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Article

Effects of the management of extensive beef grazing systems on the mitigation of greenhouse gas emissions in semi-arid rangelands of central Argentina

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Abstract: The livestock sector can be a major contributor to the mitigation of greenhouse (GHG) emissions. Within the sector, beef production produces the largest proportion of the livestock sector's direct emissions. The objective of this study was to assess the on-farm GHG emissions in semi-arid rangelands in Argentina and to identify the relationships between emissions and current farm management practices. A survey recorded detailed information on farm management and characteristics. Assessments of GHG emissions were based on the IPCC Tier 2 protocols [1]. The relationships between farm management and GHG emissions were identified using General Linear Models. Cluster analysis was used to identify groups of farms that differed from others in emissions and farm characteristics. Emissions per product sold were low on farms that had improved livestock care management, rotational grazing, received technical advice, and had high animal and land productivities. Emissions per hectare of farmland were low on farms that had low stocking rates, low number of grazing paddocks, little or no land dedicated to improved pastures and forage crops, and low land productivity. Our results suggest that the implementation of realistic, relatively easy-to-adopt farming management practices has considerable potential for mitigating GHG emissions in semi-arid rangelands of central Argentina.

Keywords: livestock care management; rotational/continuous grazing; technical advice; stocking rate; functional units

1. Introduction

Livestock production is an important source of greenhouse gas (GHG) emissions worldwide. The livestock sector contributes 14.5% of global GHG emissions (GHG) [2]. Since human population is expected to increase from 7.2 to 9.6 billion by 2050 [3], together with improvement of standard of living, there is an increasing demand for livestock products [4], which is expected to double by the mid-21st Century [5]. The livestock sector will have to be a major contributor in the mitigation of GHG emissions and in the improvement of global food security [6]. Within the sector, beef production contributes to the majority of emissions, with 41% of the livestock sector's direct emissions produced [7]. Methane (CH_4) and nitrous oxide (N_2O) are the largest contributors to global livestock emissions in CO_2equivalent (CO_2e) per year [2]. In countries where pastoral agriculture is the dominant sector,

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CH_4 and N_2O emissions contribute up to 50% of the total GHG emissions [8]. Due to the negative relation between efficiency of production and GHG emissions per output produced, the greatest mitigation potential lies in ruminant systems that operate at low productivity (e.g., in South Asia, Latin America and the Caribbean, and Africa) [2].

Argentina is a major world beef producer: is the sixth largest beef producer in the world [9] and the ninth largest beef exporter [10]. Meat chain generates around 4% of the total jobs in the country [10]. Argentina and four other Latin American main beef exporters plan to increase beef production in response to the forecasted growth in international markets [11]. Of the 156.94 Mt CO_2e emitted by 'Agriculture, Forestry and other land uses' Argentinean sector, livestock directly accounts for 54 Mt CO_2e produced by enteric fermentation (of which beef accounts for 83%), 20.26 MtCO_2e are produced by manure deposition on pastures (76% from beef) and 2.14 MtCO_2e are produced by manure management (83% from beef) [12]. Thus, methane emitted by enteric fermentation is especially important: as of 2008, methane emissions from domestic ruminants in Argentina was the sixth highest in the world, and the per capita rate was one of the highest [13]. Rearte and Pordomingo [11] indicated there are ample opportunities to reduce methane emissions per unit of product in Argentina and other temperate regions of Latin America.

The GHG emissions of a product can be expressed as kg of CO_2e per kg of product, or it can be expressed as kg of CO_2e per unit of area (ha) of the production system, depending on the standpoint of view (of the consumer vs. the producer) [14-16], product perspective vs. an IPCC inventory perspective [17,18], and global vs. local environmental issues assessed [19]. Some studies have shown that the use of different functional units (FU, kg of product vs. land area) can produce contradictory results in assessing GHG emissions [14,15,17], illustrating the potential trade-off between carbon efficiencies per unit of product and per unit of land. Nevertheless, several studies suggest that mitigation of the emissions per unit of product and per unit of land area can be reconciled [15,17]. Casey and Holden [17], Halberg et al. [19] and Veysset et al. [20] suggested that product-based and land area-based indicators should be used to characterize the environmental impacts caused by food production.

Many studies have assessed mitigation strategies for reducing GHG emissions intensity in terms of emissions per unit animal product in several ruminant livestock farming systems worldwide, which have been reviewed extensively [2,6,21-28]. The mitigation strategies that reduce emission intensity by increasing herd productivity through improved animal husbandry practices (e.g., animal feeding, genetics, health, fertility, and overall management of the animal operations) can be important in low–input ruminant systems [22,23] and have greater mitigation potential in developing than they do in developed economies [23].

In Argentina, >70% of the beef is produced in pasture-based grazing systems [11], mostly in extensive conditions [13]. As the opportunity for soybeans and cereal grains became structural to Argentinean agriculture, livestock businesses were displaced towards less productive, marginal lands [29,11]. Eight percent of beef production is in the semi-arid Central Region (18% of the country) [30]. Rangeland native grasslands are the main source of feed for cow-calf livestock systems, which is an important economic sector in the region [31]. Rangelands are the world's most common land type [32] and they provide the livelihoods for many vulnerable communities throughout the world [33]. Their relevance is linked to their multifunctional nature and provision of ecosystem services [34]. Extensively managed livestock production is the most sustainable and common form of agriculture on rangelands [34]. Global demand for livestock products will increase the pressure on rangelands, which are experiencing high degradation and losses in biodiversity worldwide [35], especially in arid and semi-arid grasslands in developing countries [34].

Identifying the relationships between GHG emissions and farm management and system productivity can help livestock producers improve operations, where productivity can be improved considerably by implementing simple management practices [36]. Furthermore, in the transition to sustainable livestock production, assessments of mitigation measures that have been tailored to the location and livestock production system in use are needed [6,15]. Our study assessed commercial farms that were representative of the extensive beef systems based on natural rangelands in the San Luis Province, which is typical of the semi-arid Central Region of Argentina [29]. Beef cattle stocks

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have increased in San Luis because of the displacement of livestock into semiarid marginal areas [37] and incipient intensification has been reported [29]. The main objective was to assess GHG emissions from representative farms to identify realistic farming practices that will favor low GHG emissions. Specifically, we (i) estimated the CH_4 and N_2O on-farm livestock emissions intensity based on two functional units: product-based (kg CO_2e per total live weight sold) and area-based (kg CO_2e per land area used), (ii) identified farm attributes and management practices that were associated with low emission intensities, and (iii) assessed the implications of using each of the two functional units in identifying the farming practices that minimize GHG emissions.he introduction should briefly place the study in a broad context and highlight why it is important. It should define the purpose of the work and its significance. The current state of the research field should be reviewed carefully and key publications cited. Please highlight controversial and diverging hypotheses when necessary. Finally, briefly mention the main aim of the work and highlight the principal conclusions. As far as possible, please keep the introduction comprehensible to scientists outside your particular field of research. References should be numbered in order of appearance and indicated by a numeral or numerals in square brackets, e.g., [1] or [2,3], or [4–6]. See the end of the document for further details on references.

