

Article - Environmental Sciences

Farm Characteristics and Cradle to Farm Gate Beef Carbon Footprint of Grass-based Beef Cattle Fattening Farms in Colombia

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HIGHLIGHTS

- The carbon footprint (CF) of large beef cattle farms was determined using LCA.
- Higher farm productivity was related to greater use of fossil fuels and electricity.
- Average daily gain was the variable that most influenced the carbon footprint.
- Two farm clusters were identified that differed greatly in carbon footprint.

Abstract: The proper management of agricultural systems requires knowledge of their characteristics, which is also necessary to optimize their productivity and reduce their environmental impact. The cradle-to-farm gate carbon footprint (CF) of 39 beef production farms located in nine departments of Colombia was estimated using the life cycle assessment (LCA) methodology. Farms were characterized with respect to livestock composition and management, pasture management practices, and productive (live weight gain, LWG) and reproductive information. Average daily gain (ADG) was the variable that most influenced the magnitude of the CF. By grouping by their main characteristics, a farm cluster containing 56% of the farms showed an average footprint of 11.6 kg CO₂-eq kgLWG⁻¹, lower than the average for Colombian farms (15.5 kg CO₂-eq kgLWG⁻¹) and a ADG of 0,49 kg d⁻¹. In turn, a second farm cluster (44% of the farms) had an average footprint of 21.1 kg CO₂-eq kgLWG⁻¹ and a ADG of 0,37 kg d⁻¹. In general, farms with higher animal productivity and stocking rate, had also greater use of fossil fuels and electricity, and also greater area of the farm as forests, all of which was associated to lower CF. Under the conditions evaluated, to produce meat with lower CF, strategies designed to increase ADG must be promoted, especially those related to adequate grazing management.

Keywords: Animal productivity; beef cattle systems; farm characterization; grazing management; life cycle assessment.

INTRODUCTION

Meat and milk production is one of the main agricultural activities in Latin America, with a high proportion of animals in extensive grazing systems [1]. Global greenhouse gas (GHG) emissions of the livestock supply chain corresponded to approximately 7.1 Gt CO₂-eq yr⁻¹, or about 14.5% of total global anthropogenic emissions [2]. It is estimated that 44% of these emissions come from methane (CH₄), 29% from nitrous oxide (N₂O) and 27% from carbon dioxide (CO₂) [2]. In Colombia, agriculture is one of the main GHG-emitting sectors (26%), of which enteric fermentation and renewal of permanent crops contribute to 31% and 30% of those emissions [3].

Colombia ranks fourth in Latin America in bovine inventory [4], with approximately 29.6 million animals in 2023 [5], 46, 39 and 15% of which are in beef, dual-purpose and dairy farms, respectively [6]. Livestock farming, the main agricultural activity in the country, generates 810,000 direct jobs (6% of national and 19% of agricultural employment), and contributes 1.4% of the national gross domestic product (GDP), 21.8% of the agricultural GDP and 48.7% of the livestock GDP [7]. This activity is carried out on approximately 621,000 farms, of which 82% have less than 50 animals, and the main products are milk and meat. From 2018 to 2023, the annual production of carcass meat was 743,000 tons [8]. The beef production chain in Colombia comprises cow-calf, fattening, and full-cycle farms, that account for 43, 39 and 18% of the Colombian beef herd, respectively [9]. Gonzalez – Quintero and coauthors [9] identified three farm clusters either for the cow-calf and fattening systems. Both production systems had a cluster of farms with low carbon footprint, non-renewable energy use, and land use, and were characterized by a higher percentage of the area of improved pastures, forage production, and better grazing management practices.

Farm characterization allows to identify strengths and weaknesses in their technical, productive, reproductive and environmental components [10]. This enables the identification of the factors limiting farm productive efficiency and of technological strategies to increase their productivity and guide the implementation of GHG mitigation actions [11]. Identifying the different types of producers within a region allows development actions to be specifically focused, so that resources and efforts are not dispersed or wasted [12].

The CF is an indicator of the direct and indirect GHG emissions of a product or service, and its estimation allows us to implement GHG emissions reduction and/or mitigation strategies and is quantified through a Life Cycle Assessment (LCA) methodology. The LCA allows to quantify and evaluate the use of natural resources, and the environmental impacts associated with a product or service throughout its “life cycle”, a term that refers to the main activities that take place during the life of a product, from its manufacturing, use and maintenance, to its final disposal, including the manufacturing and transportation of the raw materials required for its production [13].

The present study was carried out to characterize beef farms located in nine Departments in Colombia using primary information obtained from surveys carried out on ranchers and/or farm managers. In the second stage, GHG emissions arising from on- and off-farm activities were quantified using the LCA methodology.

