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Research article

Economic-environmental indices in beef production. Results in livestock models from Corrientes, Argentina

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Abstract: Consumer markets increasingly demand beef produced under environmentally sustainable conditions. In Argentina, cattle production on grasslands focuses on reducing greenhouse gas (GHG) emissions while achieving economic yields that support long-term sustainability and rural livelihoods. This study aimed to select productive alternatives with improved economic and environmental performance. The analysis was based on a traditional livestock model from the central-southern region of Corrientes, characterized by purebred cattle raised on natural grasslands. This baseline model was compared with four alternative models incorporating additional production phases (growing and fattening) and enhanced management practices (pasture improvement and strategic supplementation). Economic performance was assessed through gross margin analysis, while environmental performance was evaluated by estimating the carbon footprint using the Cool Farm Tool. Higher absolute carbon footprints were observed in full-cycle models (breeding, growing, and fattening). However, when expressed per kilogram of live weight produced, the relative carbon footprint did not follow the same trend. Systems that integrated improved pastures (with higher dry matter yields and better digestibility) and targeted supplementation, as well as additional production stages, achieved greater economic efficiency per unit of GHG emissions. Further assessment under variable conditions is recommended to enhance the robustness of the analysis.

Keywords: carbon footprint; gross margin; cattle

1. Introduction

The current global context, shaped by consumer demand, is increasingly driving farmers to adopt sustainable practices that enhance environmental protection while ensuring economic and social sustainability.

In livestock production systems, particular attention is paid to reducing greenhouse gas (GHG) emissions. Since the release of influential reports such as "Livestock's Long Shadow" [1], ruminant-based livestock farming has been under persistent public scrutiny due to its association with freshwater consumption and GHG emissions. These emissions primarily result from digestive processes that release methane (CH_4) into the atmosphere, along with contributions of other GHGs, including carbon dioxide (CO_2) and nitrous oxide (N_2O), which are linked to various direct and indirect livestock production processes [2].

Research on animal nutrition suggests that rations with higher energy density (cereal-based diets) result in a shorter rumination process and lower methanogenesis compared with fiber-rich diets [3, 4]. Berra et al. in 2019 [5] argued that extensive production relying on forages with variable quality and lower levels of technological input tends to exhibit higher methane emissions per kilogram of beef produced than more intensive systems. In the same way, Nieto et al. in 2014 [6] and the dynamic simulation model proposed by Feldkamp et al. in 2014 [7] reported increased GHG fluxes associated with rumination, flatulence, and eructation. These findings raise concerns for livestock systems in several regions of Argentina, due to the extensive nature of livestock systems, based on native grasslands and pastures. According to the 2018 National Agricultural Census [8], approximately 92% of the 112,400 surveyed establishments operate under extensive management schemes. Of these, 60% applied feed supplementation practices, while 32% do not incorporate such practices. Gutman et al. in 2015 [9] highlighted the challenges of reducing GHG emissions from the breeding stage (responsible for 73%–76% of total emissions), due to its reliance on moderate-quality natural and cultivated pastures.

Conversely, grazing-based models contribute positively to agroecosystem biodiversity, including both plant and animal species [10], and help mitigate the risk of wildfire [11] by reducing dry matter accumulation through grazing (without the use of agrochemicals, machinery, or fire). Moreover, unlike highly mechanized and input-intensive agricultural models, these grazing-based systems foster a stronger connection between rural communities and their surrounding environments [12–14].

These characteristics of extensive production on grasslands, with limited technification, are common in the province of Corrientes, which holds the third-largest cow stock in Argentina (10%) [15], making it a representative case for evaluating the impacts of such systems. Building on this context, the objective of this study was to select alternative productive strategies with improved economic and environmental performance, providing relevant information to stakeholders in the livestock sector, particularly cattle farmers, to guide them on the economic and environmental costs associated with implementing different management practices.

2. Materials and methods

2.1. Models

The central-southern region of Corrientes Province (Figure 1) is characterized by a humid subtropical climate, with an average annual rainfall of 1,505 mm (based on data recorded between 1993 and 2023 by the Agrometeorological Observatory of INTA EEA Mercedes). The region experiences a dry season during winter and occasional water deficits in summer due to elevated temperatures. The landscape is composed of gently undulating plains intersected by numerous streams, featuring grassland vegetation and open forests. The most common woody species is *ñandubay* or *espinillo* (*Prosopis affinis*). The region's grasslands are characterized by their mosaic structure, combining decumbent and upright grasses. Three main vegetation communities can be identified: *flechillares* (e.g., *Aristida venustula*), short grasses such as *Paspalum notatum*, and *pajonales* (e.g., *Andropogon lateralis*).

According to records from the Plant Production Group at INTA EEA Mercedes, average annual aboveground net primary production (ANPP) between 1980 and 2000 was 2,815, 5,906, and 5,076 kg of dry matter (DM) per hectare in flechillares, short grasses, and pajonales, respectively. Grassland productivity and forage quality are closely linked to the composition and spatial distribution of these plant communities. A significant characteristic of the region is phosphorus deficiency in soil (P close to 2 ppm). This deficiency is transferred to pastures and grasslands.