2. Materials and Methods

The study was conducted in a 4160-km^2 area in San Luis province, Central Region, Argentina (center of the study area: 34°17'22.46"S; 66°25'40.89"W), where an extensive cow-calf system based on year-round, open-air grazing is the main land use. The climate is semiarid, and annual precipitation ranges from 350 to 500 mm. Average daily temperature ranges from 8.5 ºC (coldest month) to 23 ºC (warmest month) [38]. Soils are shallow, poor in organic matter, have low water retention capacity, and low-medium productivity [39]. The climate and soil conditions are unsuited for croplands, and rangeland native grasslands are the main source of feed for livestock [31]. Natural vegetation consists of two main types [40]: (i) woodland-shrubland mixture dominated by legume trees (*Prosopis flexuosa* and *Geoffroea decorticans*) and shrubs (*Larrea divaricata*), and (ii) grass-dominated steppes of *Nassella tenuis*, *Piptochaetium napostaense*, *Poa ligularis* and *Poa lanuginose*, and small scattered woodlands of legume trees (mainly *G. decorticans*). Most of the cattle are Hereford, Aberdeen Angus, or crossbreeds of the two, although some farms also have Creole [41]. Low productivity and potential improving of the farm system have been previously reported in the region [11].

In 2014, 30 of the 67 beef cattle farms in the study area were surveyed. The farms were representative of the region based on earlier studies [31]. The survey, recorded in a structured questionnaire, collected detailed information about the size and structure of the farm, livestock management, infrastructures, productivity, as well as the ages and levels of education of the producer and the labor, referred to a one-year production cycle. With that information, a characterization of the farms was obtained and variables were calculated that were used in the analysis.

The general characteristics of the farms are detailed in Table 1. Seven percent of the farmers did not have any type of education, 61% had a primary or secondary education, and 32% had higher education. Half of the farms surveyed had salaried employees. In addition to natural grassland areas, 23% of the farms improved grasslands by introducing grasses such as *Eragrostis curvula, Digitaria eriantha,* and *Panicum coloratm cv. verde,* and 17% had annual forage crops such as maize (*Zea mays*), sorghum (*Sorghum vulgare*), rye (*Secale cereale*) with melilotus (*Melilotus albus*), and oats (*Avena sativa*), although in both cases, the areas were much smaller than were the natural pastures (Table 1). Three types of production systems were observed: (i) cow-calf (CC) systems (60% of the farms), where calves are sold at weaning, (ii) backgrounding (BG) systems (10%) (i.e., farmers purchase weaned calves that are sold once they are fattened, and (iii) cow-calf+backgrounding (CCBG) systems (30%). The calves are weaned at 6 months and 130-150 kg of live weight (LW) and sold fattened at 15 months (280-300 kg LW). On the CC and CCBG farms, the reproductive system was either (i) year-round mating (44% of the farms), or (ii) seasonal. Only 7% of farms employed artificial insemination. On the farms, water was collected in artificial dams, by drilling, from wells and, to a lesser extent, natural streams were used.

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Table 1. General characteristics of the beef cattle farms in San Luis province, central Argentina

Variable	Mean	s.d.	Min	Max
Socio-economic data				
Age (years)	56	11.3	34	75
+Hired labor (WU/LU) (x10^{-3})	0.7	0.8	0	2.5
Land use				
+Total land area (ha)	3598	4706	67	23400
+Land area used for native pastures (%)	95	14	33	100
+Land area used for improved pastures (%)	4	13	0	67
Land area for annual forage crops (%)	2	6	0	29
Beef cattle				
+Total Livestock Units[1] (LU)	337	399	17	1856
Mortality rate (%)	6.7	11.1	0.6	50.0
Stocking rate (LU/ha)	0.13	0.09	0.02	0.46
Grazing infrastructures				
Water reservoirs per total land/ha (x10^{-3})	2.8	3.2	0.3	14.9
Water reservoirs/LU (x10^{-3})	25	21	4	89
+Grazing paddocks/ha (x10^{-3})	3.7	4.5	0.6	19.6
System productivity				
Average LW of livestock (kg)	283	50	195	399
Weaning rate [2] (%)	65	17	26	95
+Land productivity (kg LW sold/ha)	18.3	20.4	1.1	93.8
+Animal productivity (kg LW sold/LU)	138	91	53	337

s.d., standard deviation; Min and Max, minimum and maximum values (n=30 farms); WU, Work Units; LU, Livestock Units; LW, Live Weight.

+Variables used for the typification of the beef cattle farms.

[1]Livestock Units were calculated based on Cocimano et al. [40].

[2] n=27 (remaining three farms are backgrounding systems, they do not have breeding).

Greenhouse gas (GHG) emissions were estimated on-farm, based on CH_4 emissions from cattle enteric fermentation and N_2O emissions from managed soils used by grazing animals. Animals graze year-round and manure is not managed, as defined by the Intergovernmental Panel on Climate Change (IPCC) [1]. As far as no animal housing was involved and crops and imported feeds were not relevant in the study area, CO_2 emissions from infrastructure, energy used for crops, and off-farm GHG emissions were not included in this study. GHG emissions were expressed as CO_2 equivalents (CO_2e) for a time horizon of 100 years: CH_4 kg × 25 and N_2O kg × 298 [43]. Emissions were expressed as kgCO_2e per kg LW sold (sum of weaned calves and culled cows), and per hectare (ha) of farmland.

Assessments of GHG emissions were based on the IPCC Tier 2 protocols [1]. Appendix A shows the IPCC (2006) equations used in the calculations. Further updates of IPCC (2006) protocols did not affect those equations. Enteric CH_4 was estimated for each category of cattle on the farm: cow, weaned calf, replacement heifer, bull and steer.

Estimates of the gross energy (GE) intake of the animals were calculated based on the net energy (NE) requirements for maintenance, activity, growth, pregnancy and lactation. Enteric emissions were estimated based on GE intake and using methane conversion factors (*Ym*). We refined *Ym* calculations by means of the use of Cambra-López *et al.* (2008) [44] equation: $Ym = -0.0038*DE^2 + 0.351*DE-0.8111$, where DE is feed digestibility expressed as a percentage of the GE of the feed. DE was estimated based on earlier studies on the quality of the pastures in the study area [45], percentage

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of land with annual forage crops, and the opinions of local experts of the 'Estación Experimental Agropecuaria San Luis' del 'Instituto Nacional de Tecnología Agropecuaria' (INTA). Average DE was 58% (range = 52-60; SD = 1.3). Average *Ym* was 6.7% (range = 6.5-7.1; SD = 0.12).

N_2O emissions from managed soils were calculated based on the N deposited on pastures by grazing animals (urine and dung). The amount of N deposited on the pasture by each cattle type while grazing was estimated based on the number of animals, feed intake, pasture N content, and N retention of the animals, following IPCC [1] and National Research Council [46].

Two analyses were conducted: statistical models that described GHG emissions, and cluster analysis to identify homogeneous groups of farms that differed in emissions and management practices.

The relationship between farm management practices and GHG emission was investigated using Generalized Linear Models (GLM) [47] with the assumption that the data followed a Tweedie distribution, and using a logarithmic link function. The dependent variable was CO_2e emissions, which was expressed as either (a) per kg of LW sold or (b) per hectare of land.