MATERIAL AND METHODS

Life Cycle Assessment approach

GHG emissions and their intensity (GHG emitted per unit of farm product) were estimated based on the LCA methodology. The LCA was carried out using the attributional method, whose objective is to quantify the possible environmental impacts of the main co-products of a system in a “status quo” situation. The standard employed was PAS 2050 [13], which is based on the LCA methodology and allows the quantification of GHG emissions in the life cycle of a product [14]. The modelling of each of the properties was carried out with Microsoft Excel®. To estimate the CF, the global warming potential (GWP) was used for a time horizon of 100 years for each of the GHG to be quantified: 1 for CO₂, 28 for CH₄ and 265 for N₂O [15].

Objective, scope, and functional unit

The system boundary was defined by the environmental impacts related to beef production farms in a “cradle to farm gate” perspective (Figure 1). Primary GHG emissions, also called direct emissions, are those generated within the farm, and secondary GHG emissions are those generated outside the farm related to the production and transportation of raw materials such as supplementary feeds, agrochemicals, fossil fuels and electrical energy [14]. The functional unit used corresponded to 1 kg of live weight gain produced on the farm.

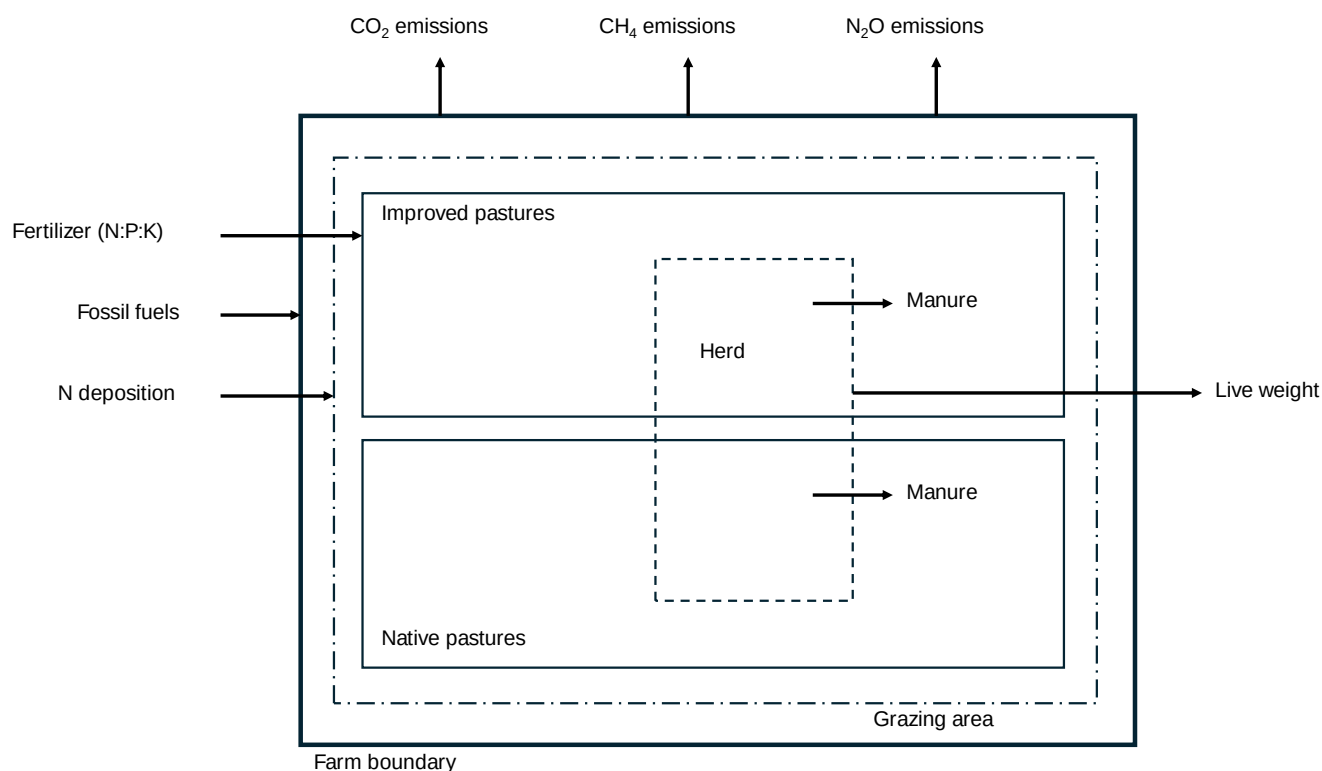


Figure 1. System boundaries and flows considered for carbon footprint estimation on fattening farms in a “cradle-to-farm gate” approach. Adopted from González-Quintero and coauthors [9]. Manure includes both cattle dung and urine [16].

