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Carbon footprint, non-renewable energy and land use of dual-purpose cattle systems in Colombia using a life cycle assessment approach

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Abstract

Dual-purpose cattle systems (DPS) include more than 75% of all dairy cows in Latin America and produce 40% of total milk production. Colombia has the fourth largest cattle herd in Latin America, and DPS account for 39% of the cattle population, and 58% of national milk production. Therefore, focusing on reducing the carbon footprint of DPS can have a huge contribution on mitigating the environmental impacts of the cattle farming sector. The present study aimed to estimate, based on a farm gate life cycle assessment (LCA) approach, the environmental impact of 1313 dual-purpose farms in Colombia. The study also aimed at identifying the main hotspots of negative environmental impacts and proposing possible mitigation options and their cost-effectiveness. The impact categories such as carbon footprint (CF), non-renewable energy use, and land use were estimated using the 2019 Refinement to 2006 IPCC, databases, and locally estimated emission factors. Three methods of allocating environmental burdens to meat and milk products were applied. A principal component multivariate analysis (PCA) and a Hierarchical Clustering on Principal Components (HCPC) were performed. The largest source of GHG in dual-purpose cattle systems comes directly from enteric fermentation, and manure deposited on pasture. The proportion of environmental burdens allocated to meat differed, with the economic method assigning the greater burden (36%), followed by energy content (30%) and mass production (13%). Four farms clusters and two production strategies were identified, a more intensive strategy with high proportion of improved pastures and higher fertilizer application rates (Clusters 1 and 2), and a more extensive with low input of fertilizers and grazing on natural pastures (Clusters 3 and 4). Carbon footprint (CF) values ranged between 2.2 and 4.4 kgCO$_2$-eq per kg fat and protein corrected milk (FPCM) and between 9.5 and 19.5 kgCO_2-eq per kg meat among clusters. CF, land use, and non-renewable energy use were lowest for clusters 1 and 3. Concerning cost-effectiveness, the adoption of improved pastures is a negative-cost measure and a promising climate change mitigation option. Overall, the CF could be reduced by around 25 to 48% for milk and meat. Therefore, our results suggest that it is possible to reduce GHG emissions by adopting improved pastures, better agricultural management practices, efficient fertilizer usage, and using the optimal stocking rate. It is expected that these reductions can be achieved with at negative costs.

Keywords: Colombian cattle systems; environmental impact; global warming potential, greenhouse gases (GHG); livestock production systems; Mitigation

1. Introduction

By 2050, the global demand for animal products is expected to increase by more than 70% compared to the demand in the year 2010, due to accelerated population growth and increased individual incomes. Consequently, the livestock sector should increase production levels to satisfy the demand increase (Steinfeld et al., 2006). Yet, increasing production levels following a business as usual (BAU) approach would lead to increased greenhouse gas (GHG) emissions and greater use of natural resources. Therefore, livestock producers must adopt cost-effective and climate-friendly practices to increase their productivity, while also reducing their negative environmental impacts.

Dual-purpose cattle systems (DPS) constitute more than 75% of all dairy cows in Latin America, and are responsible for 40% of total milk production (Rivas and Holmann, 2002). DPS are defined as cattle production systems where the objective of the farmer is to derive economic benefits from the sale of both milk and meat. Specifically, cows are partially milked, and the residual milk is consumed by their calves (Rojo-Rubio et al., 2009). In Latin America, DPS based on extensive grazing systems, where the herd of cattle are maintained exclusively on pastures, with little or no use of external inputs. Consequently, production levels are low in comparison to specialized dairy systems (González-Quintero et al., 2020).

Colombia has the fourth largest cattle herd in Latin America (FAO, 2013), which in 2019 was comprised of 27.3 million heads with an annual milk and beef production of 7.3 million liters and 933 million kg, respectively (FEDEGAN, 2019). In Colombia, DPS account for 35% of the cattle population, and 58% of national milk production of the regular market. Most of the Colombian DPS farms are characterized by large natural open pastures, using low amounts of inputs and having low milk production per lactation (3.5 L cow^{-1} day^{-1}) (Carulla and Ortega, 2016; González-Quintero et al., 2020).

The Colombian government is committed to reduce the national GHG emissions by 20% from the national BAU scenario between the baseline year 2010 and the year 2030 (Gobierno de Colombia, 2015). This goal has underscored the need for implementing mitigation actions focusing on the productive sectors that contribute a large proportion of the GHG emissions. In Colombia, agriculture is responsible for 26% of national GHG emissions, and ruminant enteric fermentation contributes more than 31% of the GHG emissions attributed to the agriculture sector (IDEAM et al., 2016). Therefore, mitigation efforts to effectively reduce GHG emissions and meet the set targets should, inevitably, consider the Colombian cattle production sector.

Life cycle assessment (LCA) allows for the compilation and appraisal of inputs, outputs and potential environmental impacts of a product throughout its life from cradle to farm gate or to grave (Guinée, 2002). Worldwide, several studies have used the LCA methodology for the integral assessment of the environmental impacts and the identification of hotspots as well as enabling the identification of mitigation options for the activities with the higher impacts (Cardoso et al., 2016; Oishi et al., 2013; Rotz et al., 2016; Sejian et al., 2018; Styles and Jones, 2008; Thomassen et al., 2008b; Weiler et al., 2014). However, there are no studies that have evaluated the environmental performance of the Colombian DPS especially with data collected directly from producers, and in the Latin American region, studies that have assessed the carbon footprint of DPS are few (Gaitán et al., 2016; Mazzetto et al., 2020). To our knowledge, this study uses the largest number of farms for LCA's in DPS, dairy and beef systems in the world. The general lack of comprehensive studies makes it is difficult to establish appropriate GHG mitigation actions for the DPS. Such comprehensive studies would inform the development of more sustainable livestock farming systems and contribute to the accomplishment of national GHG emission reduction targets.

The present study aims to (1) estimate the environmental impact of dual-purpose farms quantified based on GHG emissions, non-renewable energy use, and land use (LU), using a farm gate LCA approach with data gathered directly from the farms in Colombia; and (2) to identify the main hotspots of negative environmental impacts; and propose possible mitigation options and their cost-effectiveness.

2. Materials and methods

2.1 Life cycle assessment approach

A LCA approach was used to assess the carbon footprint (CF; GHG emissions per kg product), non-renewable energy use, and land use of DPS in Colombia. The LCA was done by the attributional method, which aims to quantify the environmental impact of the main co-products of a system in a status quo situation (Thomassen et al., 2008a). The publicly available specification (PAS, 2050: 2011) (BSI and Carbon Trust, 2011) was used, which is based on LCA and allows the quantification of GHG emissions in the life cycle of products. Modelling was done with Microsoft Excel. For estimating CF, global warming potentials for a time-frame of 100 years were used: 28 for methane; 265 for nitrous oxide; and 1 for carbon dioxide (IPCC, 2014).

2.1.1 Goal and Scope

2.1.1.1 System boundary definition

The system boundary was defined by the environmental impacts related to the DPS in a "cradle to farm-gate" perspective (Figure 1). The direct or primary emissions are those generated within the farm system (on-farm) and the secondary (off-farm) emissions are those upstream emissions related to the production and transport of imported resources such as feed, fertilizer, and amendments to soils (BSI and Carbon Trust, 2011).