A set of explanatory variables was used for the models of each of the two dependent variables. The values of all explanatory variables (nominal, ordinal, or continuous) were transformed to 0-1 values and included as 'factors' (categorical predictors with values 0-1) in the models. Nominal variables included feed purchase (0, no; 1, yes), reproductive management of the livestock (0, year-round mating; 1, seasonal mating), technical advice (0, no; 1, yes), type of production system (0, cow-calf (CC); 1, cow-calf+backgrounding (CCBG), and grazing system (0, continuous; 1, rotational). For the ordinal and continuous variables, the scoring criteria were based on the median (values $\leq$ median = 0; values > median = 1), except for land area used for introduced pastures or annual forage crops. Ordinal variables included water reservoirs per total land (0, low; 1, moderate; median = 16.7×10^{-4} water reservoirs/ha), grazing paddocks per total land (0, low; 1, moderate; median = 16×10^{-4} grazing paddocks/ha), livestock care controls (0, poor = three or fewer types of controls; 1, good = four to six types of controls). Types of livestock care controls were body condition, teeth examination, rectal palpation/ecography, parasite control, reproductive vaccine, and bull review control. Continuous variables included land area used for introduced pastures or annual forage crops (0, null/very low if area $\leq$ 4%; 1, low/moderate if area > 4%), average live weight of livestock (0, low; 1, moderate; median = 292 kg), cows-to-total animals rate (0, low; 1, moderate; median = 55%), average weight of sold calf (0, low; 1, moderate; median = 204 kg), mortality rate (0, low; 1, moderate; median = 2.6%), stocking rate (0, low; 1, moderate; median = 0.10 LU/ha), weaning rate (0, low; 1, moderate; median = 66.5%), land productivity (0, low; 1, moderate; median = 9.2 kg LW sold/ha), and animal productivity (0, low; 1, moderate; median = 100 kg LW sold/LU).

Prior to the GLM analysis, an exploratory analysis was done based on Mann-Whitney test to identify the independent effects of variables on GHG emissions, and a Spearman's non-parametric test was used to identify co-linearity among variables. Non-correlated variables ($r_s < 0.40$, $P > 0.05$), only, were included in a given GLM. Backgrounding farms were excluded from the analysis because they do not have a breeding herd.

Several analyses were performed based on all possible combinations of non-correlated variables and removing the non-significant explanatory variables one at a time (variables that did not reach $p<0.05$ in a Wald's Chi-square test) until the final models contained significant explanatory variables, only.

Only models that were significant ($p<0.05$) based on an Omnibus Test were included in the analyses. The resulting models were defined as:

$$LnE = \alpha + \beta_1 \mathrm{var}_1 + \beta_2 \mathrm{var}_2 + \ldots + \beta_i \mathrm{var}_i$$

where E = CO_2e emission, the first term 'α' contains the regression intercept, and the remaining terms include the variables used in the model. The model indicates the partial regression β coefficients, which indicate the weights of the variables *1,2,…,i* in the model when the variable is '0'. Thus, if β is > 0, E and the variable (level '0') are positively correlated, and if β is < 0, E and the variable

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(level '0') are negatively correlated. If the variable is '1', the model takes the reference value (β=0 and, hence, LnE=α). Emissions are calculated as:

$$E = e^{\alpha} \cdot e^{\beta_1 \mathrm{var}_1} \cdot e^{\beta_2 \mathrm{var}_2} \cdot \ldots \cdot e^{\beta_i \mathrm{var}_i}$$

The statistical significance of the coefficients of individual variables in the models was tested using Wald's Chi-square test. Significant interaction effects were not detected. To express the main effects in each model, the estimated marginal means were calculated. For all possible combinations of non-correlated variables in the models, model fit was evaluated based on Akaike's Information Criterion for finite samples (AICc). Models that had the lowest AICC were selected as best models within a set of models that included the same set of variables [48]. The explained deviance reflected the contributions of significant individual explanatory variables to the model as follows: $D^2 = (D_0 – D_{model})/D_0$, where D_0 is the deviance of the null model (intercept, only), and D_{model} is the deviance of the analyzed model [49]. The contribution of each explanatory variable was estimated based on the change in D^2 after the variable was deleted from the model divided by the total explained deviance [50], which is expressed, here, as 'D^2 change on deletion' (%DCD). As the values of the variables were 0 or 1, to standardize the explanatory variables was not done. The statistical significance of the independent effects of each management variable on GHG emissions was assessed based on Spearman's correlation non-parametric tests.

For the typification of the farms, 7 continuous and 4 discrete variables were selected (Tables 5 and 6). To identify the main factors (eigenvalues > 1) that characterized the changes observed, the 11 variables was subjected to Principal Component Analysis (PCA) with varimax rotation. The Bartlett Sphericity Test and a Kaiser-Meyer-Olkin (KMO) Test for sampling adequacy were used to validate the sampling. To identify a typology of the farms, we subjected the main factors of the PCA to a hierarchical cluster analysis (CA), with squared Euclidean distance and Ward's Aggregation Method. In that way, five groups of farms were identified. To validate the results, we used a non-parametric Kruskal-Wallis test, known as 'analysis of variance by ranges' [51], which verifies which continuous variables, either used in the PCA-CA (7 variables) or not (10 variables), are significant in explaining the differences between the groups. To identify which groups differ for each variable, we used the non-parametric Dunn-Bonferroni post-hoc test. The testing of variables not included in the CA is known as 'criterion validity' [52] and has been used to characterize livestock farms [53].

The statistical analyses were performed using IBM SPSS Advanced Statistics software ver. 22 [54].

3. Results

3.1. Farm GHG emissions

Among the beef farms in San Luis province, central Argentina, mean GHG emission intensity was 19.6 Kg CO_2e/kg LW sold, but varied widely (range = 6.2 - 39.7). Backgrounding (BG) farms produced fewer emissions than did cow-calf (CC) farms, and mixed CCBG farms produced average emissions. On a farm-area basis, the average emission rate was 261 Kg CO_2e/ha (range = 26 to 1042), which did not differ significantly among types of production systems (Table 2).

Table 2. Farm greenhouse gas emission of the beef cattle farms in San Luis province, central Argentina.

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Farm greenhouse gases emission intensity	Production system	Mean[1]	s.d.	Min	Max	n
Kg CO_2e/kg LW sold	Cow-calf	23.6[b]	7.3	12.4	39.7	18
	Backgrounding	6.9[a]	1.1	6.2	8.1	3
	Cow-calf + Backgrounding	15.7[ab]	6.3	7.0	22.6	9
	Overall	*19.6*	*8.6*	*6.2*	*39.7*	*30*
Kg CO_2e/ha	Cow-calf	243	225	26	1042	18
	Backgrounding	345	70	270	409	3
	Cow-calf + Backgrounding	269	200	83	671	9
	Overall	*261*	*205*	*26*	*1042*	*30*

s.d., standard deviation; Min and Max, minimum and maximum values; LW, Live Weight.