Life cycle inventory and impact assessment

The present study included data collected in surveys carried out in 9 Departments (Antioquia, Bolívar, Casanare, Cesar, Córdoba, Magdalena, Meta, Norte de Santander, and Santander) during the months of September 2022 to March 2023. To that end, either farm managers or cattle ranchers were interviewed to provide answers for a questionnaire that included five components: (1) general information about the farm, (2) cattle herd composition and management, (3) pasture management practices, (4) cattle productive and reproductive information, and (5) environmental information as described by Gonzalez – Quintero and coauthors [9]. Both categorical and numerical variables were included in each of the five information components mentioned. Data was obtained to represent a typical cattle fattening farm during a calendar (365-d) year and animal inventories included both information on purchased and farm-grown animals.

Live weight gain (LWG) was quantified as the weight of animals produced on the farm, and that were sold or left the farm. The total live weight produced by the farms corresponded to the difference between final and initial weight of the animals. The gross energy (GE) requirement was estimated for each animal category, and was derived from the digestibility of the diet, which corresponded mainly to pastures, and the daily energy requirements for maintenance, activity, and growth.

Dry matter intake was calculated by dividing the gross energy requirement for each animal category by the energy density of the feed ($18.45 \text{ MJ kg DM}^{-1}$) [17]. Pasture productivity ($\text{t DM ha}^{-1} \text{ yr}^{-1}$) and nutrient content and digestibility (%) were obtained from ALIMENTRO [18], an information system that provides data on the nutritional composition of forage resources available in Colombia.

Estimation of on-farm GHG emissions

Primary and secondary emissions were estimated following the 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories [17]. Equations and emission factors (EF) used to estimate emissions within the farm for each gas are presented in Table 1. The amount of dry organic matter in the manure was calculated based on DMI of the different animal categories, the digestibility and ash content of the diet, in addition to the methane production capacity, and the CH₄ conversion factor. GHG emissions generated from animal respiration and those resulting from the construction of infrastructure and acquisition of machinery and equipment, were not taken into account as they represent less than 1% of total emissions [14, 19].

Nitrogen (N) balance at farm level

The nutrient balance is a tool that allows quantifying the flow of nutrients in agricultural systems [20]. The N balance at the farm level was carried out to identify possible N surpluses and, therefore, the risk of N leaching. The N surplus is defined as the difference between the net production of N in the live weight and the net input of N to the farm [21], as follows:

$$\text{Total N surplus (kgN ha}^{-1}\text{yr}^{-1}) = \Sigma \text{N inputs} - \Sigma \text{N outputs}$$

Nitrogen inputs were calculated by multiplying the amount of external feeds and fertilizers used by the farm in a year by its N content, values that were obtained from the literature. A standard annual N deposition (N input) of 15 kg N ha⁻¹ yr⁻¹ was assumed [22]. N fixation was assumed null due to the absence of legumes on the farms. N outputs were calculated by multiplying the amount of N by the live weight produced. The N content in live weight was estimated based on its protein content [23]. The surplus N must be translated to different emissions, with N₂O-N and NH₃-N losses being calculated using emission factors provided by Hergoualc'h and coauthors [24] (Table 1).

Table 1. Emission factors for estimating emissions within the farm.

Gas	Sources	Equation	Equation number ¹
CH ₄	Enteric fermentation	CH ₄ = [GE × (Ym /100) × 365]/ 55.65]	Equation 10.21 in IPCC
		GE = [(NEm + NEa + NEI + NEp /REM) + (Neg / REG)] (DE%/100)	Equation 10.16 in IPCC
		NEm: net energy required by the animal for its maintenance, MJ day ⁻¹	Equation 10.3 in IPCC
		NEa: net energy for animal activity, MJ day ⁻¹	Equation 10.4 in IPCC
		NEg: net energy required for growth, MJ day ⁻¹	Equation 10.6 in IPCC
		NEI: net energy for lactation, MJ day ⁻¹	Equation 10.8 in IPCC
		NEp: net energy required for pregnancy, MJ day ⁻¹	Equation 10.13 in IPCC
		REM: ratio between net energy available in the diet for maintenance and digestible energy	Equation 10.14 in IPCC
		REG: ratio between the net energy available for growth in a diet and the digestible energy consumed	Equation 10.15 in IPCC
		Ym : 0.07 (grazing)	
N ₂ O direct	N excretion in pastures and fertilization - N ₂ ON direct	CH ₄ = VS × B0 × 0.67 × MCF/100 × MS	Equation 10.23 in IPCC
		VS = [GE × (1 - DE/100) + (UE × GE)] × [(1 - Ash)/18.45]	Equation 10.24 in IPCC
		DE: degradability of feed MCF pasture: 0.47	
		Bo: 0.19	
N ₂ O indirect	N excretion in pastures and fertilization - indirect N ₂ O N from NH ₃	N ₂ ON = (FSN × EF1) + (Nex × EF3PRP, CPP)	Equation 11.1 in IPCC
		EF1: 0.01	Table 11.1 in IPCC
		EF3PRP, CPP: 0.004	Table 11.1 in IPCC
		Nex = N consumption – N retention	Equation 10.31 in IPCC
		N intake : DMI × (CP%/100/ 6.25)	Equation 10.32 in IPCC
		N retention: [(Milk × (Milk % / 100) /6.38] + {WG × [268 - (7.03 × Neg /WG)]/ (1000×6.25)}	Equation 10.33 in IPCC
		Milk PR%: [1.9 + 0.4 × % fat]	
		N ₂ ON = [(FSN × FracGASF) + (FPRP × FracGASM)] × EF4	Equation 11.9 in IPCC
		FracGASF Based on ammonia: 0.08 (0.02 - 0.3)	Table 11.3 in IPCC
		FracGASM : 0.21 (0.00 - 0.31)	Table 11.3 in IPCC
		EF4: 0.01 (0.002 - 0.05)	Table 11.3 in IPCC