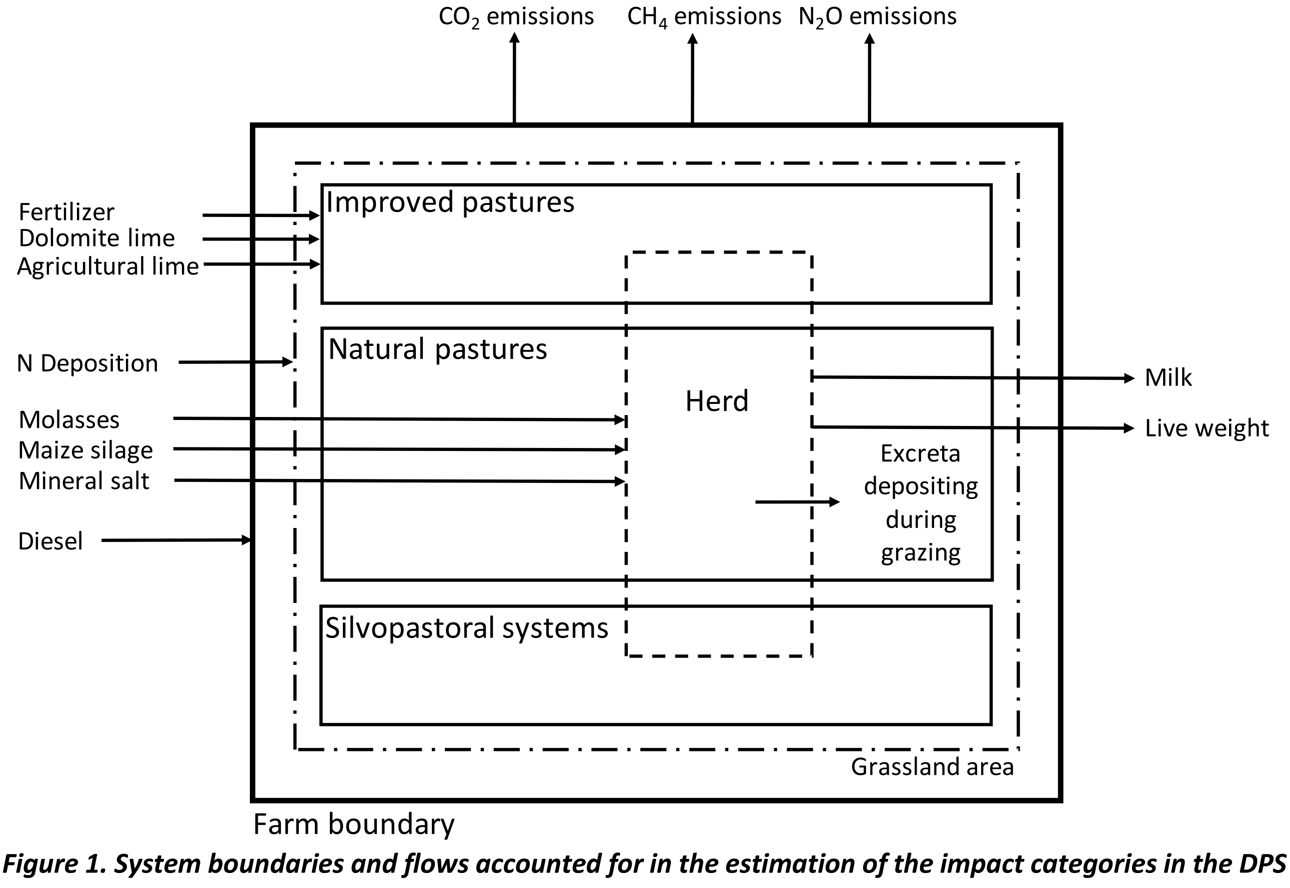

Figure 1. System boundaries and flows accounted for in the estimation of the impact categories in the DPS in a "cradle to farm-gate" approach

2.1.1.2 Functional unit and allocation

The functional units used were 1 kg fat and protein corrected milk (FPCM) and 1 kg live weight gain (LWG) leaving the farm gate.

When a process produces more than one output, the environmental burden must be assigned between those outputs based on an allocation method (BSI and Carbon Trust, 2011). To divide the environmental burden between milk and meat three methods were used (Rice et al., 2017):

a) Economic allocation that was based on the price per kg and the total amount of milk (FPCM) and meat (LWG) produced per year.
b) Energy allocation that was based on the energy content (MJ) and the total amount of milk (FPCM) and meat (LWG) produced per year.
c) Mass allocation was based on the quantity of milk (FPCM) and live weight gain (LWG) produced per year.

2.1.2 Life Cycle Inventory and impact assessment

2.1.2.1 Farm data

The present study includes data collected by using surveys conducted on 1313 farms located in 13 Departments within Colombia. The data represent one calendar year and were collected during the period 2014 to 2015 by 2 projects: Ganadería Colombiana Sostenible and LivestockPlus. The criteria used to select these farms, the information included in the surveys, the main characteristics of farms, and the description of the study area were specifically described by González-Quintero et al. (González-Quintero et al., 2020).

Milk production was standardized to fat (3.7%) and protein (3.3%) corrected milk (FPCM) (Carulla and Ortega, 2016). Live weight gain (LWG) was quantified as weight (kg) of animals produced from the farm, assuming no change in size of stock on the farm and no animals bought into the farm. Gross energy concentration was calculated from daily gross energy (GE) intake estimated for each animal category based on diet digestibility and daily net energy requirements for maintenance, activity, growth, lactation, and pregnancy. Dry matter intake (DMI) was computed by dividing herd specific gross energy intake values by the energy density of the feed (18.45 MJ per kg DM)(IPCC, 2019). Pasture productivity (t DM ha^{-1} yr^{-1}) and nutrient content and digestibility (%) were estimated based on (i) the region and municipality where the farm was located into the country, (ii) the identification of the main types of pastures for each region by using the atlas of bovine production systems in Colombia (Pulido-Herrera et al., 2005), and (iii) expert criteria. Use of fertilizer and lime was expressed as the amount applied over an area (ha) of improved pasture.

The average and the 5th, 25th, 50th, 75th and 95th percentiles of the variables used to describe the farms are presented in Table 1.

Table 1

Farm characteristics based on the 1313 farms located 13 states in Colombia.