[1]Different letters in the same column indicate significant differences between production system groups (P = 0.002). Kruskal Wallis test

3.2. Effects of farm system and management on GHG emissions

Considered independently, each of six variables had a significant effect on emission intensity per kg of LW sold (Table 3). Emissions were significantly lower under good than they were under poor livestock care management controls, if technical advice was sought, if rotational grazing was used, and in CCBG than in CC systems. Land and animal productivity affected the emissions, with lower emission intensities under higher land and animal productivity. Furthermore, emission intensity was negatively correlated with land and animal productivities ($r = -0.46$, $P < 0.05$; $r = 0.87$, $P < 0.001$, respectively). Weaning rate and emission intensity were negatively correlated ($r = -0.39$, $P<0.05$); however, a Mann-Whitney test did not indicate statistical significance ($P < 0.10$, Table 3).

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Table 3. Individual effects of farm characteristics and management on greenhouse gas emission intensity

Variable	Level/Type	Farm greenhouse gases emissions intensity Kg CO_2e/kg LW sold Mean ± s.d.	n	Sig.[a]	Kg CO_2e/ha Mean ±	n	Sig.[a]
Land use							
Land area used for improved pastures or annual forage crops (%)	0/very low	21.29 ± 7.76	24	n.s.	221 ± 199	24	**
	Low/moderate	18.28 ± 9.72	3		503 ± 184	3	
Feed purchase	No	22.28 ± 9.19	14	n.s.	232 ± 263	14	n.s.
	Yes	19.54 ± 6.12	13		273 ± 153	13	
Beef cattle							
Average Live Weight of livestock (kg)	Low	21.94 ± 7.39	14	n.s.	257 ± 251	14	n.s.
	Moderate	19.91 ± 8.47	13		246 ± 175	13	
Cows to total animals rate (%)	Low	19.82 ± 6.25	14	n.s.	237 ± 171	14	n.s.
	Moderate	22.18 ± 9.37	13		268 ± 258	13	
Average Weight of sold calf (kg)	Low	22.00 ± 6.94	14	n.s.	258 ± 258	14	n.s.
	Moderate	19.84 ± 8.85	13		246 ± 164	13	
Mortality rate (%)	Low	21.31 ± 8.70	14	n.s.	170 ± 75	14	*
	Moderate	20.58 ±7.13	13		341 ± 277	13	
Stocking rate (LU/ha)	Low	20.83 ± 9.65	14	n.s.	145 ± 73	14	***
	Moderate	21.10 ± 5.67	13		367 ± 256	13	
Grazing infrastructures							
Water reservoirs/ha^{-1} ($x10^{-3}$)	Low	20.30 ± 8.21	14	n.s.	196 ± 114	14	n.s.
	Moderate	21.67 ± 7.68	13		312 ± 268	13	
Grazing paddocks/ha ($x10^{-3}$)	Low	20.09 ± 8.56	14	n.s.	157 ± 71	14	*
	Moderate	21.90 ± 7.21	13		354 ± 268	13	
Technical management of the farm							
Livestock care management controls	Poor	24.23 ± 7.36	15	*	262 ± 245	15	n.s.
	Good	16.87 ± 6.59	12		239 ± 177	12	
Reproductive management of the livestock (mating)	Year-round	23.72 ± 9.51	12	n.s.	227 ± 269	12	n.s.
	Seasonal	18.75 ± 5.60	15		272 ± 165	15	
Technical advice	No	23.96 ± 7.40	15	*	254 ± 245	15	n.s.
	Yes	17.21 ± 6.92	12		249 ± 177	12	
Grazing system	Continuous	27.65 ± 7.74	7	**	323 ± 350	7	n.s.
	Rotational	18.62 ± 6.55	20		227 ± 146	20	
Type of production system	CC	23.60 ± 7.29	18	*	243 ± 225	18	n.s.
	CCBG	15.68 ± 6.31	9		269 ± 200	9	
Reproductive efficiency							
Weaning rate (%)	Low	23.67 ± 7.53	14	(*)	262 ± 252	14	n.s.
	Moderate	18.04 ± 7.34	13		241 ± 173	13	
System productivity							
Land productivity (kg LW sold/ha)	Low	24.28 ± 7.78	14	*	148 ± 67	14	***
	Moderate	17.38 ± 6.40	13		364 ± 261	13	
Animal productivity (kg LW sold/LU)	Low	26.00 ± 6.27	14	***	262 ± 253	14	n.s.
	Moderate	15.53 ± 5.39	13		241 ± 172	13	

LU, Livestock Units. LW, Live Weight. CC, Cow-calf. CCBG, Cow-calf + Backgrounding

[a] Sig. = significance based on Mann-Whitney test. (*) = P < 0.10, * = P < 0.05, ** = P < 0.01, *** = P < 0.001

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The set of variables that, considered independently, had a significant effect on emissions per hectare of farmland differed from those that affected emission intensity per kg of LW sold, with the exception of land productivity, which was correlated with both but in opposite directions (Table 3). Emissions per hectare were significantly lower if little or no land had been dedicated to improved pastures or annual forage crops, if mortality rate was low, if stocking rate was low, and if the number of grazing paddocks per total land was low. Emissions were higher under moderate than they were under low land productivity. Furthermore, land productivity and emissions per hectare were positively correlated ($r = 0.66$, $P < 0.001$).

For emissions per kg of LW sold and per hectare of farmland, respectively, eleven and eight of the models had significant ($P<0.05$) values for the intercept and explanatory variables (Table 4). All of the variables that had a significant effect on emission intensity, individually (Table 3), yielded significant models.

In the best model for emissions per kg LW sold (lowest AICC and D^2), animal and land productivities were significant explanatory variables (Table 4 and Fig. 1). Systems that had higher animal and land productivity emitted less than those systems with lower productiviy. In this model, the partial regression coefficients indicated that animal productivity had more weight in influencing emission intensity than did land productivity. Calculated square deviance (D^2) indicated that the model explained 51.2% of the variation in the response variable. Other models, which performed worse (had lower AICC and D^2), included the following explanatory variables: management care controls of livestock (systems that had good management controls emitted less than those that did not), type of production system (CCBG systems emitted less than did CC systems), grazing system (rotational emitted less than did continuous), technical advice (systems that received technical advice emitted less than did those that did not). Based on %DCD, in descending order the variables that had greatest influence on emissions were animal production, three variables that had a similar influence (management controls, type of system, and grazing system), land productivity, and technical advice.

The best model to explain the variance in emissions per hectare of farmland included land productivity and number of grazing paddocks per total land (Table 4 and Fig. 1). Systems that had lower land productivity emitted less than did those systems with higher land productivity. In addition, systems that had less grazing paddocks emitted less. In this model, the partial regression coefficients indicated that land productivity had more weight than did the number of grazing paddocks. Calculated square deviance (D^2) indicated that the model explained 57.4% of the variation in the response variable. Other models, which performed worse, included the following explanatory variables: mortality rate (systems that had a lower mortality rate emitted less than did those that had a higher mortality rate), stocking rate (systems that had a lower stocking rate emitted less than did those that had a higher stocking rate), and land use (systems that had lower land area used for improved pastures or annual forage crops emitted less than did those that had higher land area for this purpose). Based on %DCD, in descending order the variables that had greatest influence on emissions were stocking rate and land productivity, two variables that had a similar influence (number of grazing paddocks per total land and mortality rate), and land area used for improved pastures or annual forage crops.