¹Gavrilova and coauthors [23]

Estimation of emissions within the farm

The emission factors used to estimate off-farm GHG emissions from imported foods and fertilizers are summarized in Table 2. These GHG emissions corresponded to the production and transportation of these agricultural inputs.

Table 2. Estimation of off-farm GHG emissions (secondary emissions).

Input	Carbon footprint (kgCO ₂ -eq kg ⁻¹ input)
Synthetic fertilizer –	
N	6.6
P	3.6
K	0.7
Hay ^a	0.226
Mineralized salt ^c	0.155
Corn ground ^b	0.316
Soy cake ^b	0.186
Corn silage ^a	0.206
Truck 10-20t, Euro 4, 50%FL, default/GLO Economical ^a	0.254 ^d
^a Ecoinvent 3 [25]	
^b Agri-footprint [26]	
^c Life Cycle Data Network [27]	
^d kgCO ₂ eq t ⁻¹ km ⁻¹	

Multivariate statistics

A multivariate principal component analysis (PCA) and a hierarchical principal component cluster analysis (HCPC) were performed for the 39 surveyed farms following the PCA procedure of the FactoMineR package [28]. The PCA shows relationships between the CF and selected variables of interest such as LWG, number of animal units on the farm, average weight of animals, consumption of fossil fuels, use of electrical energy, and stocking rates. A numerical classification of the farms was performed using the HCPC procedure. Ward's algorithm was used to build the tree and to consolidate the k- means to establish farm groups or “clusters”.

RESULTS

Farm characterization

A typical herd in the farms evaluated was mainly composed of young (1 to 2 yr-old) and fattening (2 to 3 yr-old) steers, denoting their orientation towards meat production. The animal feeding system was based on annual grazing on natural and improved pastures, together with the supply of mineralized salt *ad libitum*. Farms had mostly a flat topography. The predominant improved pasture species corresponded to *Cynodon nlemfuensis*, *Bothriochloa pertusa*, *Dichanthium aristatum*, *Brachiaria arrecta*, *Megathyrus maximum*, and *Brachiaria decumbens*.

Concerning facility availability, all farms had a management corral, and the share of farms with warehouses, electric fencing, salting, and drinking troughs was greater than 83%. The most common machinery and/or equipment on the farms were manual sprayer (98%), motor sprayer (90%), scythe (88%), chainsaw (70%), electronic scale (68%), mechanical scale (63%), and electrical pump (50%). All farms possessed a scale, whether mechanical or electronic, hence live weight gain was determined with adequate precision.

Regarding pasture management practices, chemical fertilization and the application of soil amendments were not widely adopted practices: only one farm carried out pasture fertilization, and no single farm used soil amendments. On average, 95% of the farms keep production records, 85% practiced pastures rotation, and 98% controlled weeds through different methods (manual, mechanical, chemical, or mixed). Two farms used fires to renew their pastures and none of the farms implemented any excreta management practices, as all excretions were deposited over pastures. The use of supplementary (external) feeds was very low and only mineralized salt was supplied in all farms evaluated.

Carbon footprint of fattening production systems

In the present study, the average CF in the evaluated farms corresponded to 15.5 kg CO₂-eq kgLWG⁻¹, with a variation between 7.2 to 31.0. One of the processes that contributed the most to GHG emissions on the evaluated farms was enteric fermentation, a digestive process of ruminants in which different microorganisms ferment feeds and as a result, CH₄ is generated. All farms presented the same emissions pattern, to the effect that animal emissions (enteric fermentation and excretions) contributed on average 97.3% of the total CF. In turn, on average CH₄ emissions from enteric fermentation contributed the most to animal emissions (94.4%), while manure deposited in pastures contributed the remaining 5.6%.

