

The contribution of local shrubs to the carbon footprint reduction of traditional dairy systems in Cundinamarca, Colombia

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Abstract

Cattle farming is responsible for about 15% of Colombian greenhouse gas emissions (GHGE). In Cundinamarca Department, specialized dairy farms located in the high tropics contribute to 14% of national milk production, and 94% correspond to small-scale producers. Therefore, mitigation strategies for dairy farms are needed to achieve the national GHGE reduction targets. This study aims to quantify the carbon footprint (CF), through of a Life Cycle Assessment methodology, of 82 specialized dairy farms at the farm gate in 3 regions of Cundinamarca: Center Savanna, West Savanna, and Ubaté Valley; and identify the contribution of *Acacia decurrens*, *Sambucus peruviana*, and *Baccharis latifolia* on milk production increases and GHGE mitigation potential. The GHGE were calculated with the 2019 Refinement to 2006 IPCC guidelines and impact factors from databases. The functional units corresponded to one kg fat and protein corrected milk (FPCM) and one kg live weight gain, in a cradle-to-farm-gate approach. For the 3 regions, the enteric fermentation and manure left in pastures corresponded to the primary sources of on-farm GHGE, and the manufacturing of feed was the main off-farm source. Milk CFs ranged between 1.5 and 2.2 kgCO₂-eq kgFPCM⁻¹. Incorporating *Acacia decurrens*, *Sambucus peruviana*, and *Baccharis latifolia* in cattle diets resulted in a reduction of CF by 13–26% and increased milk yields by 19–37% across the three regions. These findings provide evidence of GHGE mitigation and increased milk productivity through the inclusion of locally available feedstuffs in specialized dairy systems in the high tropics of Cundinamarca.

1. Introduction

The production of dairy products at a worldwide level is projected to increase by 1.7% per year between 2019 to 2028, and this growth is estimated to be driven by developing countries that currently have low milk yields. In addition, it is expected that global per capita milk consumption will grow around 1.1% per year up to 2028 leading by higher incomes per capita, population growth, and dietary shifts, especially in developing countries (OCDE/FAO 2019). In response to this demand, Latin American livestock production has increased its milk production due to a growth of 3% in the animal inventory (Williams and Anderson 2019). In Colombia, it is expecting growth in the future milk demand of dairy products, improvements in the current milk production systems are needed to fulfill the increasing demand. On the other hand, the Colombian government is committed to a reduction of 51% of national GHGE by 2030 (Ministry of Environment and Sustainable Development 2020), enhancements in milk production from dairy systems should prioritize sustainable cattle strategies for avoiding further increases of GHGE. Livestock activities contribute approximately to 10–12 % of worldwide greenhouse gas emissions (GHGE) (Mbow et al. 2019), and from this, around 30% arise from dairy cattle systems (Herrero et al. 2016). The 55% of the Colombian national GHGE come from the Agriculture, Forestry, and Other Land Use (AFOLU) sector (IDEAM 2018). Activities such as enteric fermentation, excreta deposition over pastures, and management of paddocks and soils contribute to 52% of GHGE from this sector, which corresponds to 15% of national GHGE (IDEAM 2018).

In Colombia, the ruminant livestock is an important economic activity, and has a participation of 1.9% from national GDP and 24% from agricultural GDP (DANE 2020). The cattle sector corresponds to pasture-based systems and geographically its coverage is circa of 31 million hectares with around 28.8 million heads of cattle. From this cattle inventory, 45% of animals corresponded to dairy production systems such as specialized dairy (6%) and dual-purpose (39%), and the remainder 55% corresponded to the beef production chain (Astaíza-Martínez et al., 2017; Fedegan, 2018b; ICA, 2020a; Rodríguez, J.; Llano, M.; Fonseca, 2018; UPRA, 2020a). Dairy cattle farms (specialized and dual-purpose) generate 7.9 employments per 100 animals and produce around of 7393 million liters of milk per year (UPRA 2020b), from these production figures, 32% of milk is produced on farms located in the high tropics (above 2000 m.a.s.l.) of Antioquia, Boyacá, Cundinamarca, and Nariño departments, with an average production rate ranging between 13 to 18.4 L cow⁻¹ day⁻¹. The current national milk consumption per capita (156 L hab⁻¹ yr⁻¹) is adequately fulfilled by the Colombian dairy farms. However, as increases in the population growth rates for the next years in Colombia are expected, raises in the national demand for dairy products are also projected (UPRA 2020b). In consequence, improvements in milk yields of dairy cattle farms in Colombia are needed to fulfill the future milk demand of the country.