3.3. Farm typification

The PCA identified the following five groups of farms (Tables 5, 6 and 7):

- Group I (23% of farms): Highest emitters per LW sold and lowest emitters per hectare. Worse management and lowest stocking rates. Cow-calf systems, only. Predominantly, continuous grazing. On those farms, all the land area is natural grasslands, and off-farm feeds are not used. Highest percentage of farms that have no type of livestock care management controls, lowest reproductive management of the herd, lowest weaning rates. None of the farms receive technical advice. Lowest level of record keeping. Least productive farms.

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Table 4. GLM models for the response of emission intensity (Kg CO_2e/kg LW sold, and as Kg CO_2e/ha) from beef cattle farms to farm management and characteristics.

Emission	Model	Management	Technical	Grazing	Production	Animal	Land	Land	Mortality	Stocking	Grazing	Sig.	AICc	D^2 (%)
	1					+0.459***	+0.218*					***	176.67	51.23
	2					+0.515***						***	177.78	43.81
	3	+0.360**					+0.332**					**	182.43	39.83
	4				+0.342**		+0.261**					**	184.88	34.22
KgCO_2e	5			+0.330**			+0.264*					**	185.23	33.39
kg^{-1}LW	6		+0.282*				+0.287**					**	186.07	31.34
sold	7				+0.409**							**	186.29	23.45
	8			+0.396**								**	186.69	22.34
	9	+0.362**										*	187.00	21.44
	10						+0.334**					*	187.94	18.74
	11		+0.331*									*	188.20	17.97
	1						-0.784***				-0.675***	***	334.64	57.39
	2						-0.748***		-0.442*			***	341.82	45.25
	3									-0.929***		***	342.02	39.32
Kg CO_2e	4						-0.903***					***	342.98	37.29
ha^{-1}	5										-0.811***	**	346.01	30.45
	6							-0.699**	-0.620*			**	346.83	34.93
	7								-0.698**			*	349.08	22.81
	8							-0.823**				*	351.084	17.45

Partial regression ß coefficients with their statistical significance when the variable is '0', statistical significance of the model (Sig.) based on an Omnibus Test, Akaike's Information Criteria (AICc) and square deviance (D^2) are given. If β is > 0, emission and the variable are positively correlated and if β is < 0, emission and the variable are negatively correlated. Only statistically significant variables (based on Wald's Chi-square test) are shown. Empty cells indicate variables not included in a given model. * = $P < 0.05$, ** = $P < 0.01$, *** = $P < 0.001$. D^2 calculated as: $D^2 = (D_0 – D_{model})/D_0$, where D_0 is the deviance of the null model (with intercept, only), and D_{model} is the deviance of the analyzed model.

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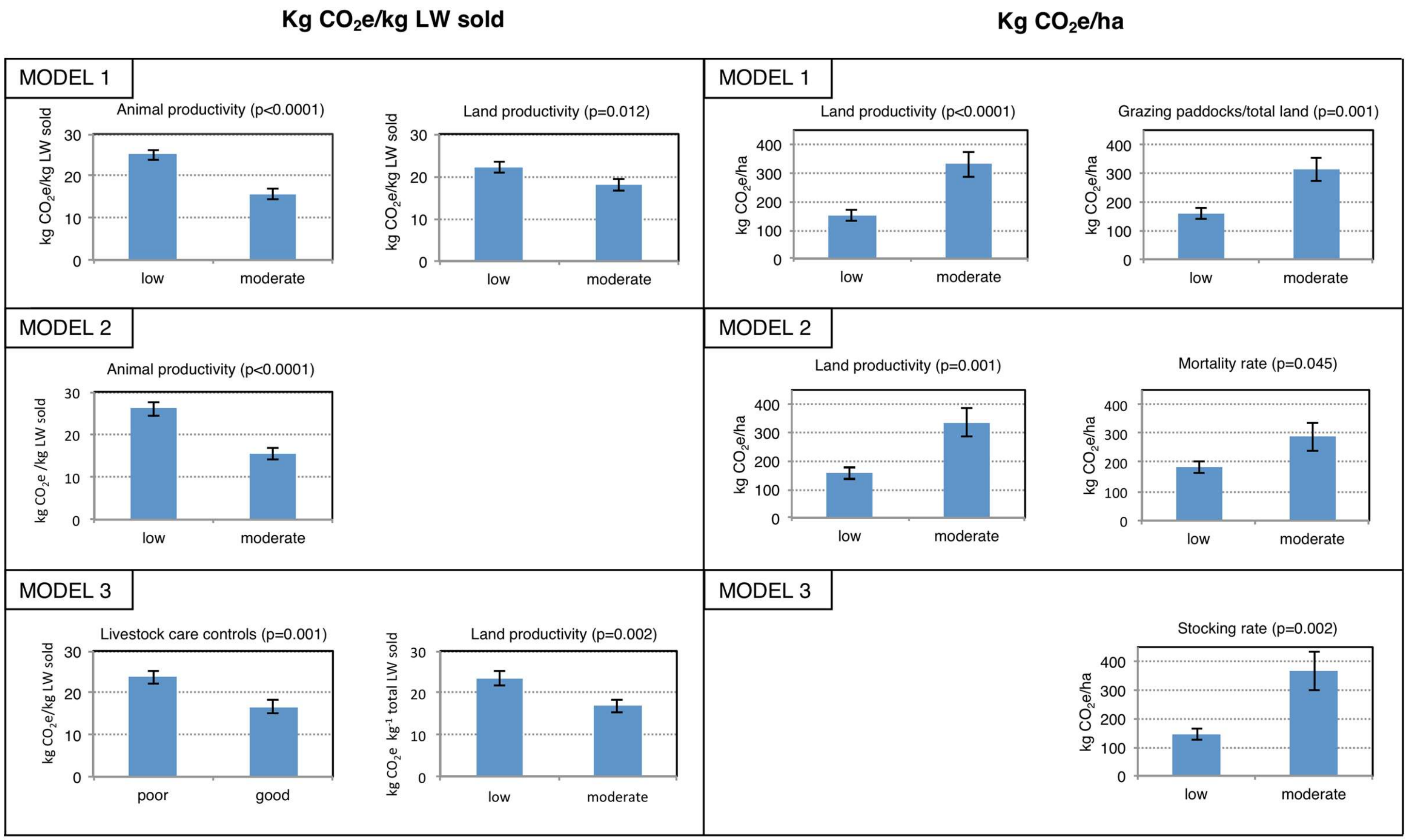

Figure 1. Marginal means and standard error of the most significant GLM models for the response of emission intensity (Kg CO_2e/kg LW sold, and Kg CO_2e/ha) from beef cattle farms in San Luis province, central Argentina. Differences were tested using Wald's Chi-square test.