	Dual-purpose cattle farms (n = 1313)					
	Mean	5th percentile	25th	50th	75th	95th
Herd, number of animals						
Cows	**25**	2	5	12	26	85
Female calves (0-1 year)	**8**	0	1	4	8	26
Male calves (0-1 year)	**7**	0	1	3	7	25
Female calves (1-2 year)	**6**	0	0	1	6	30
Male calves (1-2 year)	**5**	0	0	0	3	21
Heifers (2-3 years)	**6**	0	0	1	6	29
Steers (2-3 years)	**2**	0	0	0	0	10
Bulls, no	**1**	0	0	1	2	4
Male and female calves less 1 yr + heifers (1-3 yr) + Young bulls (1-3 yr), no per cow	**2**	0	1	1.3	2	4
FPCM[a], kg cow^{-1} year^{-1}	**1316**	571	1028	1199	1570	2385
Live weight gain, kg AU^{-1}(b)year^{-1}	**101**	50	72	93	120	181
Molasses, kg AU^{-1} yr^{-1}	**96**	0	0	131	172	196
Maize silage, kg AU^{-1} yr^{-1}	**88**	0	0	0	201	256

Mineral salt, kg AU^{-1} yr^{-1}	**31**	0	31	33	35	39
Gross energy, MJ day^{-1} AU^{-1}	**225.1**	159.8	196.0	222.2	250.8	301.3
Dry matter intake, T AU^{-1} yr^{-1}	**4.4**	3.2	3.9	4.4	5.0	6.0
Land						
Area, ha	**45**	4	8	16	39	181
Improved pastures, % of area	**22.0%**	0.0%	0.0%	0.0%	42.3%	93.0%
Silvopastoral systems, % of area	**0.31%**	0%	0%	0%	0%	0%
Natural pastures, % of area	**77.7%**	6.9%	57.1%	100%	100%	100%
For improved pastures						
Fertilizer[c], kg ha^{-1} yr^{-1}	**156**	25	119	119.32	180.23	350
Dolomite lime, kg ha^{-1} yr^{-1}	**315**	25	25	150	350	1500
Agricultural lime, kg ha^{-1} yr^{-1}	**209**	25	25	75	250	750
Production of pasture, T DM ha^{-1} yr^{-1}	**9.9**	8.0	8.0	8.0	11.5	14.6
Farm						
Stocking rate, AU ha^{-1}	**1.44**	0.26	0.65	1.18	2.05	3.41
Diesel, L ha^{-1} yr^{-1}	**1.42**	0.13	0.50	1.02	1.89	3.79

[a] FPCM: Fat Protein Corrected Milk (3.7% fat, 3.3% protein)

[b] AU: Animal Unit (1 AU being either 1 cow, or 3.3 female and male calves less than 1 year, or 1.7 female and male calves 1 - 2 yr, or 1.3 heifers 2-3 yr, or 1.3 steers 1- 2 yr, or 0.8 bulls)

[c] Fertilizer: 31(N): 8(P): 8(K)

2.1.2.2 Estimation of on-farm and off-farm emissions

Estimations of primary and secondary emissions were performed on an annual basis using 2019 Refinement to 2006 IPCC (IPCC, 2019). Equations and emission factors (EF) used for the estimation of the primary emissions of CH_4 and N_2O for each pollutant are summarized in Table 2.

Table 2

Emission factors (EF) for estimation of on – farm emission from dual-purpose farms

Pollutant	Source	Amount	Reference
CH_4	Enteric	$CH_4 = [GE \times (Y_m/100) \times 365)/55.65]$	Equation 10.21 in IPCC (Gavrilova et al., 2019)
		$GE = [(NE_m + NE_a + NE_l + NE_p/REM) + (NE_g /REG]/(DE\%/100)$	Equation 10.16 in IPCC (Gavrilova et al., 2019)
		Y_m: 0.07	(IPCC, 2019)
	Manure pasture	$CH_4 = VS \times B_0 \times 0.67 \times MCF/100 \times MS$	Equation 10.23 in IPCC (Gavrilova et al., 2019)
		$VS = [GE \times (1 - DE/100) + (UE \times GE)]\times [(1 - Ash)/18.45]$	Equation 10.24 in IPCC (Gavrilova et al., 2019)
		DE: feed digestibility	
		MCF pasture: 0.47	(Gavrilova et al., 2019)
		Bo: 0.19	(Gavrilova et al., 2019)
N_2O-N direct	Pasture (excretions and fertilizer)	$N_2O\text{-}N = (F_{SN} \times EF_1) + (N_{ex} \times EF_{3PRP,\ CPP})$	Equation 11.1 in IPCC (Gavrilova et al., 2019)
		EF_1: 0.01	Table 11.1 in IPCC (Gavrilova et al., 2019)
		$EF_{3PRP,\ CPP}$: 0.004	Table 11.1 in IPCC (Gavrilova et al., 2019)
		$N_{ex} = N_{intake} - N_{retention}$	Equation 10.31 in IPCC (Gavrilova et al., 2019)
		N_{intake}: $DMI \times (CP\%/100/6.25)$	Equation 10.32 in IPCC (Gavrilova et al., 2019)
		$N_{retention}$: $[(Milk \times (Milk\ PR\%/100)/6.38] + \{WG \times [268 - (7.03 \times Neg/WG)]/(1000 \times 6.25)\}$	Equation 10.33 in IPCC (Gavrilova et al., 2019)
		Milk PR%: $[1.9 + 0.4 \times \%Fat]$	
N_2O-N indirect	Pasture (From NH_3)	$N_2O\text{-}N = [(F_{SN} \times Frac_{GASF}) + (F_{PRP} \times Frac_{GASM})] \times EF_4$	Equation 11.9 in IPCC (Gavrilova et al., 2019)
		$Frac_{GASF}$ Ammonium-based: 0.08 (0.02 − 0.3)	Table 11.3 in IPCC (Gavrilova et al., 2019)
		$Frac_{GASM}$: 0.21 (0.00 − 0.31)	Table 11.3 in IPCC (Gavrilova et al., 2019)
		EF_4: 0.01 (0.002 − 0.05)	Table 11.3 in IPCC (Gavrilova et al., 2019)
CO_2-C direct	Lime application	$CO_2\text{-}C = (M_{Limestone} \times EF_{Limestone}) + (M_{Dolomite} \times EF_{Dolomite})$	Equation 11.12 in IPCC (Gavrilova et al., 2019)

	$EF_{Limestone}$: 0.12 $EF_{Dolomite}$: 0.13	
Diesel fuel consumption	CO_2-C = Fuel consumption x EF_{Diesel} EF_{Diesel}: 2.23 kg CO2eq L^{-1} $diesel^{-1}$	UPME (2016)

The amount of organic dry matter in manure was calculated from the herd specific gross energy intake; digestibility of feed consumed; default values for ash content in dry matter and CH_4 producing capacity; and the methane conversion factor.

A nitrogen balance at farm level was made to check for possible N surplus and thus risk of N leaching. For each farm, surplus of N was quantified and expressed in kilogram N applied per ha. N input was estimated by multiplying the amount of each input purchased by its percent N content. Annual N deposition was assumed by a standard (15 kg N ha^{-1}) (Bobbink et al., 2010), and N fixation was set as zero. The N outputs were estimated by multiplying the amount of milk and live weight produced by their N content. The difference between the N surplus at farm level and the N lost by gaseous emissions was too low for most of farms, therefore, N loss from manure and N fertilizers through leaching of the N was assumed to be negligible. Emissions from livestock respiration (Steinfeld et al., 2006) and the variation in soil carbon stocks at farm level were not taken into account.

Emission factors (EF) used for the estimation of the secondary emissions from imported feeds and fertilizers are summarized in Table 3. These GHG emissions corresponded to production and transport of these agricultural inputs.