In the present study, due to the greater use of machinery and equipment, the consumption of fossil fuels was high (on average 13.5 L ha⁻¹ yr⁻¹).

Principal component analysis

A principal component analysis (PCA) was carried out by including the characteristics and environmental performance of all farms belonging to the cow-calf or fattening systems, following the Kaiser-Guttman rule, which establishes that components with eigenvalues greater than 1 must be retained. Therefore, the first three components were retained in the PCA analysis, which explained 68.2% of the cumulative variance (Figure 2).

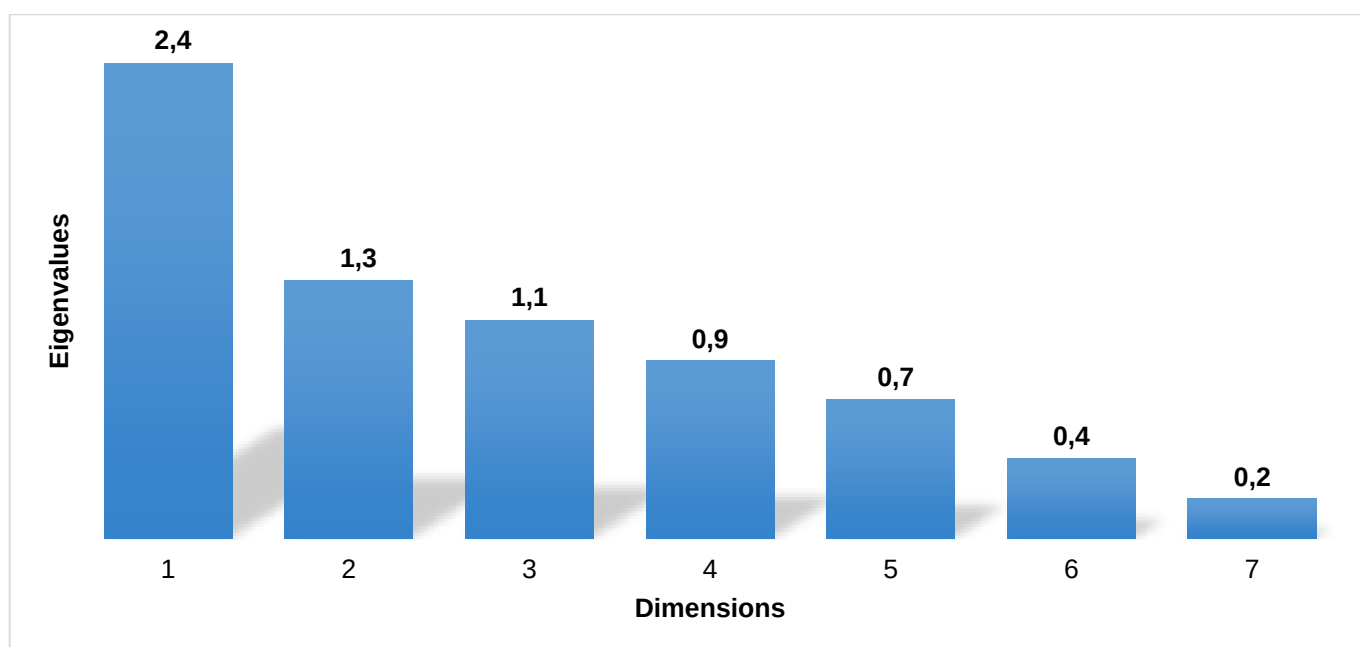


Figure 2. Eigenvalues for the principal component analysis

Analysis of the biplot for dimensions 1 and 2 resulting from the PCA (Figure 3), meat production, measured as LWG, was negatively correlated with the CF. Therefore, increasing the ADG would reduce the CF of the farms studied. Additionally, a positive correlation was evident between ADG and the use of fossil fuels on the farm, which suggests that the most productive farms had a greater use of machinery and equipment. The stocking rate, the number of animal units per farm, the average weight of the animals, and the use of electrical energy were positively correlated, which suggests that the largest farms, in terms of number of animals, had greater electric energy usage, heavier more animals, and a greater stocking rate.