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- Group II (30% of farms): Intermediate emitters per LW sold and highest emitters per hectare. Medium level of management and highest stocking rates. Cow-calf systems and rotational grazing predominate. Almost all of the land area consists of natural grasslands, and these farms had the highest proportion of farms that use off-farm feeds. Medium level of livestock management controls, 50% of farms had year-round mating, medium weaning rates and 78% of farms received no technical advice. Medium level of record keeping. Highest productivity per land area and moderately productive farms per LU.
- Group III (17% of farms): Intermediate emitters per LW sold and per hectare. Very good management and intermediate stocking rates. Cow-calf or mixed CCBG systems, and all farms used rotational grazing. The entire land area consists of natural grasslands, and off-farm feeds are not used. All of the farms implemented at least 3 types of livestock management controls, 80% of the farms had seasonal mating of the herd, medium weaning rates, and all farms had medium or high levels of technical advice. Highest level of record keeping. Moderately productive farms.
- Group IV (20% of farms): Intermediate emitters per LW sold and per hectare. Very good management, highest weaning and intermediate stocking rates. Cow-calf, BG or mixed CCBG systems, and all farms had rotational grazing. Almost all of the land area is natural grasslands, and most of farms use off-farm feeds. All of the farms provided the highest level of livestock management controls and had seasonal mating of the herd, highest weaning rates, and 83% of farms had technical advice. Medium level of record keeping. Moderately productive farms.
- Group V (10% of the farms): Lowest emitters per LW sold, and intermediate emitters per hectare. Good management and intermediate stocking rates. None of the farms were cow-calf systems, solely. All farms had rotational grazing. Highest proportion of land used for introduced pastures and annual forage crops, and most farms used off-farm feeds. All of the farms provided the highest level of livestock management controls, had seasonal mating of the herd, and 67% of farms had technical advice. Low levels of record keeping. Highest farm productivity.

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Table 5. Mean values for continuus variables by cluster group

Variable	Cluster group I n=7	II n=9	III n=5	IV n=6	V n=3	Sig.[a]
Socio-economic data						
Age (years)	61	58	48	49	55	n.s.
+Hired labor (WU/LU) (x10^{-3})	1.0[a]	0.2[a]	4.6[b]	2.9[ab]	1.3[ab]	***
Land use						
+Total land area (ha)	1077[a]	1673[a]	7010[b]	3284[ab]	10200[ab]	**
+Land area used for native pastures (%)	100[b]	98[b]	100[b]	94[ab]	64[a]	**
+Land area used for improved pastures (%)	0[b]	0[b]	0[b]	6[ab]	26[a]	***
Land area used for forage crops (%)	0[b]	2[ab]	0[b]	0[b]	10[a]	*
Beef cattle						
+Total Livestock Units	51.6[a]	194.4[ab]	482.1[b]	328.0[ab]	1207.0[b]	***
Mortality rate (%)	11.9	10.0	2.3	2.2	2.2	n.s.
Stocking rate (LU/ha)	0.07[a]	0.19[b]	0.08[ab]	0.10[ab]	0.19[ab]	*
Grazing infrastructures						
Water reservoirs per ha (x10^{-3})	3.0[ab]	5.2[a]	0.9[b]	1.4[ab]	1.4[ab]	*
Water reservoirs/LU (x10^{-3})	46[b]	27[ab]	12[a]	17[ab]	8[a]	**
+Grazing paddocks/ha (x10^{-3})	2.6	7.2	1.1	2.4	2.2	n.s.
System productivity						
Average Live Weight of livestock (kg)	272	284	302	283	271	n.s.
Weaning rate (%)	49[a]	63[ab]	69[ab]	82[b]	73[ab]	*
+Land productivity (kg LW sold/ha)	4.7[a]	20.3[b]	11.3[ab]	19.6[ab]	52.9[b]	***
Animal productivity (kg LW sold/LU)	74[a]	123[ab]	160[ab]	144[ab]	283[b]	*
Farm greenhouse gases emission intensity						
Kg CO_2e/kg LW sold	27[b]	20[ab]	15[ab]	19[ab]	8[a]	*
Kg CO_2e/ha	121[a]	372[b]	166[ab]	266[ab]	403[ab]	**

WU, Work Unit. LU, Livestock Unit. LW, Live Weight

+ Variables used in the Principal Component Analysis and in the Cluster Analysis.

[a] Sig. = significance based on Kruskal Wallis test.

* = P < 0.05, ** = P < 0.01, *** = P < 0.001. Different letters in the same row indicate significant differences between groups (Dunn-Bonferroni post-hoc test).

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Table 6. Frequency (% of farms) of discrete variables by cluster group.

Variable	Cluster group				
	I	**II**	**III**	**IV**	**V**
	n=7	**n=9**	**n=5**	**n=6**	**n=3**
Socio-economic data					
+Level of education of farmer [1]					
None	0	22	20	0	0
Primary or Secondary school	100	78	20	0	100
Higher education	0	0	60	83	0
Willingness toward innovative changes[1]					
Positive	43	56	20	100	33
Negative	43	44	40	0	67
Type of production system					
Cow-calf	100	78	60	50	0
Backgrounding	0	11	0	17	33
Cow-calf+ Backgrounding	0	11	40	33	67
Grazing system					
Continuous	71	22	0	0	0
Rotational	22	78	100	100	100
+**Feed purchase**					
Yes	0	89	0	83	67
No	100	11	100	17	33
Technical management of the farm					
+Livestock care controls[2,3]					
None	43	13	0	0	0
One or two control types	43	25	0	0	0
Three or more control types	14	62	100	100	100
Reproductive management of the livestock [3]					
Year-round mating	100	50	20	0	0
Seasonal mating	0	50	60	100	50
Seasonal mating + artificial insemination	0	0	20	0	50
+Technical advice					
None	100	78	0	17	33
Veterinarian or Agronomist	0	22	60	33	67
Veterinarian and Agronomist	0	0	40	50	0
Record-keeping[1]					
Yes	29	56	80	67	33
No	57	44	0	17	67

+ Variables used in the Principal Component Analysis and in the Cluster Analysis.

[1]Remaining farmers, Do not know/No answer.

[2]Types of livestock care controls: body condition, teeth examination, rectal palpation/ecography, parasite control, reproductive vaccine, bull review control.

[3]n=27 (backgrounding farms excluded).

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Table 7. Main characteristics of each cluster group, based on Tables 5 and 6.

	Cluster group				
	I	II	III	IV	V
Education level	medium	lowest	medium	highest	medium
Hired labor	low	lowest	highest	medium	medium
Total land area	lowest	low	highest	medium	medium
Land area used for native pastures	highest	highest	highest	high	lowest
Land area used for improved pastures	lowest	lowest	lowest	low	highest
Land area used for annual forage crops	lowest	low	lowest	lowest	highest
Livestock Units	lowest	medium	high	medium	highest
Stocking rate	lowest	highest	medium	medium	medium
Dependence on off-farm feeds	lowest	highest	lowest	high	medium
Water reservoirs per total land	medium	highest	lowest	medium	medium
Water reservoirs per LU	highest	medium	low	medium	lowest
Livestock care controls	lowest	medium	highest	highest	highest
Technical advice	lowest	low	highest	high	high
Record-keeping	lowest	medium	highest	medium	low
Weaning rate	lowest	medium	medium	highest	medium
Land productivity	lowest	highest	medium	medium	highest
Animal productivity	lowest	medium	medium	medium	highest
Emission intensity per LW sold	highest	medium	medium	medium	lowest
Emission intensity per land area	lowest	highest	medium	medium	medium
Main grazing system	CON	ROT	ORO	ORO	ORO
Main system	OCC	CC	CC	CC	CCBG
Main reproductive management	OYR	YRS	S	S	S

Cell shading indicates the values reached by the variable (☐ lowest; ☐ low; ☐ medium; ■ high; ■ highest). CON=Continuous, ROT=Rotational, ORO=Only rotational, OCC= Only cow-calf, CC= Cow-calf, CCBG=Cow-calf and Backgrounding, OYR=Only year-round, YR=Year-round, YRS=Year-round/Seasonal, S=Seasonal

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4. Discussion

GHG farm emissions varied widely among the 30 farms surveyed in the semiarid rangelands of central Argentina, which reflected the high diversity in the types of production systems [27, 55]. Variability is especially high in studies that have been based on actual farm survey data [15,27].