Table 3

Estimation of off-farm emissions, energy use, and land use for dual-purpose-farms

Input	GWP (kgCO_2 eq kg^{-1} input)	Energy demand (MJ kg^{-1} input)	Land use (m^2 kg^{-1} input)
Synthetic nitrogen fertilizer			
N[a]	6.6	43.6	---
P[b]	3.6	55.7	---
K[b]	0.7	8.1	---
Lime[a]	0.03	0.7	---
Maize silage[b]	0.0762	0.963	0.237
Mineral salt[c]	0.155	1.92	---
Molasses[a]	0.871	4.36	0.584
Transport[b]	254*	3.62**	---

[a] Agri-footprint, 2015
[b] Ecoinvent 3, 2013
[c] ELCD: European Life Cycle Database
* kgCO_2 eq t^{-1} km^{-1}; ** Mj t^{-1} km^{-1}

2.1.2.3 Non-renewable energy use and land use

Energy used for consumption of fossil fuels on-farm and transportation of inputs from factory to farm, were calculated according to the Planning Unit of the Mines and Energy of Colombia (UPME, 2016), and the Ecoinvent database (Weidema et al., 2013). Off-farm energy requirements related to the production of agricultural inputs were estimated by using specific factors obtained from Agri-Footprint, Ecoinvent, and European Life Cycle Reference Databases (Durlinger et al., 2014; Weidema et al., 2013) as shown in Table 3.

The land use was calculated as the sum of the on-farm grazing area, and the area off-farm required to produce the purchased feeds. The grazing area was obtained from the surveys of each farm, and the off-farm area from Agri-Footprint database and Ecoinvent database as shown in Table 3.

2.2 Statistical Analyses

Results are presented as means, minimum and maximum values. A principal component multivariate analysis (PCA) was performed with the PCA procedure from the FactoMineR package (Husson et al., 2015). This shows relationships among total environmental impacts (CF, land use, and non-renewable energy use) per kilogram

FPCM and kilogram LWG resulted from economic allocation, and several quantitative variables (kg FPCM cow^{-1} year^{-1}; kg FPCM ha^{-1} year^{-1}, kg LWG^{-1} year^{-1} ; kg LWG ha^{-1} year^{-1}, stocking rate, % of area under improved pastures, kg fertilizer ha^{-1} yr^{-1}, feed purchased as % of DMI, T forage production DM ha^{-1} yr^{-1}, and L diesel consumption ha^{-1} year^{-1}). To perform a numerical classification of farms, a Hierarchical Clustering on Principal Components (HCPC) was done with the HCPC procedure from the FactoMineR package (Husson et al., 2015). The Ward algorithm was used to build the tree, and then the k-means consolidation to establish the clusters. For each cluster, average of farm characteristics and environmental impacts were computed. In addition, a nonparametric approach of Kruskal-Wallis was used to determine differences among clusters, followed by a post hoc test using the Kruskal-Nemenyi test (Pohlert, 2016).

2.3 Mitigation measures and economic analysis

Scenario analysis was conducted by introducing improvement strategies for analyzing possible future technological changes that lead to GHG emissions reductions. The selection of these strategies was based on the characteristics of clusters identified, literature review and expert opinion (Bogaerts et al., 2017; Cardoso et al., 2016; Mazzetto et al., 2015). In the scenario analysis, we considered as a mitigation measure the establishment of improved pastures to increase forage yield and the stocking rate and improve the forage quality on-farm. In addition, the adoption of electric fences that allow rotational grazing was also considered as a good pasture management practice that could be adopted by farmers in conjunction with the mitigation measure. We evaluated the adoption of improved pastures only in the area necessary for producing the current forage demand of cattle, which is less than the current area that farmers use for cattle rearing activities, and by this, the stocking rate can increase. We assumed the establishment of a forage plant with dry matter digestibility equal to 65%, crude protein content of 12%, dry matter productivity of 35 T ha yr^{-1}, and that can be implemented in the low tropics (< 1200 masl).

Additionally, we estimated the relative costs of the establishment and maintenance of improved pastures and electric fence, and the quantities of GHG emissions that would be reduced after implementing these measures. Consequently, we were able to quantify the economic benefits associated with achieving reductions in GHG emissions. The GHG emissions reductions of this measure were estimated as the annual average of the difference between the total GHG emissions of the baseline scenario and the total emissions under the scenario based on the adoption of the different mitigation measures (de Oliveira Silva et al., 2015). For estimating the GHG emissions from electric energy use by operation of electric fences, we used an electricity consumption of 42 kWh ha^{-1} yr^{-1} (Gutiérrez et al., 2018), and an emission factor for electric energy use in Colombia of 0.199 kgCO$_2$ kWh^{-1} (UPME, 2016). The cost-effectiveness of the mitigation measures was estimated as the difference between the gross margin in the baseline and the gross margin in the scenario with the mitigation measure implemented, divided by the GHG emissions reductions. The gross margin in both scenarios was estimated as the difference between the revenues and expenses of farms in a period of one year. Revenues come only from the hypothetical sale of all live weight (LW), and all milk produced per farm per year. Prices of milk and meat sold were obtained from the Colombian National Cattle Ranchers Federation (FEDEGAN, 2019). Farm expenses were composed of investment and maintenance costs for the implementation of improved pastures and electric fence. The associated costs for the establishment and maintenance of this measure was calculated according to Gutierrez et al. (2018), which accounted for farm operations and quantities of inputs required (e.g., land adaptation, seeding, fertilizers, amendments to the soil, forage seed, and electric fence).

3. Results and discussion

3.1 Nitrogen balance

Nitrogen surpluses obtained at the farm gate are usually attributed to N lost by gaseous emissions (i.e. NH_3, N_2O and NO_X), leaching and runoff of nitrate to surface or groundwater, and soil N stock changes (Penati et al., 2011). Due to the low amounts of inputs and low stocking rates, the DPS was characterized by low N surplus per ha (14.7 kg N ha^{-1} year^{-1}) in most of the farms used in the current study. In comparison high input farms used as much as 186 kg N ha^{-1} year^{-1} (Penati et al., 2011). In some farms, the main N input was the atmospheric deposition (15 kg N ha^{-1}), as purchased N fertilizer was low (11 kg N ha^{-1} year^{-1}). The mean N outputs in milk (6.5 kg N ha^{-1} year^{-1}) and meat (6.0 kg N ha^{-1} year^{-1}) were similar, which reflects the dual–purpose orientation of the farms. On average, the total N surplus was 15.0 kg N ha^{-1} year^{-1}, at the same time, direct and indirect N emissions were 15.9 kg N ha^{-1} year^{-1}. These results are comparable to those of Penati et al. (2011) for Italian extensive highland dairy systems (6.4 kg N ha^{-1} year^{-1}), which are characterized by the low N inputs.

3.2 Annual methane (CH_4), nitrous oxide (N_2O), and carbon dioxide (CO_2) emissions

Emissions from enteric fermentation was the main source of CH_4 emissions, while the contribution of manure deposited on pastures was very small (Table 4). This behavior is typical for extensive cattle systems in the Latin American tropical region where excreta management is rare (Cerri et al., 2016; Gaitán et al., 2016; Mazzetto et al., 2020).