Figure 1. Spatial location of the study area: Mercedes (Province of Corrientes, Argentina). Source: Google Maps (2025).

According to the agro-economic zoning of Corrientes Province [16], this region is classified as Zone V, characterized by a combination of livestock and rice production (Figure 2). Regarding the analyzed system, the livestock enterprise system with beef cattle from the central-southern region of the province of Corrientes was selected, defined by Acosta et al. in 2012 [17] as one of the representative livestock systems of northeastern Argentina. The methodology described in this study involves the analysis of nine characteristic production systems that are predominant in the region, determined based on census data, surveys, and expert consultations.

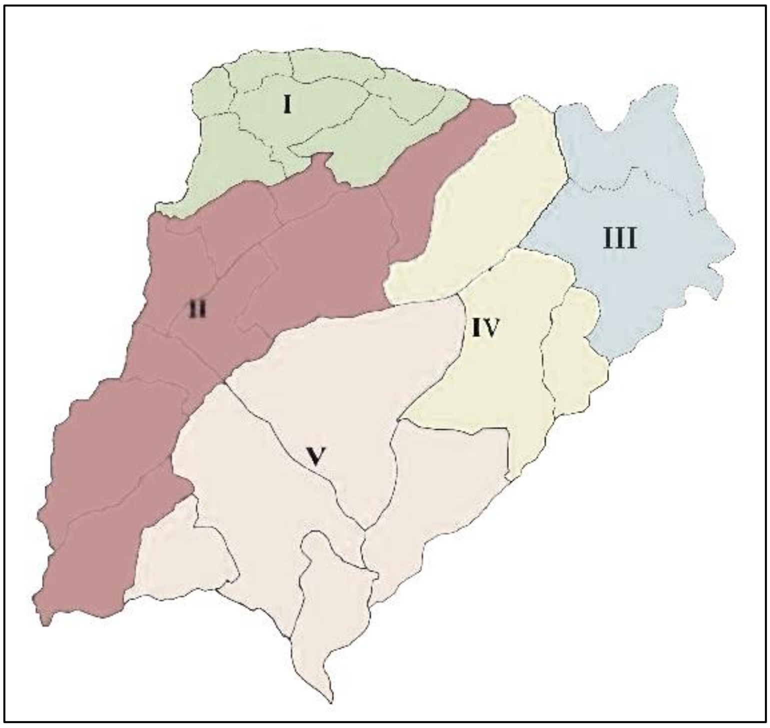

Figure 2. Homogeneous agro-economic zones of Corrientes. Source: Acosta et al. in 2009 [16]. I: Livestock zone of the northwest; II: horticultural, citrus, and forestry zone of the southwest; III: livestock and forestry zone of the northeast; IV: livestock zone of the southeast; V: livestock and rice zone of the central west.

A production model was developed for 2,820 hectares of grazing land supporting a herd of 2,025 Braford cattle. This system includes the infrastructure and human resources required to sustain breeding activities in the region in a traditional way. The predominant forage is grassland, managed under continuous grazing at a stocking rate of 0.65 cow equivalents (EV) per hectare, which is a recommended level to maintain herd productivity while preserving pasture integrity.

Natural mating occurs seasonally during the spring (October to December). Heifers are first bred at 26 months of age, and 22% of the calf crop is retained for herd replacement, undergoing a two-year rearing period. Calves are conventionally weaned in March. Pregnancy diagnosis is carried out in autumn, and non-pregnant cows are culled. Pre-breeding management includes fertility assessments of bulls and dental inspections of adult cows to evaluate wear, which determines the selection of cows for raising their final calf (CUT).

Health management includes mandatory vaccinations, tick control, deworming during breeding, and other treatments recommended by the regional veterinary guidelines. Mineral supplements are provided ad libitum to address the region's phosphorus (P) deficiency.

Breeding bulls are purchased. They are replaced at an annual rate of 20%. Under this management system, pregnancy and weaning rates reach 75% and 69%, respectively. At sale, calves reach an average of 170 kg of live weight (LW), while surplus heifers reach 150 kg LW. Cull cows are sold at 390 kg LW, except for 30% of the herd, which are sold as fattened cows at 450 kg LW. This model yields an annual beef production of 67.4 kg LW per hectare.

Building upon the baseline grassland-based pure breeding model (M1), additional scenarios were developed based on applied experiences at INTA EEA Mercedes. These alternative models incorporate a growing phase for 50% of the weaned male calves (M2 and M3) and a fattening phase for 50% of the steers (M4 and M5). The growing phase includes improved nutritional strategies, such as pasture implantation and strategic winter supplementation as suggested by P. Barbera (personal communication, August 2024). The fattening phase involves confined feeding systems, suitable for the area, capable of providing the required nutrients, proposed by J. Flores (personal communication, August 2024). Table 1 describes the 5 models used for economic-environmental analysis.