Cundinamarca department has an area of 22.663 km² which corresponds to 2% of Colombia surface area. This department has a cattle activity vocation, with an animal inventory around of 1.5 million heads distributed in 59179 farms, which contribute to 15% of national milk production, and makes it ranking as the second milk producer Department at the national level (Fedegan 2014; ICA 2020b; Ministerio de Agricultura y Desarrollo Rural 2021), which correspond to cow-calf systems with 30%, specialized dairy systems 27%, fattening systems 24%, and dual-purpose systems 19% (Fedegan 2014). In Cundinamarca, 94% of the specialized dairy farms correspond to small producers with less than 50 heads of cattle (ICA 2020b), farm areas between 6 to 24 ha, stocking rates between 1 to 2 cows per hectare, and yields per cow between 12 to 14 L cow⁻¹ day⁻¹ (Carulla and Ortega 2016). The dairy breeds mainly correspond to Holstein, Jersey, Normande, and its crosses, and considering the herd structure, productive and dry cows reach around the 59 to 63% of total animals in the herd (Carulla and Ortega 2016). The most common grass species are *Cenchrus clandestinus* (Kikuyo grass), and *Lolium sp.* (Ryegrass) in a lower proportion, which are mixed with clovers (*Trifolium repens* and *Trifolium pratense*) and other legumes. It is also possible to find areas with some shrub of *Sambucus nigra* and *Sambucus peruviana*, and tree species such as *Salix sp.*, *Alnus acuminata*, *Acacia sp.*, and *Eucalyptus sp.* mainly (Pulido 2005; Avellaneda 2013). On the other hand, the dairy systems in Cundinamarca have relevant contributions on the economy and social aspects. Thus, on the national milk production figures is expected that will be a key actor to fulfill the future demand for dairy products in Colombia. Considering the cattle numbers, these systems play an important role in the achievement of national GHGE reduction goals from the cattle sector in Colombia by 2030. Therefore, the quantification of GHGE arising from these systems, and the identification of the main hotspots of emissions are required to establish appropriate GHG mitigation measures.

Life cycle assessment is a methodology that allows the estimation of GHGE along the production chain of milk, the identification of the main sources of emissions (hotspots), and the evaluation and modeling of potential mitigation options (Apdini et al. 2021). The carbon footprint (CF) is an impact category known as the global warming potential evaluated in a time horizon of 100 years (GWP_{100}), which is commonly used in LCA studies of livestock systems for quantifying the GHGE and interpret them in terms of climate change. In the global cattle dairy chain, enteric fermentation, feed production, and manure management were reported as the main hotspots of GHGE, contributing to 47, 26, and 19% of total GHGE respectively (Gerber et al. 2013). This trend was also reported for conventional pasture-based dairy systems in Brazil, Colombia, Costa Rica, Peru, and Uruguay (Bartl et al. 2011; Lizarralde et al. 2014; de Léis et al. 2015; Rivera et al. 2016; Mazzetto et al. 2020; González-Quintero et al. 2021b). In Latin America, it has been reported that reductions in GHGE intensities in dairy systems should focus on the intensification by improving the diet quality with the inclusion of higher proportion of seeded pastures and concentrate feeds (Lizarralde et al. 2014; de Léis et al. 2015; Gerssen-Gondelach et al. 2017; González-Quintero et al. 2021b). To our knowledge, in LCA studies for specialized dairy systems in the high tropics, the inclusion of local feed sources (such as trees and shrubs available on-farm) in the diet has not been evaluated yet as a possible mitigation option. The present study has two aims. Firstly, to estimate the CF and the main sources of GHGE from specialized dairy farms of Cundinamarca Department in Colombia, by using the LCA methodology and primary data directly collected from the farms. Secondly, to generate environmental and productive development scenarios to identify the contribution of locally available shrubs on GHGE mitigation potential and possible increases in milk yields of the farms.

2. Methodology

2.1 Life cycle assessment (LCA)

The standard methodology Publicly Available Specification (PAS, 2050: 2011) (BSI and Carbon Trust 2011) was utilized for the estimation of an impact category in the life cycle of products such as the CF. According to IPCC (IPCC 2014), the characterization factors for expressing emissions from different on-farm activities into CO_2 equivalents (CO_2 -eq) were 28, 265, and 1 for methane (CH_4), nitrous oxide (N_2O), and carbon dioxide (CO_2), respectively.