Table 4

Annual methane (CH_4) emission from farm production estimated using both the IPCC's 2006 and 2019 Refinement to the IPCC's 2006 greenhouse gas inventory guidelines

	Dual purpose cattle farms (n = 1313)		
	2019 Refinement to IPCC 2006 inventory guidelines		
	Mean	Min	Max
Enteric fermentation			
Herd, kg CH_4 per AU[a]	103.3 (99%)	52.2	181.1
Manure			
Pasture, kg CH_4 per AU	1.3 (1%)	0.6	2.4
Total, kg CH_4 per AU	104.6	52.8	183.5

[a] AU: Animal Unit (1 AU being either 1 cow, or 3.3 female and male calves less than 1 year, or 1.7 female and male calves 1 - 2 yr, or 1.3 heifers 2-3 yr, or 1.3 steers 1- 2 yr, or 0.8 bulls)

In general, we observed that direct N_2O emissions from excreta deposited on grazed pastures were the main source of N_2O emissions (51%), while indirect N_2O emissions from volatilization of NH_3 amounted to 28.7% of total emissions, mostly coming from animal excreta (27%) (Table 5). The contribution of fertilizers, in both direct and indirect emissions, was too low mainly due to the low adoption of this practice.

Table 5

Annual nitrous oxide emissions (N_2O) from the farm production

	Dual purpose cattle farms (n = 1313)		
	2019 Refinement to IPCC 2006 inventory guidelines		
	Mean	Min	Max
Directly (kg N_2O-N per ha)			
Manure (pasture)	0.3 (51%)	0.01	1.0
Fertilizer	0.1 (20.3%)	0	6.2
Indirectly (kg N_2O-N per ha)			
From NH_3 (excretions)	0.1 (27%)	0.003	0.5
From NH_3 (fertilizer)	0.01 (1.7%)	0	0.50
Total (kg N_2O-N per ha)	0.52	0.01	8.2

Carbon dioxide emissions due to liming and burning of diesel fuel had large variation among farms, which depended on the quantities of lime and diesel fuel used (Table 6).

Table 6

Annual carbon dioxide emission (CO_2) from the farm production

	Dual purpose cattle farms (n = 1313)

CO_2 emissions	Mean	Min	Max
Directly			
Liming, kg CO_2 per ha	4 (56%)	0.0	260
Diesel fuel, kg CO_2 per ha	3.2 (44%)	0.03	53.5
Total (kg CO_2 per ha)	7.2 (100%)	0.00	260.0

3.3 Allocation of environmental burdens between meat (LWG) and milk (FPCM)

Economic, energy, and mass methods were used to assign the environmental burdens between milk and live weight gain and to identify variations. When using these allocation methods, the proportion of environmental burdens allocated to meat differed, with the economic method assigning the greater burden, followed by energy content (Table 7). When applying mass allocation, emissions per kg LWG were lowest and emissions per kg FPCM were highest. Rice et al. (2017) found a similar trend as ours for the proportion of GHG allocated to meat depending on the allocation method used, increasing from the mass, to the energy, and to the economic allocation method.

Table 7
Effect on emission per kg products with different allocation methods of greenhouse gas emission between meat and milk

	Dual-purpose cattle farms (n = 1313)		
	Mean	Min	Max
Meat CO_2-eq, % of total			
Economic[a]	36	4	84
Energy[b]	30	3	79
Mass	13	1	55
Emission after allocation (meat), kg CO_2-eq per kg LWG			
Economic	12.8	4.5	36.6
Energy	10.5	3.5	32.8
Mass	4.4	1.2	18.2
Emission after allocation (milk), kg CO_2-eq per kg FPCM			
Economic	2.9	1	8.4
Energy	3.3	1	10.2
Mass	4.3	1	18.2

[a] 1 kg FPCM = 1000 COP; 1 kg live weight gain = 4364 COP
[b] Energy value of milk = 2.9 MJ kg^{-1}; energy value of carcass meat = 9.25 MJ kg^{-1}

As recommended by Rice et al. (2017) when selecting an allocation method, the quality and reliability of data should be the most important factor. Consequently, in the multivariate analysis we decided to include results of the environmental performance of farms after economic allocation, which is associated to the fact that the ratio of milk and meat prices has been steady in Colombia (FEDEGAN, 2017).

In Latin America, an LCA study for DPS in Nicaragua allocated the total environmental burden to milk (Gaitán et al., 2016). Similarly, an LCA dairy study in Brazil did not consider allocation approaches (de Léis et al., 2015). An LCA study for dairy systems in Peru (Bartl et al., 2011) and the evaluation of cow-calf stage in an LCA for beef production in Mexico (Rivera-Huerta et al., 2016), found identical proportions as our economic approach after applying the economic allocation method. In addition, an LCA study in Costa Rica that included DPS, applied an expanded boundary LCA of coupled dairy and beef production to avoid the allocation of environmental burdens (Mazzetto et al., 2020). As there is no consensus among LCA studies regarding which allocation method to apply, the estimation of impacts per product cannot be established precisely, and variations in results can exist. A common framework for allocation would allow, for future LCA evaluations, the partitioning of environmental burdens amongst co-products on a consistent basis, and consequently, identify hotspots and behaviors per product, and compare results between studies. This would also facilitate the establishment of policies aimed at supporting mitigation and adaptation actions for the cattle sector.

3.4 Contribution of on-farm and off-farm processes to total greenhouse gas emissions (GHG) by cluster

In all the clusters most of the GHG emissions arose from on-farm activities related to enteric fermentation and manure deposited on pasture (Figure 2). Fertilization, and excreta management were limited, therefore the contribution of N_2O to on-farm emissions was much lower than CH_4 from enteric fermentation. On-farm carbon dioxide emissions were low due to the little use of machinery and liming. The ranking of off-farm emissions was mostly influenced by the amount of purchased feed, followed by agrochemical inputs and transport. A similar structure of GHG emissions distribution was also reported for DPS in Nicaragua and Costa Rica, which were low input dependent and based the feeding strategy adopted in sown and naturalized pastures (Gaitán et al., 2016; Mazzetto et al., 2020). Our results have a similar trend in the distribution of GHG emission of cattle milk and meat for the Latin American countries reported by Gerber et al. (2013), with methane being the main source of emissions. Gerber et al. (2013) assigned around 50% of total emissions to enteric fermentation (without counting emissions from land-use change), however, these figures are lower than our findings where this source of emissions accounted for more than 70% of total emissions. The above is mainly related to the fact that studied farms were low input farms and most emissions were from the animals. When farms intensify their production, GHG emissions arising from animals reduce, while those from excreta management and inputs production and use increase (Rotz, 2018).