In all models, mineral supplementation containing 6% P was supplied ad libitum to all cattle categories throughout the year, with an average annual intake of 27.4 kg/head. In the growing phase of models M2, M3, M4, and M5, protein supplementation was implemented during the winter through a field ration of cottonseed expeller or balanced rearing feed, provided at 1 kg/head/day for a period of 120 days.

The permanent pasture used in M3 and M5 is *Setaria sphacelata* (a megathermic grass with an estimated lifespan of six years) which, due to its dry matter production (approximately 7,000 kg DM/ha/year) and higher digestibility compared to grassland (10% higher), supports a stocking rate of 1.5 steers per hectare.

In M4 and M5, energy supplementation involved feeding in pens, with a ration composed of 90% corn grain and 10% cottonseed expeller at 2.7% of the LW or balanced finishing feed at 3% of LW. This feeding protocol continued until steers reached a target final live weight of 415 kg, with an expected daily live weight gain (LWG) of 1.4 kg/head. Table 2 summarizes the key parameters associated with the suggested nutritional management practices.

It is important to note that the M1 model remained unaltered; therefore, the productive parameters remained unchanged: a stocking rate of 0.65 EV/ha, a pregnancy rate of 75%, a weaning rate of 69%, feeder cows at 70%, and finished cows at 30%. Given that the total grazing area (2,820 ha) was kept constant, the incorporation of rearing and fattening stages in M2, M3, M4, and M5 required a reduction in the number of breeding cows to maintain an appropriate overall stocking rate.

Table 1. Characterization of livestock models in the central-southern region of Corrientes, Argentina.

	M1		**M2**		**M3**		**M4**		**M5**	
Model description	Pure breeding on grassland (PN)		Breeding (PN) + growing (PN + Winter supp.)		Breeding (PN) + growing (PP + Winter supp.)		Breeding (PN) + growing (PN + Winter supp.) + feed lot		Breeding (PN) + growing (PP + Winter supp.) + feed lot	
Feeding/supplementation	PN + mineral supp. (whole herd)		PN + mineral supp. (whole herd) Protein supp. to young steers		PN + mineral supp. (whole herd) PP *Setaria* + protein supp. to young steers		PN + mineral supp. (whole herd) Protein supp. to young steers Energy supp. to steers		PN + mineral supp. (whole herd) PP *Setaria* + protein to young steers Energy supp. to steers	
HERD	Heads		Heads		Heads		Heads		Heads	
Cows	1,235		1,148		1,176		1,148		1,176	
Heifers (2 years)	247		230		235		230		235	
Heifers (1 year)	272		253		259		253		259	
Bulls	222		207		212		207		212	
Feeder cows	49		46		47		46		47	
Young steers	0		198		203		198		203	
Steers	0		0		0		99		101	
Total	2,025		2,081		2,132		2,180		2,233	
SOLD ANIMALS	Kg	Heads	Kg	Heads	Kg	Heads	Kg	Heads	Kg	Heads
Calves	170	426	170	198	170	203	170	198	170	203
Veals	150	154	150	144	150	147	150	144	150	147
Feeder cows	390	156	390	145	390	148	390	145	390	148
Finished cows	450	67	450	62	450	64	450	62	450	64
Young steers	--	--	290	198	330	203	290	99	330	101
Steers	--	--	--	--	--	--	415	99	415	101
Others	--	34	--	31	--	32	--	31	--	32
Beef production (kg)	190,239		200,602		213,609		213,077		222,129	
Beef production (kg/ha)	67.5		71.1		75.7		75.6		78.8	

References: M: models; PN: grassland; PP: pasture; Supp: supplementation; ha: hectares; kg: kilograms live weight.

Table 2. Nutritional management practice parameters in livestock models in the central-southern region of Corrientes, Argentina.

	M1	M2	M3	M4	M5
			Breeding stage		
Final live weight (kg LW/head)	170	170	170	170	170
			Growing phase		
Stocking rate (head/ha)	--	1	1.5	1	1.5
Duration (months)	--	12	12	12	12
Weight gain (kg LW/head)	--	120	160	120	160
Final live weight (kg LW/head)	--	290	330	290	330
			Fattening stage		
Stocking rate (head/ha)	--	--	--	0	0
Duration (months)	--	--	--	3	2
Weight gain (kg LW/head)	--	--	--	125	85
Final live weight (kg LW/head)	--	--	--	415	415

References: M: models; kg LW: kilograms of live weight; kg LW/head: kilograms of live weight per head; head/ha: heads per hectare. **Source:** Own elaboration based on personal communication with P. Barbera and J. Flores (August, 2024).

2.2. Gross margin

The gross margin (GM) serves as a key indicator of the economic efficiency of the productive system. It is determined by subtracting direct costs (DC) from gross income (GI). GI includes revenues from livestock sales, while DC includes the sum of production expenses and amortizations. In these models, DC encompasses purchase of replacement bulls, livestock marketing expenses, health and mineral supplementation (in all cases, and year-round), protein supplementation, energy feed, and amortization of pastures (where applicable), as well as labor costs (including additional daily wages during supplementation/feeding periods).