In our study, on a product sold basis, cow-calf systems emitted more GHG than did backgrounding systems. Similar results have been reported in grasslands-based beef systems in Uruguay [15,16,56] and Argentina [57]. In our study, GHG emissions of cow-calf systems were similar to those of 295 cow-calf farms in Canada [27] and cow-calf systems based on native and improved grasslands in Uruguay [15]. Emissions from backgrounding systems were similar to those from background-finishing systems that had seeded pastures and feedlots in Uruguay [56].

On a farm-area basis, in our study, GHG emissions did not differ significantly among types of systems. The average was much lower that were previously reported values, which ranged between 265 and 9782 [27], and between 2334 and 3037 [58] in Canadian beef cattle production systems, between 1490 and 2827 in Uruguayan beef systems [15], and between 7902 and 10913 in New Zealand pasture-based dairy systems [59]. The higher stocking rates in those studies (0.31, 0.77 and 2.3-3.0 LU/ha in Canadian, Uruguayan and New Zealander systems, respectively, versus 0.13 LU/ha in our study) were, mainly, responsible for the differences in emissions between those studies and ours. In our study, emission per hectare and stocking rate were positively correlated ($r = 0.900$, $P < 0.001$). In beef systems in the Brazilian Amazon [60] and in dairy systems in Ireland [61], emissions per hectare and stocking rates were positively correlated. Livestock density on extensively managed grazing lands are relatively low; therefore, CH_4 emissions per unit area from these grazing lands is much lower than are those from intensively managed grazing lands [34,62]. Although the contribution of extensively managed grasslands to GHG emissions is expected to be low per unit area because of low livestock densities and agronomic inputs, the absolute global contribution might be high because of their large land area [62].

In our study, on a product sold basis, animal productivity was the variable that best explained the largest amount of the variance in emission intensity, which was negatively correlated with productivity. To a lesser degree, land productivity and emission intensity were negatively correlated. Improving production efficiency has been recommended as a strategy to mitigate GHG emissions in beef systems [15,16,27,56,63,64,65]. For instance, Alemu et al. [27] found that low-emitting farms had higher animal and land productivities than did high-emitting farms in Canadian cow-calf systems. In French suckler-beef production farms, animal productivity was the main factor influencing GHG emissions (64), which suggested that technical efficiency was a factor. Becoña et al. [15] found that beef farm productivity was one of the main determinants of GHG emission in Uruguayan cow-calf systems. The same negative correlation was found in dairy systems [66,67], mainly because emissions are spread over more units of output per cow, which dilutes emission intensity. Productivity gains are generally achieved through improved husbandry practices and technologies that increase the proportion of resources used for production purposes rather than for the maintenance of the animals, which contribute to emissions reductions [2]. Farm improved productivity can result from a combination of several types of strategies.

On the beef farms in our study, continuous stocking practices emitted significantly more GHG per product sold than did rotational stocking. Beef cattle in rotational stocking systems emitted less methane than did cattle in continuous grazing [36]. Furthermore, good grazing management can have a positive impact on soil carbon sequestration [2].

Improved livestock care management were associated with reduced GHG emission intensity per kg LW sold in our study. Improved animal health can increase herd productivity and reduce GHG emission intensity [25]. Along with improved reproduction management, improved animal health helps to reduce the unproductive portion of the herd and associated emissions and, concomitantly, these measures increase productivity [2]. Preventive health measures can play a role in increasing growth and fertility rates, which improves animal and herd performance [2]. Llonch et al. [28] reported a reduction in rumen methanogenesis in response to an increase in production efficiency

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caused by improvements in the health status of the herd, which is a win-win strategy because it increases environmental sustainability and animal welfare.

In our study, farms that had received technical advice had lower emissions per unit of product sold, which reflected the importance of the technical advice in grazing management planning, feeding, health care and reproductive management of the herd, and overall farm system management [68,69].

Land-related variables can affect GHG emissions from animals through diet quality [27]. Diet digestibility directly reduces CH_4 emission intensity [63,70], which was apparent on farms that had increased the area of improved pastures, including seeded pastures, oversowing with legumes, and annual winter crops for grazing [15]. In our study, such an effect was not apparent, probably because of the small proportion of the farmland that had been used for improved pastures or annual forage crops (mean = 6%, vs. 20.5% in the study by Becoña et al [15].

Many of those husbandry practices are associated with increases in productivity, which suggests that an economic benefit can be realized with a concurrent reduction in GHG emissions [27]. Strategies that both improve production efficiency and reduce GHG emissions are those most attractive to and most likely to be adopted by farmers [27]. Further studies should compare the economic impact of several measures to mitigate GHG emissions and willingness to adopt them in our study area.

In our study, emission intensity per hectare of farmland was positively correlated with stocking rate and land productivity. Similar results were reported by Becoña et al. [15] in beef cow-calf systems. In Irish dairy farms, Casey and Holden [17] found a significant positive correlation between stocking rate and the amount of GHG emissions per hectare. Bava et al. [67] found a strong positive correlation between emissions per land area and stocking rate in dairy systems. Stocking rate and total dry matter intake, are the main factors driving production per hectare and GHG emissions from grazed pastoral systems [8]. The number of grazing paddocks per hectare and the proportion of land used for improved pastures and annual forage crops were positively correlated with GHG emissions per hectare of land area in our study. Higher stocking rates and land productivity, coupled with higher density of grazing paddocks and land use for improved pastures and forage crops, reflect a certain degree of intensification of the farming system, i.e., intensification implied higher emissions per hectare. Bava et al. [67] concluded that intensification, defined as increase in output per hectare, invariably led to higher emissions on a per-area basis. Nevertheless, emissions per unit of product and land productivity were negatively correlated, which illustrates the potential trade-off between carbon efficiencies per unit of product and per unit of land, i.e., is it possible to reduce emissions per unit of land and per unit of product at the same time?