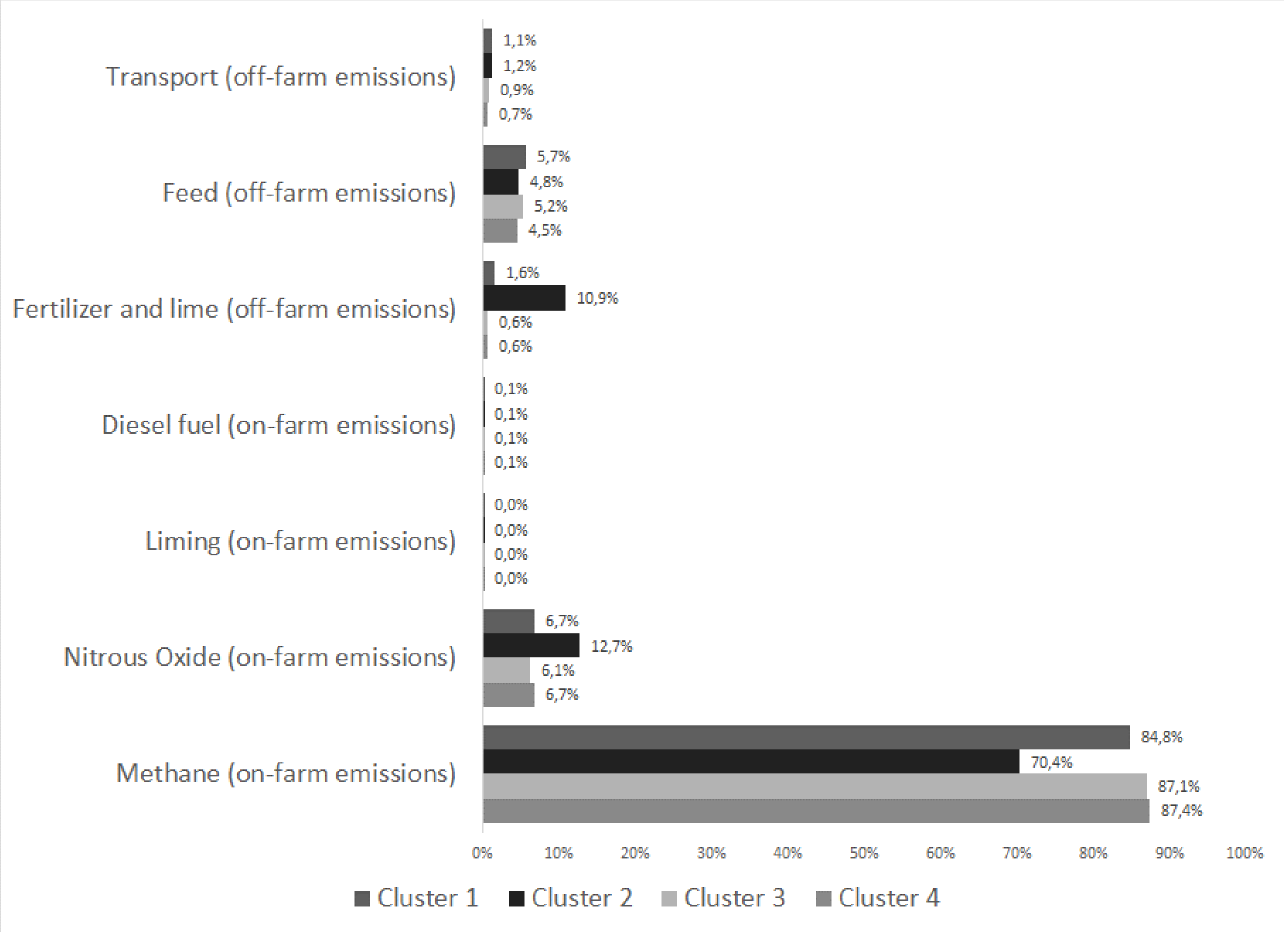

Figure 2. Contributions of different on – farm and off – farm processes to total greenhouse gas emissions from dual – purpose farms at the farm gate located in 13 departments of Colombia (n=1313)

3.5 Variation among farms and interpretation of clusters

The large number of farms assessed (n=1313) provides a potential to identify relationships among environmental performance and farming practices, allowing for the proposal of strategies to increase productivity and mitigate GHG emissions.

According to the bi-plot resulting from the PCA (Figure 3), milk yield (kg FPCM cow^{-1} year^{-1}; kg FPCM ha^{-1} year^{1}) and meat production per hectare were positively correlated to the stocking rate (AU ha^{-1}), as they were located in the same area of the graph. These variables were negatively correlated to emission (per kg FPCM and per kg LWG) and LU (per kg FPCM and per kg LWG). This means that increased milk per cow and ha, and meat per ha leads to reduced CF and LU per kilogram FPCM and per kilogram LWG. The analysis also showed a positive correlation among percentages of area of improved pastures, fertilizers application rate, forage production per ha, and non-renewable energy use (per kg FPCM and per kg LWG). Farms with high percentages of improved pastures used more synthetic fertilizers, which explains the positive correlation with non-renewable energy use.

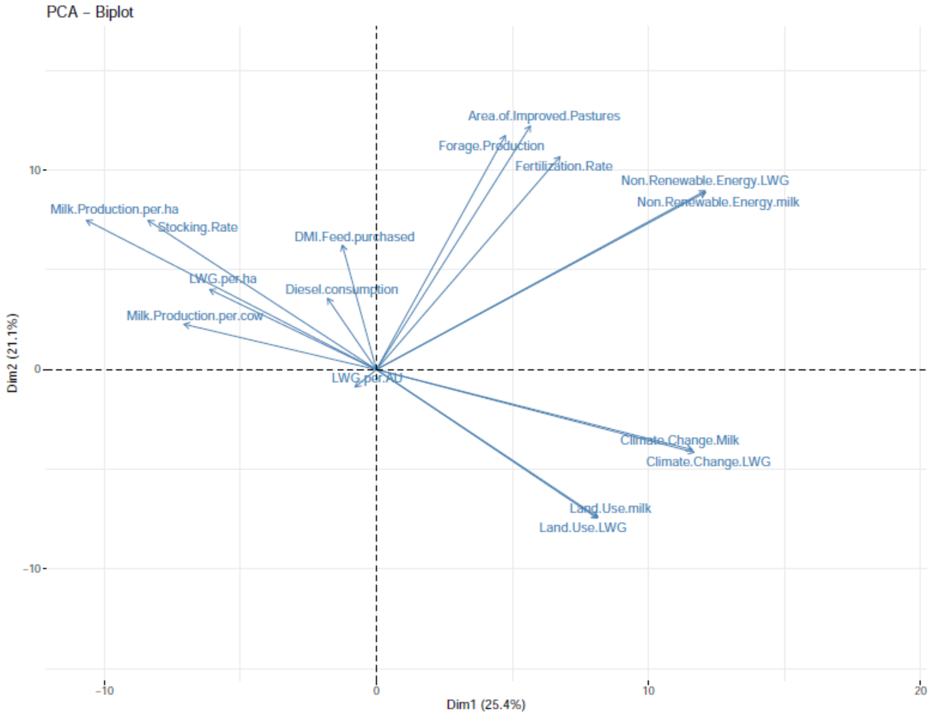

Figure 3. Bi-plot for the principal component analysis (PCA) with information collected from 1313 DPS of Colombia

After cluster analysis, four groups of farms were identified (Table 8). Average milk production for all farms are similar to the lower values of the production ranges reported for DPS in Latin America (Gaitán et al., 2016; Rojo-Rubio et al., 2009). However, results of cluster 1 and 3 are comparable with average values reported for DPS in Colombia, while clusters 2 and 4 presented lower yields. Farms of all groups base their feeding strategy on grazing on sown pastures all year round, with feed purchased (% of DM) being lower than 4% of DM in all clusters, a typical characteristic of extensive cattle systems in Latin America (Rao et al., 2015).