Price data were sourced from April 2024, coinciding with the sale of calves and heifers, as well as young steers for M2 and M3, due to the year-long growing phase. Steer prices for M5 and M4 were based on June and July prices, respectively, reflecting the time required for fattening to the target weight.

All prices were converted to the same month's US dollars according to the reference exchange rate Communication "A" 3500 (Wholesale) from the Central Bank of the Argentine Republic (BCRA). Prices excluded value-added tax (VAT). Data sources included the Mercado Ganadero de Rosario, ROSGAN (Santa Fe), for fattening cattle and Mercado Agroganadero of Cañuelas S.A, MAG (Buenos Aires), for slaughter-ready animals.

2.3. Carbon footprint

The carbon footprint (CF) quantifies the sum of GHG emissions and removals generated by a product or activity throughout its life cycle [18,19]. This metric highlights the contribution of human activities to global warming.

For the CF evaluation of the livestock models, the Cool Farm Tool [20] was employed. This software, developed in Microsoft Excel ® spreadsheets, enables the collection of data on farm management practices, including crop, forestry, and livestock systems, as well as energy use and outputs. Calculations follow the Intergovernmental Panel on Climate Change (IPCC) methodology, with results presented in matrices and graphs.

It should be noted that this tool provides emissions related to the main GHGs associated with agricultural production: CO_2, CH_4, and N_2O; and the version used on this occasion (2.0_beta 3) considers global warming potentials (GWP) of 1, 25, and 296, respectively.

For the results obtained, the term *carbon footprint* was used rather than *carbon balance*, as the Cool Farm Tool is limited in its ability to determine carbon sequestration, being virtually restricted to sequestration associated with afforestation. This excludes the contribution of natural grasslands and pastures as potential carbon sinks.

Two CF indicators were calculated:

1. Absolute carbon footprint. This refers to the GHG emissions of each model once stabilized, meaning when the herd composition includes all animal categories corresponding to the activities carried out (i.e., breeding and, where applicable, rearing and fattening alternatives). It is expressed in tons of CO_2 equivalent emitted over a one-year period, standardizing the timeframe for both indicators (gross margin and carbon footprint), and facilitating the development of economic-environmental indices.

2. Relative carbon footprint. This refers to GHG emissions quantified in relation to specific variables within each model. For the purposes of this study, the assessment of the relative carbon footprint was conducted with respect to:

• Livestock surface, with the unit of measurement expressed as kilograms of CO_2 equivalent per hectare (kg CO_2 eq/ha).

• Beef production, expressed as kilograms of CO_2 equivalent per kilogram of live weight produced (kg CO_2 eq/kg LW).

This calculation is useful for comparing systems and/or models with variable areas or differing yields (in terms of beef output). For both indicators, a “cradle-to-gate” system boundary was applied; therefore, the footprint was evaluated in relation to the live animal’s sale weight (kilograms of live weight), and refers solely to the primary production phase, excluding downstream stages of the value chain (processing, transportation, wholesale distribution, retail, and consumption).

2.4. Economy-environment interaction

As highlighted by Mayer in 2008 [21], an index is a quantitative aggregation of indicators, which can provide a simplified, coherent, and multidimensional overview of systems. The indices are based on indicators that do not necessarily share a common unit of measurement. While this can pose challenges for weighting methods, it also allows for the representation of economic, social, or environmental conditions in a defined context [22].

In this analysis, the livestock model indicators were assessed using indicators from two dimensions: income and gross margin (economic dimension) and carbon footprint (environmental dimension). Based on their relationship, the following indices can be proposed:

$$Rate\ of\ Return\ per\ GHG\ emissions\ (\frac{U\$D}{t\ CO2\ eq}) = \frac{\text{Gross Income }(\frac{\text{U\$D}}{\text{year}})}{\text{Absolute Carbon Footprint }(\frac{\text{t CO2 eq}}{\text{year}})}$$

For this index, the gross income of the model is determined covering a financial year, expressed in currency units; the absolute CF refers to the total GHG emissions during the same analysis period, expressed in terms of tons of CO_2 equivalent.

$$Gross\ Efficiency\ per\ GHG\ emissions\ (\frac{U\$D}{t\ CO2\ eq}) = \frac{\text{Gross Margin }(\frac{\text{U\$D}}{\text{year}})}{\text{Absolute Carbon Footprint }(\frac{\text{t CO2 eq}}{\text{year}})}$$

In this case, the gross margin of the model is calculated for an evaluation cycle and expressed in monetary units. The absolute carbon footprint is the same as that used in the return rate index.

3. Results

3.1. Gross margin

The economic results of each model are presented in Table 3.

Table 3. Gross margin calculation of livestock models in the central-southern region of Corrientes, Argentina.

