total farm emissions remaining constant. Enteric methane (representing 56.7% of total emissions) emerged as the dominant emission source, which is consistent with the high-fiber diets and long rearing periods characteristic of mountainous grazing systems. Additionally, modifying the methane emissions by ±10% produced the largest absolute shifts in total GHG output and correspondingly altered emission intensity by +7.7% and −5.7%, respectively. Variations in replacement rate produced smaller but meaningful changes, reflecting the importance of herd structure and reproductive efficiency. Overall, the analysis underscores that mitigation strategies in traditional systems should prioritize improvements in productivity, forage quality, and reproductive management while recognizing the biological constraints inherent to indigenous breeds.

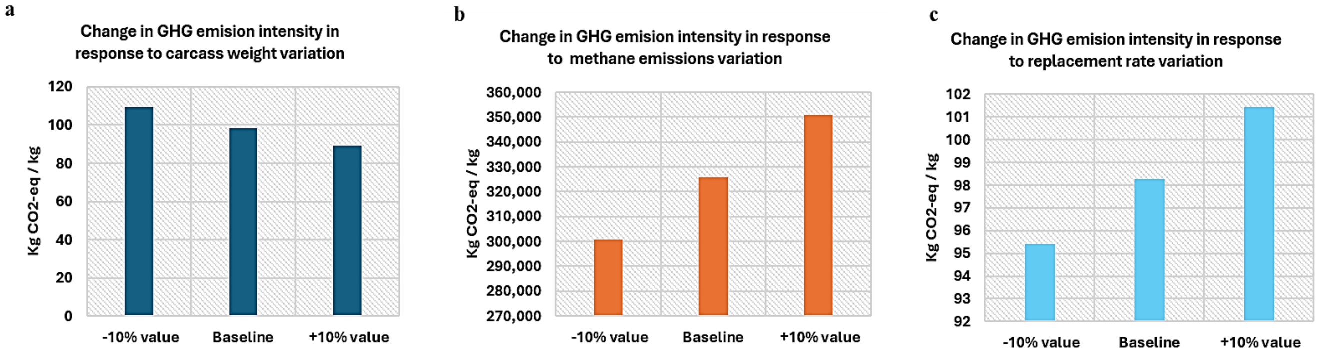

Figure 3. Sensitivity analysis results of GHG emissions (CO_2-eq/kg) under alternative production parameter scenarios (± 10% value variation from baseline scenario). (a) Change in emission intensity (kg CO_2-eq/kg carcass) in response to ±10% variation in produced carcass weight, illustrating important effect of productivity on per-unit emissions; (b) effect of modifying enteric methane emissions by ±10% on total farm GHG emissions, reflecting the significant contribution of enteric CH_4 to overall system emissions; and (c) influence of ±10% variation in replacement rate on emission intensity, reflecting the measurable impact of herd turnover on total emissions.

At the farm level, several mitigation strategies have been proposed for the extensive systems, though their applicability varies with landscape and management constraints. Adjusting grazing intensity and improving sward structure can lower emissions by enhancing forage quality and reducing enteric methane output [41]. However, such measures are difficult to implement in Greek rangelands, where steep topography, fragmented grazing areas, and heterogeneous vegetation limit the degree of sward control achievable in practice. Dietary improvements using high-quality organic forages can reduce methane production and increase productivity [42], though availability and cost may restrict adoption in low-input systems. More integrated approaches combining silvopastoral systems with optimized diets may reduce CH_4 and N_2O emissions up to 50% [43], offering a potentially feasible strategy for the studied farm. Macklin [25] highlighted the importance of maintaining productive swards through targeted reseeding, controlled grazing, and improved nutrient management, which can reduce methane and nitrous oxide emissions by preventing pasture degradation. CIEL [44] highlighted that achieving net-zero beef production will require, apart from improvements in feed efficiency and land management, also improvements in productivity (reduce the age of first calving and days to slaughter, optimize the calving interval etc.), and proper management of stored manure (additives to reduce emissions from stored manure, precise application of manure and fertilizer, etc.). Overall, the effectiveness of mitigation strategies at the farm level hinges on aligning technical options with the ecological, structural, and socio-economic realities of the production environment.

Broader mitigation frameworks emphasize the need for herd dynamics, farming systems, socio-economic constraints, and animal welfare [45,46]. Extensive systems offer greater flexibility for implementing mitigation measures without compromising welfare, unlike intensive systems where options are more constrained. Moreover, key strategies target emissions from enteric fermentation and manure management [47,48]. Feed interventions such as lipid supplementation can reduce methanogenesis, while manure management options include acidification, anaerobic digestion, biochar incorporation, and composting, with acidification and anaerobic digestion being the most effective [48,49]. In Greece, transitioning toward more intensive systems could reduce emissions up to 8% due to improved manure handling, and extending the fattening period may increase carcass weight and lower emission intensity [9]. Adaptation strategies remain essential, as extensive systems are particularly vulnerable to climate-related impacts. Finally, from a policy perspective, integrating locally adapted breed conservation into mitigation planning is critical, as indigenous breeds often display superior resilience to heat stress, low-quality forage, and climatic variability, thereby supporting system stability under future conditions [50,51]. Integrating genetic resources into national mitigation and adaptation strategies, such as agri-environmental payments and support for extensive grazing systems, can simultaneously safeguard genetic diversity and enhance the adaptive capacity of livestock systems within national climate strategies [51,52].

5. Conclusions

In this study, we provide one of the few detailed GHG assessments of an extensive cattle system using an autochthonous Greek breed, offering valuable empirical data for a production model missing from global inventories. The results show that methane from enteric fermentation dominates total farm emissions and that emission intensities per kilogram of meat are substantially higher than those reported for intensive or mixed systems, reflecting the lower productivity and grazing-based nature of mountainous extensive farming. The comparison between literature-based and farm-specific intensities underscores the need for regionally grounded data to support accurate national inventories and credible climate-labeling initiatives. The product-level assessment further demonstrates how farm-level realities translate into the footprint of a final packaged burger. Finally, we identify feasible mitigation options tailored to extensive systems, supporting the development of climate-smart strategies that respect environmental goals and the preservation of local breeds and rural landscapes. Recognizing the dual role of indigenous breeds in biodiversity preservation and sustainable food systems is essential for developing balanced climate policies in mountainous and marginal regions.

Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

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Conflict of interest

The authors declare no conflict of interest.

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