Table 8.

Means for selected farm variables for four farm clusters of 1313 dual-purpose cattle farms in Colombia

	Cluster 1, n = 261	Cluster 2, n=220	Cluster 3, n = 603	Cluster 4, n = 229
	Mean	Mean	Mean	Mean

Stocking rate, AU ha^{-1}	2.8	a	1.0	b	1.1	b	1.1	b
Milk production, kg FPCM ha^{-1} year^{-1}	3021.8	a	735.1	c	1000.5	b	522.7	c
Milk production, kg FPCM cow^{-1} year^{-1}	1510.1	a	1208.7	b	1416.4	a	930.9	c
Meat production, kg LWG AU^{-1} year^{-1}	87	bc	96.0	b	107.4	a	80.4	c
Meat production, kg LWG ha^{-1} year^{-1}	357.3	a	101.2	b	130.9	c	111.4	b
Area of improved pastures, %	32	b	72	a	5	c	6	c
Fertilizer application rate, kg ha^{-1} year^{-1}	76.9	b	185.5	a	25.6	c	25.9	c
Feed purchased, % of DMI	3.8	a	3.6	ab	3.2	b	2.6	c
Dry matter production, Ton ha^{-1} year^{-1}	10.8	b	13.3	a	8.6	c	8.6	c
Diesel consumption, L ha^{-1} year^{-1}	2.2	a	1.4	b	0.9	c	1.8	d
Carbon footprint, CO_2-eq kgFPCM^{-1}	2.1	d	3.1	b	2.4	c	4.2	a
Carbon footprint, CO_2-eq kgLWG^{-1}	9.0	d	13.6	b	10.5	c	18.3	a
Non-renewable energy use, MJ kgFPCM^{-1}	1.0	c	3.8	a	0.9	d	1.4	b
Non-renewable energy use, MJ kgLWG^{-1}	4.6	c	16.6	a	3.8	d	6.0	b
Land Use, m^2 kgFPCM^{-1}	3.0	c	13.7	a	10.2	b	25.2	a
Land Use, m^2 kg LWG^{-1}	12.5	c	59.0	a	44.5	b	108.6	a

Variable means with different letters across rows are significantly different at $P < 0.05$

Cluster 1 (261 farms) had the highest milk yield, meat production (per ha), stocking rate and diesel fuel consumption. This cluster presented the second largest application rate of fertilizers, area of improved pastures, and dry matter production. This led to the lowest results for GWP and land use among clusters, and the second lower results for non-renewable energy use due to high diesel fuel consumption.

Cluster 2 (220 farms) had the highest area of improved pastures and application rate of fertilizers. These farms had the highest dry matter production and the lowest stocking rate, which points to an inefficient use of the pasture. In addition, the production parameters were also low. Due to these characteristics, this cluster presented the highest non-renewable energy use and the second highest values for GWP and LU.

Cluster 3 consisted of 603 farms, had the highest LWG (per AU), the second highest milk yield (per cow and per hectare), meat production per ha, and stocking rate, and the lowest consumption of diesel among groups. Additionally, the area of improved pastures, fertilizer application rates, and dry matter production were the lowest amongst clusters. These characteristics led to the lowest non-renewable energy use and the second lowest value for GWP and LU. Despite the lower implementation of improved pastures and forage production among clusters, these farms had high milk and LWG production.

Cluster 4 included 229 farms, had the lowest milk yield, LGW production (per AU), area of improved pastures, application rate of fertilizer and stocking rate. The low productive performance of these farms led to the highest GWP and LU, and the second highest non-renewable energy use among groups.

3.6 *Environmental impacts and comparisons with other studies*

The CF results were negatively correlated with milk production. This result, in terms of CO_2-eq per kg FPCM, is in agreement with the findings of Gaitán et al. (2016) for DP farms in Nicaragua. This means that a general increase in productivity, per animal and per hectare, might reduce CF, as was also suggested by de Léis et al. (2015) for dairy production systems in Brazil. Results for Cluster 1 are similar to those reported for intensive silvopastoral systems in Colombia (Rivera et al., 2016), and slightly higher than those for climate smart farms in Nicaragua (Gaitán et al., 2016). In addition, results for Cluster 3 are comparable to the level estimated by Rivera et al. (2016) and Gaitán et al. (2016) for conventional systems, while values for Clusters 2 and 4 are higher than those reported in these studies. Due to the lower milk yield and stocking rate, our results are higher than CFs informed for specialized dairy farms in developed countries (Ross et al., 2017; Sejian et al., 2018; Styles et al., 2018).

In Latin-America, CF from beef systems range from 9 to 43 kg CO_2-eq per kg LWG (Dick et al., 2015; Modernel et al., 2018; Ruviaro et al., 2015). Our results are at the lower end of this range and are also similar to CF informed for specialized beef production systems (Alemu et al., 2017; Mogensen et al., 2015). Emissions for Clusters 1 and 3 are comparable with those reported for more intensive systems, while results for Clusters 2 and 4 are closer to those of extensive systems. The relatively lower values found in this study are probably a consequence of the allocation of emissions between co-products, with a lower proportion assigned to meat, while in pure beef systems all GHG emissions are allocated to meat. This suggests that meat produced through DPS could be more environmentally friendly than meat produced in purely beef systems. The existence of a system where beef can be supplied from dairy farms while maintaining productivity within the dairy industry has been proposed as a good option to reduce GHG emissions from beef production in Ireland (Casey and Holden, 2006). Thus, well managed dual-purpose farms could attain higher meat production, replacing a greater percentage of meat from exclusively beef systems and thus reduce environmental burdens from the cattle sector. This could be an effective strategy to accomplish the national goals of GHG emissions reduction.

The process which had the most energy use was fertilizer production off-farm. Cluster 2, which relies more on external inputs, showed the highest demand for non-renewable energy. Despite Cluster 1 having the second-largest fertilizer application rate, its high milk and meat yields reduced the impact of non-renewable energy use. Cluster 3 had the lowest non-renewable energy use per kg milk and meat of all the four clusters. This trend was also reported in dairy systems in Colombia, where a conventional system had higher non-renewable energy used than a silvopastoral system, mainly due to its higher used of external inputs (Rivera et al., 2016). Results for clusters 1, 3 and 4 are lower than those reported by Zucali et al. (2017), Battini et al. (2016), and Modernel et al. (2013), however, results for Cluster 2 are similar.

The grazing area was identified as the most important contributor to land use, with more than 98% in each cluster. Similarly, Dick et al. (2015) reported that grassland occupied large areas (~100% of the farm area) on farms based on extensive and improved beef systems in Brazil, and Rivera et al. (2016) found that 92% of land use in intensive silvopastoral dairy systems in Colombia was left to pasture cultivation. Increasing stocking rate while maintaining the availability and quality of forage, could be an effective strategy not only to reduce land use but also GHG emissions.