Sales	M1	M2	M3 (U$S)	M4	M5
Calves/veals	223,226	126,184	129,262	126,184	129,262
Cows	92,283	85,782	87,874	85,782	87,874
Young steers	0	121,384	141,495	60,692	70,748
Steers	0	0	0	91,711	92,797
Others	17,958	16,693	17,100	16,693	17,100
Gross income (GI)	**333,467**	**350,043**	**375,731**	**381,061**	**397,780**
Bulls purchased	34,110	31,707	32,480	31,707	32,480
Marketing expenses	11,368	11,770	12,571	12,700	13,233
Healthcare	40,286	40,472	41,460	40,917	41,849
Mineral supplementation	40,790	41,341	42,349	41,341	42,349
Supplementation	0	6,486	6,645	25,532	21,446
Pasture depreciation	0	0	7,888	0	7,888
Direct labor	30,602	33,722	34,544	36,931	37,247
Direct costs (DC)	**157,156**	**165,498**	**177,937**	**189,129**	**196,491**
Gross margin (U$S)	176,312	184,544	197,794	191,933	201,289
Gross margin (U$S/ha)	62.52	65.44	70.14	68.06	71.38

References: M: models; U$S: dollar currency; GI: gross income; DC: direct costs; ha: hectares.

3.2. Carbon footprint

3.2.1. Absolute carbon footprint

Figure 3 shows that as stages are added to the beef production process, absolute emissions tend to increase.

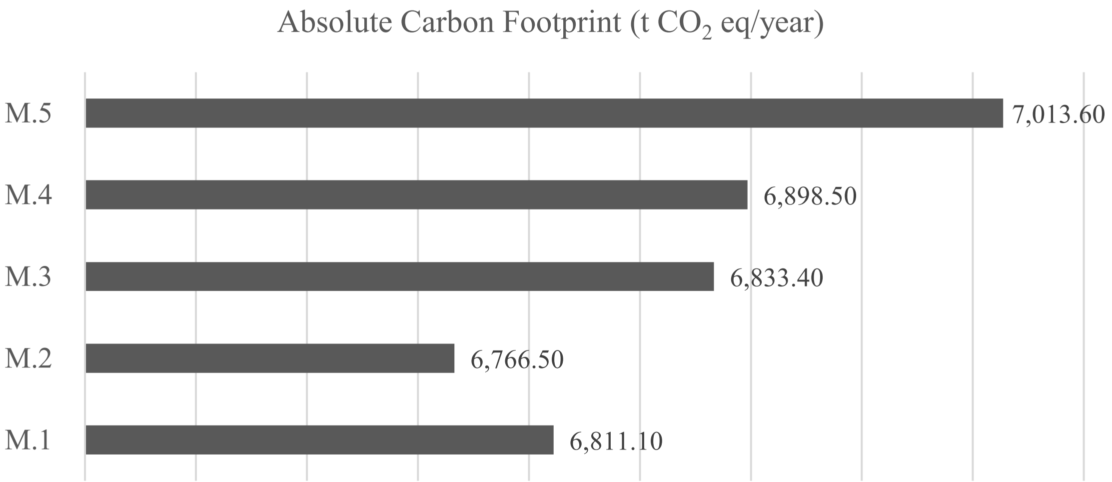

Figure 3. Absolute carbon footprint (t CO_2 eq/year) of livestock models in the central-southern region of Corrientes, Argentina.

Figure 4 shows the percentage distribution of GHG emissions according to their source.

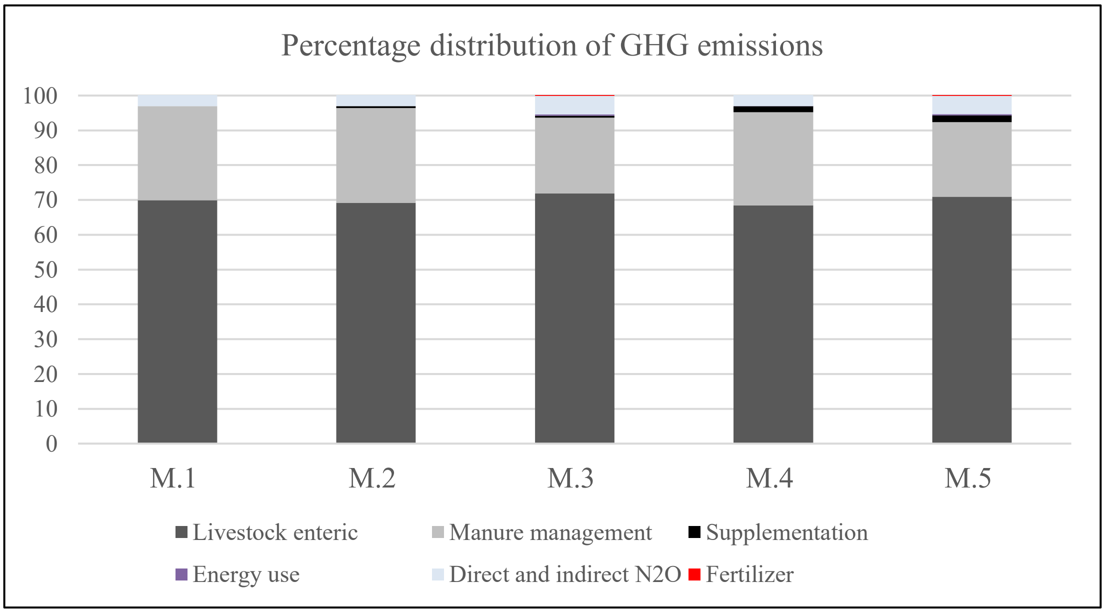

Figure 4. Percentage distribution of GHG emissions, per source, of livestock models in the central-southern region of Corrientes, Argentina.