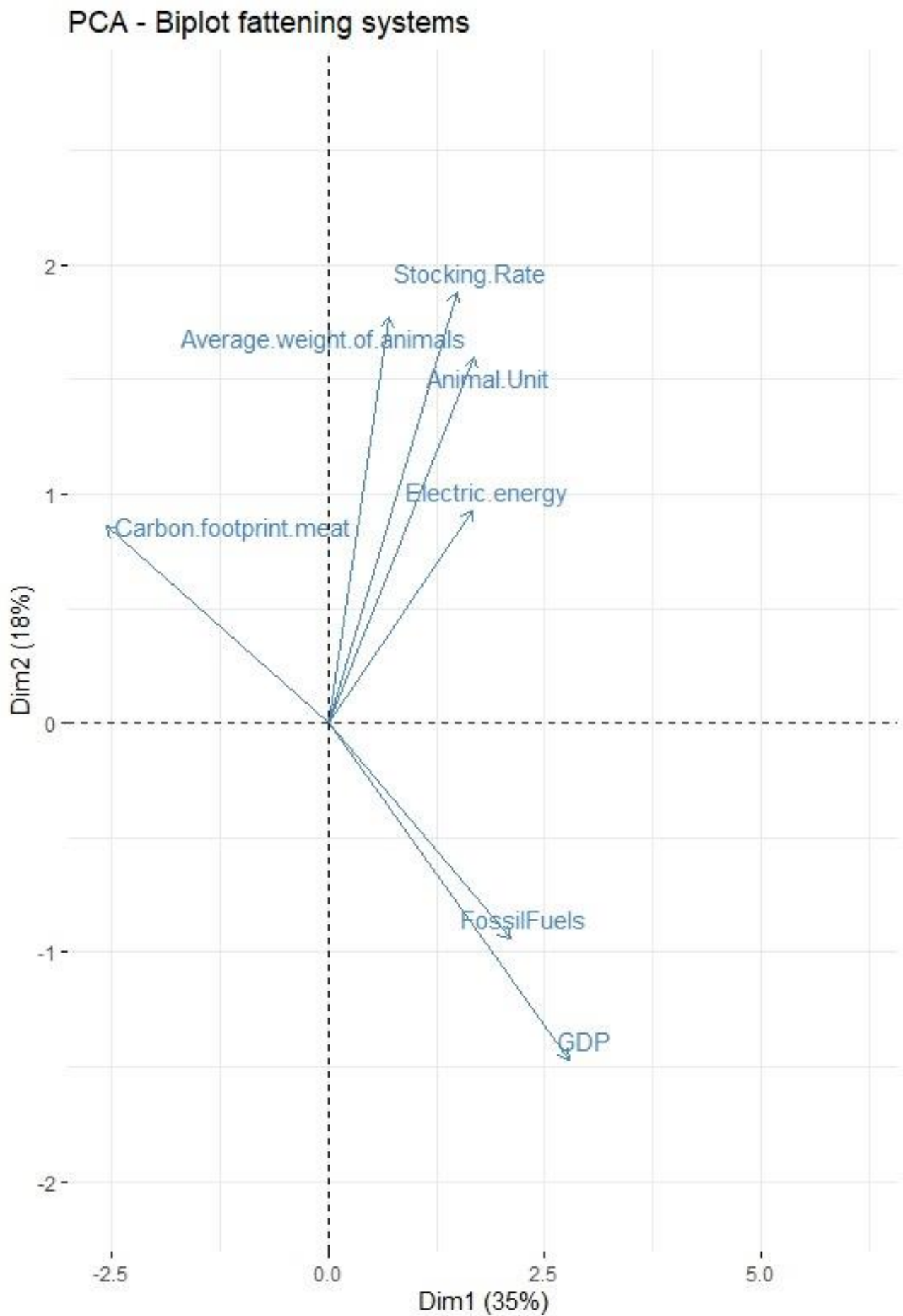


Figure 3. Biplot of dimensions 1 and 2 resulting from the principal components analysis.

Farm cluster interpretation

Two different farm clusters were identified, and their main characteristics are shown in Table 3. Farms in Cluster 2 had lower ($P \leq 0,05$) steer mortality rates and final steer age and tended to have a greater flat land area ($P = 0,11$) and meat production (kg ha^{-1} , $P = 0,059$) than farms grouped in Cluster 1. Thus, farms in Cluster 2 reported greater ($P \leq 0,05$) ADG values than those in Cluster 1. Cluster 2 also tended to have a more widespread incidence of ticks than Cluster 1 ($P = 0,09$). Finally, Cluster 2 had only 55% (11.6 vs $21.1 \text{ kg CO}_2\text{-eq kgLWG}^{-1}$; $P \leq 0,01$) the CF of Cluster 1.

Table 3. Means for selected farm variables for two farm clusters of 39 beef cattle farms in Colombia.