2.1.1 Goal and scope

2.1.1.1 System boundary description

All on-farm activities (primary emissions), along with the production of inputs such as feeds, fertilizers, amendments, fossil fuels, and related transport from the factory to the farm (secondary emissions) were included in the evaluation from the “cradle to farm gate” perspective (Fig. 1).

2.1.1.2 Functional units and handling of co-products

The main output from the specialized dairy systems in the highlands of Colombia is milk. However, cull cows and surplus weaned calves are considered another co-product from the farm. Considering the above, the environmental impacts of dairy farms were expressed as indexes by using two functional units: for milk, one kg of fat and protein corrected milk (FPCM) was used, and for meat, one kg of live weight gain (LWG) was applied. The attributional and consequential modelling approach were applied in the LCA. Allocation of co-products is typically used in the attributional approach, while for the consequential LCA the system expansion is used instead. Attributional LCA is focused on recording the physical flows and attributing emissions between co-products, and consequential LCA examines the consequences of a change (Flysjö et al. 2011a). The next are the five methods for handling the co-products that were applied:

1. The biophysical allocation method proposed in the International Dairy Federation (IDF) guide to standard life cycle assessment methodology (IDF 2015) as a common method for distributing GHGE between milk and meat in specialized dairy farms was used. This allocation rule was established and well described by Thoma et al. (2013)
2. The economic allocation method considers the quantities of milk (FPCM) and meat (LWG) produced per year and their prices per kg.
3. The energy allocation method considers the quantities of milk (FPCM) and meat (LWG) produced per year and their energy contents (MJ).
4. The mass allocation method was estimated considering the total amount of milk (FPCM) and meat (LWG) produced in a period of one year.
5. In the system expansion approach, it was established that the live weight produced by the dairy farms substituted an identical quantity of live weight produced in an alternate beef farm. Considering the above, and applying the system expansion through avoided burden, the environmental burdens of the substituted live weight were credited to the dairy farms (Marton et al. 2016). Therefore, the total environmental impacts of milk would correspond to the total environmental burdens generated in the dairy farm, including the raising of calves until weaning, minus those impacts which are caused in the production of the same amount of live weight produced by the dairy farm in the alternate beef system. We established that the live weight from dairy farms would replace the quantity of live weight produced in a cow-calf system which was the chosen alternative system. The average CF from the Colombian cow-calf systems correspond to $15 \text{ kgCO}_2\text{-eq kgLWG}^{-1}$ (González-Quintero et al. 2021a). This value was used for estimating the avoided GHGE.

2.1.2 Life Cycle Inventory

2.1.2.1 Sources of information and description of the specialized dairy cattle farms in Cundinamarca

The information used in this study was obtained between the years 2020 and 2021, through the semi-structured surveys in a total of 132 farms from 30 municipalities in the provinces of Central Savanna Centro, west Savanna and Ubaté valley located in the Department of Cundinamarca – Colombia; 82 specialized dairy farms were identified, which corresponded to the sample for this study. The milk production was standardized for a specific 3.7% of fat and 3.3% protein corrected milk (FPCM) according to Carulla and Ortega (2016). The live weight gain (LWG) was quantified as weight (kg) of animals leaving the farms, such as surplus calves and cull cows.

The gross energy concentration was calculated using IPCC tier 2 equations (Table 1) and considering 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 (IPCC 2006; Gavrilova et al. 2019). Dry matter intake (DMI) was computed by dividing herd-specific gross energy intake values by the energy density of the feed ($18.45\text{MJ kg}^{-1}\text{ DM}$) (IPCC 2006; Gavrilova et al. 2019). The nutritional compositional quality and pasture productivity ($\text{t DM ha}^{-1}\text{ yr}^{-1}$) were determined using the methodology “hand plucking” described by (Bonnet et al. 2011), where was simulated the grazing. Nutrient content and digestibility were estimated using the NIRS technology (Ariza-Nieto et al. 2018), with the aim to calculate the nutrients offered in the diet to animals. Use of fertilizer and amendments was expressed as the amount applied over an area (ha) of improved pastures.

Table 1
Emission factors (EF) for estimation of primary GHG emissions from specialized dairy systems in Cundinamarca – Colombia
(adapted from González-Quintero et al (2021a).