3.7 Improvement options and implications

Clusters 1 and 3 had higher milk productivity (per cow and per hectare) and meat production per ha than clusters 2 and 4. This can be due to better herd reproductive practices (González-Quintero et al., 2020), which have been reported as strategies that allow the increasing of herd productivity in Latin American cattle systems (Holmann et al., 2003). In turn, clusters 1 and 2 were characterized by higher dry matter per ha of pasture and a larger proportion of improved pastures. This might be due to better pasture renewal practices than the other 2 clusters. These practices are associated with mechanization, fertilization, weed control, planting grass, rotational grazing, and electric fences (González-Quintero et al., 2020).

Two production strategies can be identified among dual-purpose farms. The first, depicted in Clusters 1 and 2, is basing the feeding strategy on a combination of improved and natural pastures, combined with the highest fertilizer application rates. The second is found in farms of Clusters 3 and 4, where the feeding strategy is based on grazing natural pastures, with low input of fertilizers. However, there was a significant difference in terms of productivity of milk and meat (per ha) between clusters from each way of production strategy. This led to a lower GHG emissions in Clusters 1 and 3 compared to Clusters 2 and 4.

The above analysis provides insight into possible technological changes and management options that can increase the productivity parameters and improve the environmental performance of DPS. In order to move from Cluster 2 to Cluster 1, livestock managers should improve pasture management and increase stocking rate. Similarly, to change from Cluster 4 to Cluster 3, farmers should adopt the good agricultural practices developed by farms from Cluster 3 which corresponded to rotational grazing, reproduction practices such as artificial insemination, controlled natural mating and reproductive control on cows, and record-keeping to better control farm activities. With these changes, it would be possible to reduce GHG emissions without vast investments.

For the right establishment of policies aimed at supporting mitigation and adaptation actions for the cattle sector in Colombia, it is important to know the relative cost-effectiveness for the implementation of improved pastures as a mitigation measure. Results for the first year, after the implementation of improved pastures, showed positive cost-effectiveness for clusters 1, 2 and 4, while the result for Cluster 3 was negative (Table 9). However, for the following years after the implementation, the cost-effectiveness for all clusters was negative. The above suggests that cost savings can be achieved by adopting improved pastures, while reducing GHG emissions. Additionally, it is important to note that in the first year GHG emissions reductions were achieved for all clusters. Similar cost-effectiveness values were obtained in a study conducted in Brazil, where the implementation of improved pastures for land restoration reached negative cost-effectiveness (de Oliveira Silva et al., 2015).

Table 9.
Marginal cost effectiveness, emissions reductions, and environmental performance of clusters after improved pastures establishment

	Cluster 1	Cluster 2	Cluster 3	Cluster 4
	Mean	Mean	Mean	Mean
Marginal cost-effectiveness first year (establishment), US$ (t CO^2e)$^{-1}$ yr^{-1}	0.09	0.05	-0.05	0.03
Marginal cost-effectiveness following years (maintenance), US$ (t CO_2eq)$^{-1}$ yr^{-1}	-0.11	-0.06	-0.19	-0.13
Carbon footprint (% variation with baseline), CO_2-eq kgFPCM^{-1}	1.6 (-25%)	2.0 (-37%)	1.6 (-34%)	2.2 (-48%)
Carbon footprint (% variation with baseline), CO_2-eq kgLWG^{-1}	6.8 (-25%)	5.0 (-37%)	6.9 (-34%)	9.5 (-48%)

Reductions in total GHG emissions led to a lower CF in all clusters in comparison to the baseline (Table 9). Cluster 2 reached similar values as Cluster 1, and Cluster 4 obtain even lower values than Cluster 3, due to an increased quality and yield of grasslands. By increasing the pasture productivity, less area is required to meet the same demand of the baseline, which means forage availability optimally fulfill cattle nutritional requirements. These new CFs figures, especially for clusters 1 and 2, are close to values reported for specialized dairy systems in Latin America and developed countries (Bava et al., 2014; Dalgaard et al., 2014; de Léis et al., 2015; Salvador et al., 2017), which points out the possibility of DPS to achieve better environmental performance with negative cost-effectiveness.

Around 69.2% of the studied farms had less than 50 animals, which agrees with the percentage distribution of livestock farms in Colombia where 82% have less than 50 heads of cattle and are considered to be small ranchers (González-Quintero et al., 2020; ICA, 2019). In addition, DPS in Colombia are known to have low adoption of technology, low productive parameters and low profitability (González-Quintero et al., 2020). Studied farms were pastured based systems and rely mostly on the use of natural pastures and a lesser extent on improved ones. Because of the low farm profitability and socio-economic status of DPS, economic investment is a barrier to the adoption of improved pastures. Most of the Latin American countries, except for Brazil and Argentina, do not have policies or governmental programs for mitigation and adaptation to climate change focusing on the agricultural sector (González-Quintero et al., 2015). Therefore, it is necessary to provide incentives for the adoption of improved pastures such as increased availability and accessibility of seeds, inputs, and subsidies for labor, tax exemptions, financing technical assistance, payment for environmental services (PSE), and soft loans (Murgueitio, 2009). These incentives, which include public policy instruments, are important for achieving the implementation of these kinds of measures on a larger scale, allowing producers to have access to projects that foster measures for increasing cattle productivity and increasing environmental benefits.

4 Conclusions

The largest source of GHG emissions in dual-purpose systems in Colombia arises from cattle herds, where methane from enteric fermentation and N_2O from excretions deposited on pastures are the main contributors to GHG emissions. Therefore, the carbon footprint of products leaving the farm will be sensitive to the amount of enteric methane and nitrous oxide from pastures in relation to the amount of milk and meat produced.

The current study identified two production strategies, a more intensive strategy with high proportion of improved pasture and higher fertilizer application rates and a more extensive strategy with low input of fertilizers and grazing on natural pastures. Both strategies had a cluster of better farms (Cluster 1 and Cluster 3) that provided low carbon footprint values which were in the same range and a cluster of farms that had higher carbon footprint values (Cluster 2 and Cluster 4). Within both strategies, the two groups of farms had either low or high milk yield per cow and productivity (milk and meat) per ha. This suggests that both extensive and more intensive strategies for the dual-purpose cattle systems can lead to lower carbon footprint values and provide promising mitigation options. The balance between the inputs used and the on-farm emissions in relation to the milk and meat produced is the main determinant for the outcome of the carbon footprint and improvements that optimizes the effective use of resources will reduce the carbon footprint.

Despite the differences in management practices between both production strategies, our results suggest that the identification of an adequate fertilizer application rate and the implementation of better agricultural management practices, such as improved pastures had the potential to increase both the quality and amount of animal feed and reduce the carbon footprint. Therefore, these farming strategies are promising mitigation measures for reducing GHG emissions per kg of milk and meat at the farm gate after allocation, for dual-purpose cattle systems in Colombia. In addition, the mitigation practices showed a negative cost-effectiveness after the implementation period.

This study contributes to a better understanding of the environmental impacts of intensive and extensive dual-purpose systems in Colombia. By highlighting a cost-effective mitigation option, this paper provides an insight into the sustainable intensification process for the Colombian dual-purpose cattle systems.

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