	Cluster 1 (n = 17)	Cluster 2 (n = 22)	P-value
Quantitative variables			
Total farm area, ha	951 ± 969	946 ± 722	0.98
Farm flat area, ha	442 ± 339	775 ± 778	0.11
Farm forest area, ha	153 ± 235	112 ± 96	0.45
Typical paddock size, ha	8.3 ± 11.5	12.7 ± 20.1	0.43
Grazing time per paddock, d	6.9 ± 5.6	8.3 ± 12.4	0.67
Pasture recovery time, d	30.4 ± 11.5	32.6 ± 9.3	0.54
Weed control events, n yr^{-1}	1.7 ± 1.2	1.9 ± 1.2	0.57
Gasoline used, gallons yr^{-1}	53 ± 61	43 ± 62	0.62
Diesel used, gallons yr^{-1}	64 ± 115	96 ± 195	0.58
Steer initial age, months	23.5 ± 5.2	21.0 ± 4.6	0.14
Steer initial weight, kg	323 ± 53	299 ± 59	0.19
Steer mortality, %	0.88 ± 0.86	0.47 ± 0.32	0.046
Steer final age, months	36.9 ± 4.2	32.3 ± 4.3	0.005
Steer initial weight, kg	468 ± 59	465 ± 49	0.86
Average daily gain, kg	0.37 ± 0.13	0.49 ± 0.15	0.011
Meat production, kg ha^{-1}	286 ± 187	189 ± 93	0.059
Qualitative variables			
Lameness incidence	65 ± 49	68 ± 48	0.83
Presence of ticks	41 ± 51	68 ± 48	0.09
Incidence of diarrhea	23 ± 44	14 ± 35	0.44
Tick control practices	82 ± 39	95 ± 21	0.19
Pasture renovation practices	65 ± 49	59 ± 50	0.73
Weed control practices	94 ± 24	100 ± 0	0.26
Chemical fertilization	12 ± 33	9 ± 35	0.79
Organic fertilization	14 ± 35	23 ± 44	0.44
Drinking troughs	76 ± 44	86 ± 35	0.44
Technical assistance	65 ± 49	77 ± 43	0.40
Carbon footprint			
$\text{kg CO}_2\text{-eq kgLWG}^{-1}$	21.1 ± 4.2	11.6 ± 2.4	0.001

DISCUSSION

Farm characterization

Characterization studies, among other benefits, are useful in identifying inefficiencies and for proposing good farming practices, technological strategies, and differential public policies for sectoral development [29]. This is important when increasing productivity and reducing negative environmental impacts are policy priorities.

The predominant improved pasture species used by farmers in this study are pastures of low to medium digestibility and typically of high fiber content, which is negatively associated with DMI and animal productivity [30]. Regarding the availability of machinery and/or equipment on the farms, results from the current experiment agree with reports by Gonzalez-Quintero and coauthors [29] that there was a close association between the presence of machinery, equipment and infrastructure, and the categories large and medium size beef farms in Colombia.

Carbon footprint of fattening production systems

The satisfaction of the increased world food demand generates major environmental impacts, such as global warming, soil degradation, deforestation, water pollution, and loss of biodiversity ([31]. In Colombia, including land use change, bovine systems contribute ca. 25% of total emissions, with enteric fermentation and excretions deposited in the field contributing 37 and 9% of the CO₂-eq emissions of the agricultural sector, respectively [32].

In this study, enteric methane was the largest contributor to beef farm carbon footprint. Globally, CH₄ is the largest source of GHG emissions in the livestock sector and represents 44% of its total emissions, with about 3.5 gigatonnes of CO₂-eq [33]. On the other hand, rumen CH₄ production can represent losses of 5.5 to 6.5% of total energy intake [31], with losses in low productivity systems reported as 7.0% for beef cattle consuming a diet with more than 75 % of forage [23], although a range of 2 to 12% has been reported [34].

In the present study, due to the greater use of machinery and equipment, the consumption of fossil fuels was high (on average 13.5 L ha⁻¹ yr⁻¹) when compared to the consumption of fossil fuels reported in a study of fattening production systems in Colombia (1.4 L ha⁻¹ yr⁻¹) in which very small, small and medium-size beef farms were evaluated [9].

Farm cluster interpretation

Most of the differences between farms grouped in the different clusters in this study are explained by their characteristics. For example, if grazing occurs mostly in a flat land area (as it would be the case of Cluster 2 farms), there would be lower metabolizable energy requirements for maintenance, as animals spend as much as 10 times energy climbing than walking on a flat land [35]. Likewise, the lower mortality reported for Cluster 2 farms would contribute to increase their efficiency, thus reducing the CF of Cluster 2 farms. In turn, Cluster 2 had greater ADG (kg d⁻¹) than farms in Cluster 1 (0.49 vs 0.37, respectively), implying greater DM intake values in Cluster 2, and perhaps, higher nutritional value of the pastures, better grazing management, or both.