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)
		NE _m : net energy required by the animal for maintenance, MJ day ⁻¹	Equation 10.3 in IPCC (Gavrilova et al. 2019)
		NE _a : net energy for animal activity, MJ day ⁻¹	Equation 10.4 in IPCC (Gavrilova et al. 2019)
		NE _g : net energy needed for growth, MJ day ⁻¹	Equation 10.6 in IPCC (Gavrilova et al. 2019)
		NE _l : net energy for lactation, MJ day ⁻¹	Equation 10.8 in IPCC (Gavrilova et al. 2019)
		NE _p : net energy required for pregnancy, MJ day ⁻¹	Equation 10.13 in IPCC (Gavrilova et al. 2019)
		REM: the ratio of net energy available in a diet for maintenance to digestible energy	Equation 10.14 in IPCC (Gavrilova et al. 2019)
		REG: the ratio of net energy available for growth in a diet to digestible energy consumed	Equation 10.15 in IPCC (Gavrilova et al. 2019)
		Y _m : 0.07	IPCC (Gavrilova et al. 2019)
	Manure deposited at 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 ₂ O-N direct	Field (manure and fertilizer)	$N_2O-N = (F_{SN} \times EF_1) + (N_{ex} \times EF_{3PRP, CPP})$	Equation 11.1 in IPCC (Hergoualc'h et al. 2019)
		EF ₁ : 0.01	Table 11.1 in IPCC (Hergoualc'h et al. 2019)
		EF _{3PRP, CPP} : 0.004	Table 11.1 in IPCC (Hergoualc'h et al. 2019)
		$N_{ex} = N_{intake} \times (1 - N_{retention_frac})$	Equation 10.31 in IPCC (Gavrilova et al. 2019)
		N _{intake} : DMI × (CP%/100/6.25)	Equation 10.32 in IPCC (Gavrilova et al. 2019)
		N _{retention_frac} : [(Milk × (Milk PR%/100))/6.38] + {WG × [268 - (7.03 × Neg/WG)]/(1000 × 6.25)}	Equation 10.33 in IPCC (Gavrilova et al. 2019)
N ₂ O-N indirect	Field (From NH ₃)	Milk PR%: [1.9 + 0.4 × %Fat]	
		$N_2O-N = [(F_{SN} \times Frac_{GASF}) + (F_{PRP} \times Frac_{GASM})] \times EF_4$	Equation 11.9 in IPCC (Hergoualc'h et al. 2019)
		Frac _{GASF} Ammonium-based: 0.08 (0.02 – 0.3)	Table 11.3 in IPCC (Hergoualc'h et al. 2019)
		Frac _{GASM} : 0.21 (0.00 – 0.31)	Table 11.3 in IPCC (Hergoualc'h et al. 2019)
		EF ₄ : 0.01 (0.002 – 0.05)	Table 11.3 in IPCC (Hergoualc'h et al. 2019)
	Field (From leaching)	$N_2O-N = [(F_{SN} + F_{PRP}) \times Frac_{LEACH-H} \times EF_5]$	Equation 11.10 in IPCC (Hergoualc'h et al. 2019)

Pollutant	Source	Amount	Reference
		$\text{Frac}_{\text{LEACH-H}}: 0.24 (0.01 - 0.73)$	Table 11.3 in IPCC (Hergoualc'h et al. 2019)
		$\text{EF}_5: 0.011 (0.0005 - 0.025)$	Table 11.3 in IPCC (Hergoualc'h et al. 2019)
CO ₂ -C direct	Lime application	$\text{CO}_2\text{-C} = (M_{\text{Limestone}} \times \text{EF}_{\text{Limestone}}) + (M_{\text{Dolomite}} \times \text{EF}_{\text{Dolomite}})$	Equation 11.12 in IPCC (Hergoualc'h et al. 2019)
		$\text{EF}_{\text{Limestone}}: 0.12$	
		$\text{EF}_{\text{Dolomite}}: 0.13$	
	Urea application	$\text{CO}_2\text{-C} = M_{\text{Urea}} \times \text{EF}_{\text{urea}}$	Equation 11.13 in IPCC (Hergoualc'h et al. 2019)
		$\text{EF}_{\text{Urea}}: 0.2$	
	Fuel consumption (diesel)	$\text{CO}_2\text{-C} = \text{Fuel consumption} \times \text{EF}_{\text{Diesel}}$	
		$\text{EF}_{\text{Diesel}}: 2.23 \text{ kg CO}_2\text{eq L}^{-1} \text{ diesel}^{-1}$	UPME (2016)

The average and the minimum and maximum of the variables that describe the herd structure, milk yield, feeding, land use, and N and soil amendments application rates are displayed in Table 2.