3.2.2. Relative carbon footprint

Figure 5 shows the relative carbon footprint per unit of surface area and per unit of product (kilograms of live weight produced).

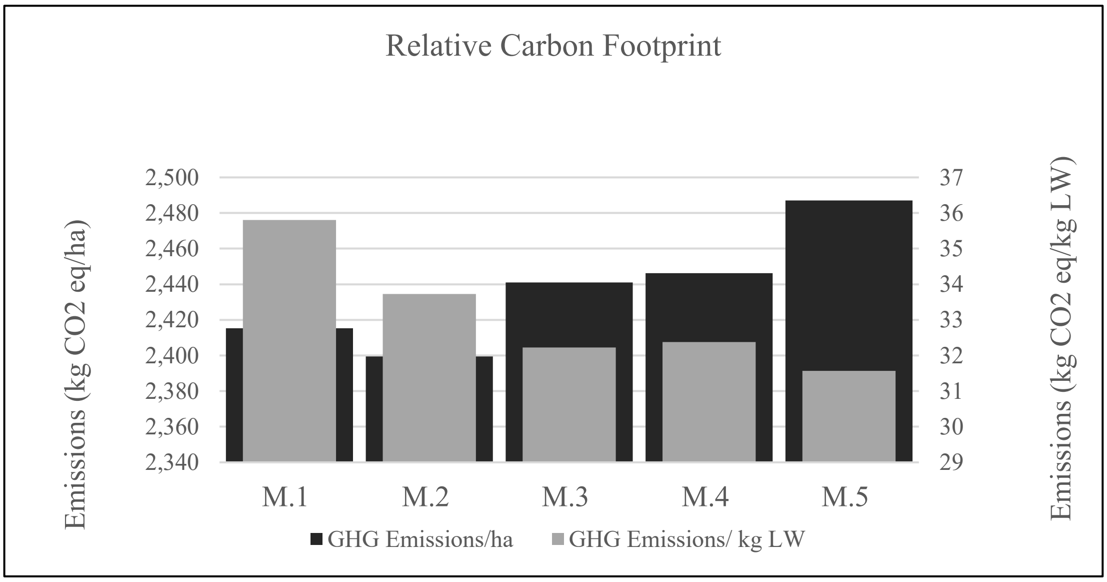

Figure 5. Relative carbon footprint per unit of surface area and per unit of product (kilograms of live weight) of livestock models in the central-southern region of Corrientes, Argentina.

Figure 6 shows how each stage of the process affects the different models of cattle production for beef.

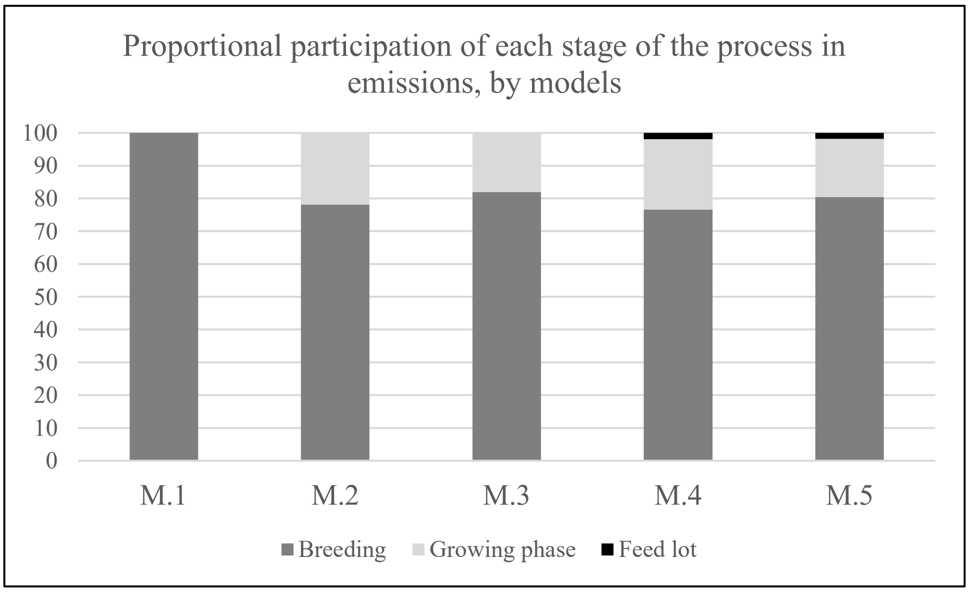

Figure 6. Proportional participation of each stage of the process in emissions by livestock models in the central-southern region of Corrientes, Argentina.