Implications of current results for reduction of GHG emissions in tropical beef farms

The present results outline the possibilities of reduction associated with greater productive parameters in tropical beef farms, generating win-win scenarios both for beef cattle ranchers and for society. Similar results have been reported in the literature. For example, [36] reported that it was possible to reduce GHG emissions through the adoption of improved pastures, better agricultural management practices, efficient use of fertilizers, and optimal stocking rates. Likewise, Rivera and coauthors [37] comparing an intensive silvopastoral system (iSPS) with a conventional intensive system reported lower environmental burdens per unit of product in iSPS, due to lower GHG emissions and lower use of non-renewable energy. In turn, Gaviria and coauthors [38] reported that the nutritional quality of cattle diets influenced both voluntary intake and enteric CH₄ emissions, observing that in 250-kg steers, the inclusion of a legume (*Leucaena leucocephala* or *L. diversifolia*) increased DMI and reduced GHG emissions. Likewise, steers fed grass harvested at 45 days of regrowth had higher DMI and lower methane emissions than steers fed grass harvested after 65 days of regrowth. In another example, the inclusion of 26% *L. leucocephala* in a stargrass-based diet resulted in higher dietary content of crude protein, calcium and gross energy and lower NDF content in the diet, leading to the greater animal productivity frequently reported in iSPS [39]. Inclusion of *L. leucocephala* led to a 22% increase in DMI and reduced the loss of energy in the form of CH₄ emitted per kg of fermented DM by 35%, with iSPS becoming a viable alternative to reduce the CF of tropical beef cattle farming [39].

The adoption of different management and production practices can either reduce the environmental impact and/or increase carbon sequestration in livestock systems. According to Lerner and coauthors [40], greater biomass production, adequate pasture management (rotation and division of paddocks), and the implementation of different SPS arrangements, can increase up to four times the farm stocking rates compared to conventional systems, thus employing less land area to produce the same quantity of products. In turn, incorporating trees into croplands and pastures results in increased net C storage [41]. Estimates of the carbon sequestration potential of agroforestry systems are highly variable, ranging from 0.29 to 15.21 Mg C ha⁻¹ year⁻¹ above ground and 30 to 300 Mg C ha⁻¹ up to 1 m soil depth [42]. For SPS, the above-ground carbon sequestration potential ranges from 1.5 [43] to 6.55 Mg ha⁻¹ year⁻¹ [44]. The content of soil organic carbon can be increased between 20 and 100% when N₂-fixing tree legumes are incorporated since they promote greater plant productivity [45]. Radrizzani and coauthors [46] reported that in Queensland (Australia), SPS with *L. leucocephala* accumulated between 79 to 267 kg of N ha⁻¹ yr⁻¹ more than adjacent plots based on monoculture. In Colombia, it was reported that the aboveground carbon stock (Mg CO₂-eq ha⁻¹) was 13.42 in iSPS and 7.55 in control sites with conventional pasture monocultures [47]. Finally, Aynekulu and coauthors [48] reported that in Colombia with the adoption of SSP, pastures went from having an initial carbon stock (Mg ha⁻¹) of 34 to 39 in a period of 15-yr. These same authors also reported that pastures in Colombia contained on average 34 Mg of C ha⁻¹, while other arable lands had 36% less.

Proper grazing management also has the capacity to capture carbon in the soil and aboveground biomass. Both Maia and coauthors [49] and Soussana and coauthors [50] reported that, depending on the type of soil, pasture species, and type of management practices, traditional pastures can achieve carbon capture rates between 0.11 to 3.01 Mg C ha⁻¹ yr⁻¹, due to improved rotations, the inclusion of legume species, pasture renovation, and fertilization practices.

Although several successful strategies have been developed to increase pasture DM availability and nutritional quality, their adoption by farmers is limited, which is partly due to inadequate/insufficient technology transfer needed to guarantee access to the inputs, capital, and knowledge necessary for their implementation [51, 52]. Besides generating effective technology transfer programs, there is also the need to understand why the adoption of seemingly beneficial production strategies is often low among farmers, making it necessary to engage in understanding the reasons behind these adoption barriers. Policy design that includes the farmers intrinsic motivation for conservation and that facilitates their altruistic behavior may be effective in overcoming such barriers [53].

CONCLUSION

Two clusters of farms were identified with significative differences in CF and animal daily gain. A significant number of farms (56%) had lower CF than the average previously reported for Colombian farms (15.5 kg CO₂-eq kgLWG⁻¹) with important implications for what is achievable both in terms of farm productivity and CF. This is of great importance, as emissions from the beef sector are responsible for a big share of emissions from animal agriculture. Animal productivity, measured as ADG, was the variable that most influenced the farm CF.

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