The CA indicated that, if GHG emissions are evaluated on a land-unit basis, farms that had less emissions (group I) were the most extensive in terms of land use, had the lowest stocking rates, dependence on off-farm feeds, land productivity, and proportion of land used for improved pastures or annual crops. Farms in that group, however, had the lowest level of husbandry practices (livestock care controls and reproductive management, technical advice, record keeping), weaning rate and animal productivity and, concomitantly, had the highest emissions per product sold. From that 'base-line' traditional farming system, strategies can differ considerably in practice and results in terms of farm productivity and emissions. Farms in group II intensified the system by increasing stocking rates and dependence on off-farm feeds, and improved some husbandry practices, which lowered emissions per product sold, but produced the highest emissions per hectare. Farms in group V had the highest proportion of land as improved pastures and annual forage crops, medium stocking rates, improved livestock husbandry practices, and had intermediate levels of emissions per hectare. That group had the lowest emissions per product sold because of those improvements, but also because of the high proportion of backgrounding on the farms in this group. Groups III and IV had the highest level of husbandry practices, but they did not have stocking rates that were as high as those in group II. Thus, those groups, III and IV, had intermediate levels of farm productivity and emissions per product sold and per hectare.

The CA suggested that farms that had a high level of husbandry 'intensification' through livestock care and reproductive management achieved high animal productivity and, therefore, low

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GHG emissions per product sold compared to 'base-line farms' (group I). Thus, if land productivity is increased by using that high-output animals strategy, emissions per hectare can be limited to intermediate levels; however, if land productivity is maximized through high stocking rates, emissions per hectare is highest, such as in group II. Becoña et al. [15] stated that both emission per unit of land and per unit of product can be reduced concurrently, and suggested that the key factor is reducing stocking rate (or increasing forage allowance) in grazing beef cow-calf systems. GHG emission intensity can be reduced through changes in animal husbandry practices that increase animal outputs [15,63]. Casey and Holden [17] suggested that it is physically and biologically possible to achieve low emissions both per unit of land and per product by using high output cows at low stocking rates in dairy systems; i.e., a move toward fewer cows producing more milk at lower stocking rates is required, which represents an extensification in terms of area, but an intensification in terms of animal husbandry practices. In a simulation experiment on pasture-based dairy farms in New Zealand, Beukes et al. [59] maintained production but reduced GHG emissions per unit of land and per unit of product by increasing efficiency (e.g., reducing the number of non-productive animals in the herd, among other mitigation strategies), which allowed stocking rates to be reduced. Mitigation of GHG emissions per unit of product should be based on husbandry systems intensification rather than on land intensification, which might lead to potential losses in ecosystem services provisioning, increases in GHG emissions per unit of area and other environmental impacts such as eutrophication and acidification [16].

Among the beef cattle farms in our study, those in groups III and IV could reduce further emissions intensity by adopting practices such as improving feed quality [63,23,27], using superior animal genetics [71], or increasing the proportion of backgrounding vs. cow-calf in the farm system. Feed quality can be increased by applying seeding grasses to improve native pastures, annual forage cropping, and by purchasing high-quality off-farm feeds. However, introduced grasses can increase the impact on native grasslands, with potential biodiversity, wildlife habitat and landscape losses [56,16]. Mitigation of climate change should not be associated with directly reducing biodiversity [16]. In several regions of the world, pasture intensification has been used to increase productivity, incomes, and mitigate GHG, but has increased rangeland degradation [33]. Annual cropping systems have relatively high levels of agronomic inputs and nutrient leakage, frequent and significant disturbances of soil surface, and net losses of soil organic content [34]. In addition, CO_2 emissions derived from fertilizers and machinery operations for annual forage crops are high [27]. Feed quality can be improved by purchasing high-quality feeds, but the embedded emissions associated with feed production should not be ignored. Alemu et al. [27] found that minimizing purchased cereal grain and forage per unit cow reduced emissions associated with the production and transportation of farm inputs. In strategies such as improving genetic merit, the animals have to be selected not only for their high efficiency in transforming feeds, but also for their ability to adapt to rough environments and low-quality feeds [72], which are characteristic of the semi-arid rangelands of central Argentina. In addition, to reduce emissions per unit of product, farmers can increase the proportion of backgrounding versus cow-calf in their system; however, this strategy can transfer the negative environmental impacts of the cow-calf phase to other areas, i.e., the emissions of the replacement stock, if purchased, have occurred elsewhere on other farms [73].

Our results from actual semi-arid rangeland beef systems in central Argentina suggest that the implementation of relatively easy-to-adopt farming management practices has considerable potential for reducing GHG emissions per unit of product and per unit of land area. At the same time, the preservation of rangeland ecosystem services should be a target.

The expansion of agriculture and an increase in the intensification of livestock systems have challenged the integrity of rangelands in Argentina and worldwide. Future research should assess the ecosystem services provided by the beef production systems in the semi-arid rangelands of Argentina; e.g., wildlife biodiversity and landscape preservation, animal welfare, nutrient cycling, hydrologic conditions, control of invasive plant species, and carbon sequestration. Grazing lands have high potential for carbon sequestration [24,74,75] which can, at least partially, mitigate the GHG emissions from ruminant production systems [76]. Extensive livestock grazing systems had lower GHG emission intensity if soil carbon uptake had been included in the emission inventory

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[16,64,77,78,79], particularly for low-input grazing systems [21]. Therefore, land-use decisions should be informed by all environmental factors, negative impacts –not only GHG emissions- and ecosystem services. In order to increase the sustainability and the efficiency of beef livestock systems in the Argentinean semi-arid rangelands, future studies should use an integrated, holistic approach.

5. Conclusions

This study assessed the relationships between GHG emissions and characteristics and management practices of commercial farms in extensive beef systems that are based on natural rangelands in the semi-arid Central Region of Argentina. The results suggest that the implementation of realistic, relatively easy-to-adopt farming management practices has considerable potential for mitigating GHG emissions. Emissions per product sold were low on farms that had improved livestock care management, had rotational grazing, received technical advice, and had high animal and land productivities. Emissions per hectare of farmland were low on farms that had low stocking rates, low number of grazing paddocks, little or no land dedicated to improved pastures and annual forage crops, and low land productivity.

Therefore, in our study, the set of variables that influenced the emissions per hectare of farmland differed from those that affected emissions per unit of product, and land productivity affected the two types of emission expressions in opposite directions, which suggests a potential trade-off between the mitigation of GHG emissions per unit of product and per unit of land. Given that GHG emissions per product and per hectare of farmland differ in their implications for the assessment of environmental impacts of food production (e.g., global vs. local scales, intensification processes), both measures should be taken into account and reconciled as much as possible.

The results of our study suggest that the mitigation of GHG emissions per unit of product should be based on the improvement of livestock care and reproductive management, rather than on land intensification through the maximization of stocking rates and land productivity, which might increase GHG emissions per unit of land area and lead to potential losses of rangeland ecosystem services provisioning.

To identify ways to increase the sustainability and efficiency of the management of beef livestock systems in the Argentinean semi-arid rangelands, future studies should use an integrated, holistic approach in which all negative environmental impacts and the provisioning of ecosystem services, e.g., diversity preservation and carbon sequestration, should be assessed.

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Appendix A

IPCC (2006) [1] equations used in the calculations of the on-farm CH4 and N2O gases emissions were: 10.3, 10.4, 10.6, 10.8, 10.13, 10.14, 10.15, 10.16, 10.17, 10.18, 10.19, 10.20, 10.21, 10.31, 10.32, 10.33, 11.1, 11.5, 11.11.

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