Table 2
Farm description - animal inventory, production rates, feeding supplementation, land uses, and fertilizers application rates in 3 provinces of Cundinamarca Department

Dairy cattle farms (n = 82)									
	Center Savanna (n = 32)			West Savanna (n = 17)			Ubate Valley (n = 33)		
	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max
<i>Herd</i>									
Cows, no (% of herd)	21 (55.9)	1	71	29 (56.8)	1	115	20 (59.7)	2	80
Female calves (0–1 year), no (% of herd)	3 (8.8)	0	27	5 (9.9)	0	23	2 (7.4)	0	10
Male calves (0–1 year), no (% of herd)	1 (1.6)	0	3	1 (1.2)	0	4	1 (4.0)	0	14
Female calves (1–2 year), no (% of herd)	2 (6.6)	0	11	7 (13.6)	0	45	3 (9.7)	0	12
Male calves (1–2 year), no (% of herd)	0	0	0	0.2 (0.4)	0	3	0.2 (0.5)	0	5
Heifers (2–3 years), no (% of herd)	10 (27.1)	0	42	9 (18.1)	0	79	6 (18.7)	0	30
Milk, L cow ⁻¹ year ⁻¹	5735	1825	14600	6464	3650	14600	5422	2053	14600
Milk, kg FPCM ^a cow ⁻¹ year ⁻¹	5560	1769	14155	6268	3539	14155	5257	1991	14155
Commercial concentrate, kg cow ⁻¹ yr ⁻¹	971	365	2190	1337	365	2920	968	365	2008
Maize silage, kg cow ⁻¹ yr ⁻¹	304	29	365	340	256	730	432	256	3650
Molasses, kg cow ⁻¹ yr ⁻¹	108	96	142	115	99	169	101	88	136
Mineral salt, kg AU ^{-1b} yr ⁻¹	50	18	110	50	24	97	53	37	91
Dry Matter Intake, T DMI AU ⁻¹ yr ⁻¹	4,8	3,0	7,4	5,0	3,5	9,4	4,5	3,0	6,9
<i>Land</i>									
Area, ha	15,0	0,6	85,1	17,5	0,4	69,9	7,9	0,6	30,0
Improved pastures, % of area	100%	100%	100%	100%	100%	100%	100%	100%	100%
Urea ^c , kg ha ⁻¹ yr ⁻¹	322	300	350	327	300	350	329	300	450
Fertilizer ^d , kg ha ⁻¹ yr ⁻¹	334	63	750	450	300	600	350	113	548
Urea + Fertilizer (N gross), kg ha ⁻¹ yr ⁻¹	258	175	401	296	249	330	266	241	338
Production of pasture, T DM ha ⁻¹ yr ⁻¹									
<i>Farm</i>									
Stocking rate, AU ha ⁻¹	4,1	0,5	15,9	3,0	0,5	11,0	4,7	0,5	32,5
Stocking rate, cow ha ⁻¹	2,6	0,3	9,4	2,0	0,1	6,5	3,3	0,3	18,8
Diesel, L ha ⁻¹ yr ⁻¹	261,1	8,9	1252,4	439,0	35,2	2052,1	689,7	28,7	3313,4
^a FPCM: Fat Protein Corrected Milk (3.5% 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 year, or 1.3 heifers 2–3 year, or 1.3 steers 1–2 year, or 0.8 bulls) ^c Urea: 46(N) ^d Fertilizer: 31(N): 8(P): 8(K)									

2.1.3 Nitrogen balance

Nutrient balance is a useful tool for quantifying the flow of nutrients in agricultural systems (Cederberg and Mattsson 2000a). A nitrogen balance at the farm level was made for checking out possible N surplus and thus the risk of N leaching. N surplus is defined as the difference between net N-output from the farm in milk and meat and the net N input to the farm (Dalgaard et al. 1998). For each farm, the surplus N was quantified and expressed per unit area (ha).