3.3. Economy-environment interaction

Figure 7 shows both indices generated to evaluate the interaction between economy and environment, based on income and margins, in relation to the carbon footprint.

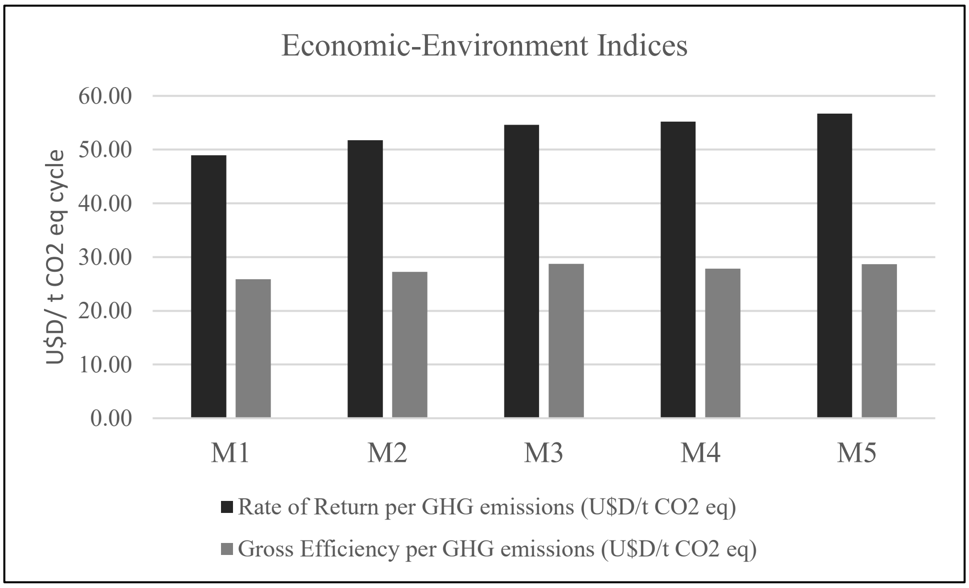

Figure 7. Economic-environment indices by livestock models in the central-southern region of Corrientes, Argentina.

4. Discussion

4.1. Gross margin

From M1 (pure breeding) to M5 (breeding, growing phase, and fattening), total and per-hectare beef production increases. This trend is reflected in both total and per-hectare gross margins, despite rising direct costs. The reason for this is that, although the number of calves sold decreases (compared to M1), the animals that undergo growth and potentially fattening after weaning produce a greater total weight for sale. This additional weight for sale compensates for the increased costs, mainly from supplementation of finishing categories and higher labor-related expenses.

When comparing models that include growing and fattening phases, those incorporating pastures (M3 and M5) achieved better physical and economic outcomes than their counterparts on natural grasslands. The key indicator in this regard was the highest animal stocking rate achieved.

Similarly to the beef production indicator, the incorporation of additional stages into the production process, as well as management practices, allows for an increased amount of live weight kilograms. Although these improvements entail a rise in costs, the upward trend is primarily reflected in marketing expenses and labor involvement. The sowing and cultivation of pastures leads to cost increases due to intrinsic factors (such as their amortization), but also to the requirement of providing mineral supplementation to the herd. The inclusion of a feedlot finishing stage results in higher feed costs stemming from protein supplementation; meanwhile, health management shows a trend of increased additive costs, which are greater if a growing phase is added, even more so if a feedlot is incorporated, and an additional increment when the system considers a diet based on cultivated pastures. This latter aspect suggests that models with a greater number of stages and with forage support from non-native species would require a higher influx of external inputs.

4.2. Carbon footprint

4.2.1. Absolute carbon footprint

The absolute CF values align with the ranges reported by Oliveira et al in 2020 [23]. The models with the highest carbon footprint are M4 and M5, which include feedlot fattening. This outcome is consistent, as the finishing phase adds animals to the herd inventory compared to the other models.

The model with the lowest absolute gas emissions was M2. Compared to M3, its emissions were almost 120 t CO_2 eq lower, likely due to the absence of pastures. Incorporating pastures in M3 entails higher energy expenditure and nitrogen fertilizer use for dry matter production. This finding supports the conclusions of Flessa et al. in 2002 [24], Tilman et al. in 2002 [25], Koknaroglu in 2008 [26], and Nemecek et al. in 2011 [27] regarding the environmental benefits of extensive or low-input systems over intensive ones.

The reduced CF compared to a pure breeding model (M1) is attributable to adjustments in herd structure. While M2 includes more animals than M1, they are younger and lighter, resulting in lower feed consumption and reduced enteric fermentation emissions (a 0.81% decrease). Additionally, replacing cows with male calves in the growing phase further lowers emissions, aligning with findings by Agudo et al. in 2022 [28], which indicate that female emissions are comparatively higher.

Across all models, enteric fermentation accounted for the largest share of emissions (70% on average). N_2O emissions from manure management and agricultural practices complete the CF quantification. However, in models incorporating feed supplementation during the finishing stage, feed-related emissions became more significant (Figure 4), consistent with findings of Bongiovanni et al. [29] and Demarchi [30] in 2023.

4.2.2. Relative carbon footprint

GHG emissions per unit of beef produced (relative CF) were higher than those reported by other authors, such as Agudo et al. [30] for Uruguay and O'Brien et al. in 2019 [31] for beef cattle farms in Ireland, Spain, Italy, and France.

Figure 5 shows that M1 (pure breeding) emits less per unit of surface area. However, since it produces the least amount of beef, it results in a larger CF per kilogram of live weight produced. Conversely, models that incorporate additional production stages (especially fattening) increase their footprint per unit of surface area while reducing the footprint per kilogram of product. The increase in the footprint per hectare may be attributed to the fact that M1 maintains only the reproductive core (cows and bulls) permanently, with calves remaining in the field only until weaning. On the other hand, models that include additional stages (growing phase and fattening) extend the period during which the land is occupied by livestock. However, the additional beef produced (almost 32,000 kilograms more in feedlot models) justifies the improvement in relative efficiency. This contrast between the relative footprints per hectare and per unit of product aligns with the findings of Oliveira et al. [23].

This quantification could be partially attributed to the contribution of each stage to total emissions: the breeding stage accounts for 76%–82%, the growing phase for 18%–22%, and the fattening stage represents 2% of total process emissions (Figure 6). These proportions are consistent with previous studies, including Nieto et al. [6] and Demarchi [30], which reported breeding emissions ranging from 75% to 80% of total emissions from primary production in Argentina's livestock value chain.

Breeding emissions ranged from 24.80 to 35.80 kg CO_2 eq/kg LW, exceeding the estimates of Feldkamp et al. [32]. In contrast, the combined growing and fattening phases yielded 6.7 kg CO_2 eq/kg LW, comparable to the findings of Bongiovanni et al. [29]. CF values in this study were higher than those reported by Felkamp et al. [32] and Bongiovanni et al. [29] (11.91 kg CO_2 eq/kg of live weight at the gate). However, it is important to note that significant differences exist between these studies, ranging from production approaches to methodological aspects.

4.3. Economy-environment interaction

Both indices (return rate index and gross efficiency index) express economic return per unit of gas emitted. It could be argued that gross efficiency for GHG emissions is somewhat more comprehensive, as it accounts for both revenue and direct production costs.

M3 and M5 emerge as the most economically efficient models per unit of GHG emitted, reflecting their ability to balance higher margins with manageable environmental impacts.

Considering that M5 represents the model with the greatest number of stages added to the process, as well as the application of technological innovations in feed management, despite requiring a higher input of external resources to sustain it and having the highest emissions per hectare, the higher live weight yield and the income generated from that yield would make it a viable option from both economic and environmental perspectives.

It is feasible that adding stages to the production process, coupled with the incorporation of specific forage and feed management practices (such as the implementation of pastures and the use of seasonal protein or energy supplementation), while maintaining adequate economic management, labor, and herd health, could represent a strategy to generate additional margins with a low environmental impact in relation to the evaluated characteristic. In fact, a comparison with the livestock model evaluated by Bongiovanni et al. [29] suggests that the lower CF could be associated with shorter weight gain cycles (with 4-month weaning) and the implementation of management practices that incorporate pastures with higher forage production (in terms of dry matter), capable of supporting higher stocking rates (1.2 cows/ha).

5. Conclusions

From a strict economic analysis, the addition of stages to the production process and the incorporation of technologies applied to herd feed management generate improvements in income but also lead to an increase in costs, which affects the growth of the farmer's gross margin.

From an environmental approach, although the absolute footprint increases, the evaluated practices that enhanced the yield of live-weight beef support a better relative footprint for full-cycle systems.

The generation of indices such as the return rate and gross efficiency for GHG emissions provides a different perspective on the balance between economic returns and environmental impact. These indices support the adoption of well-researched, straightforward practices, such as the implementation of high-yielding, nutritionally rich pastures. This approach improves animal welfare, allows for higher stocking rates through better feeding, minimizes health risks, and helps mitigate overgrazing and soil erosion. Both indices can be valid tools for productivity improvement programs applied to the livestock sector, based on the idea of an appropriate trade-off between economic results and environmental impact.

The decision to add a feedlot stage should be carefully considered in response to market signals. While it offers potential economic benefits, its environmental implications require careful management.

Future research should focus on further assessing these indicators and indices under various scenarios. This includes exploring systems across diverse locations, accounting for seasonal, climatic, and temporal variations, and incorporating different production process management practices. Such studies provide valuable insights for tailoring sustainable and profitable livestock systems to specific contexts.

Use of AI tools declaration

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

Conflict of interest

The authors declare no conflict of interest.

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