N inputs were estimated by multiplying each input's amount (feeds and fertilizers) by its N content. The N content of fertilizers and feeds were based on the product labels. Annual N deposition (N input) was assumed using a standard estimate (15 kg N ha⁻¹ yr⁻¹) described by Bobbink et al. (2010). N fixation was set at zero. The N outputs were estimated by multiplying the amount of milk and liveweight produced by their N content. The N content of meat and milk was computed based on their protein content and converted into milk and meat N content, according to Gavrilova et al. (2019). The N surplus must be transmitted into different emissions, which is performed by applying models for calculating N emissions on-farm. N₂O–N and NH₃-N losses were calculated using emission factors from Hergoualc'h et al. (2019) (Table 2).

2.1.4 Impact assessment

2.1.4.1 Estimation of on-farm GHGE

Calculations of GHGE were calculated using Chaps. 10(Gavrilova et al. 2019) and 11(Hergoualc'h et al. 2019) of Volume 4 of the *2019 Refinement to the 2006 IPCC Guidelines*. Equations and emission factors (EF) used to estimate on-farm emissions of CH₄, N₂O, and CO₂ are summarized in Table 1. The amount of dry organic matter in manure was determined from the herd-specific gross energy intake, digestibility of feed consumed, default values for ash content in dry matter and CH₄ producing capacity, and the methane conversion factor. In this study, it was not considered GHGE from cattle respiration, nor the changes in soil carbon stocks on-farm because grasslands were established more than 20 years ago and no land-use changes were conducted since establishment (Steinfeld et al. 2006).

2.1.4.2 Estimation of off-farm GHGE

Emission factors (EF) applied for the computation of the off-farm emissions from production and transportation of imported feeds, fertilizer, amendments to soils are summarized in Table 3.

Table 3
Estimation of off-farm emissions, energy use, and land use for cow-calf and fattening farms

Input	Carbon footprint (kgCO ₂ eq kg ⁻¹ input)
Synthetic nitrogen fertilizer	
N ^a	6.6
P ^a	3.6
K ^a	0.7
Urea ^a	4.43
Lime ^b	0.03
Commercial concentrate ^a	0.7
Maize silage ^a	0.0762
Mineral salt ^c	0.155
Molasses ^b	0.871
Truck 10-20t, Euro 4, 50%FL, default/GLO Economic ^a	0.254*
^a Ecoinvent 3, 2013	
^b Agri-footprint, 2015	
^c ELCD: European Life Cycle Database	
* kgCO ₂ eq t ⁻¹ km ⁻¹	
** MJ t ⁻¹ km ⁻¹	

2.2 Scenario analysis

The enteric fermentation has been reported as a the most source that contributes to total GHGE from dairy cattle production in the Latin American tropics (de Léis et al., 2015; Mazzetto et al., 2020; Ribeiro-Filho et al., 2020). Therefore, proposing strategies to mitigate methane from enteric fermentation is an important way to reduce total GHGE from dairy farms and so the CF of milk from these systems. Then, to assess how changing diet composition, by including locally available shrubs, influences the enteric CH₄ emissions and the milk CF, two scenario analyses were simulated; a sensitivity analysis was carried out to compare the current farm situation with a scenario that includes a mitigation measure of GHGE. Then, the next scenarios were considered:

- Baseline scenario: The real farm data obtained from the surveys, were modeled to estimate the current GHGE and the CF of milk produced by the farms. The allocation method used in this scenario corresponds to the biophysical one.
- Mitigation measure scenarios: As a mitigation measure, hypothetical diets were established, including the grass species currently offered by the farmers, plus a locally available shrub. The proportion of inclusion grass/shrub in a daily dry matter intake basis corresponded to 90:10. The grass species considered was *Cenchrus clandestinus* (kikuyu grass), and the locally available shrub species were *Acacia decurrens*, *Baccharis latifolia*, and *Sambucus peruviana*. Local ingredients in diets were considered one at a time, resulting this in a total of 3 hypothetical diets. The production milk, forages quality and management system, were obtain from three farms located in center savanna, west savanna and Ubaté valley; analyzed a total of 7, 10, and 12 experimental animals, respectively. The emission factor for enteric methane (g/day per cow) was estimated for each animal by considering the following equation (Niu et al. 2018):

$$\text{CH}_4 = -60.5 (17.56) + 12.4 (0.37) \times \text{DMI} - 8.78 (1.342) \times \text{EE} + 2.10 (0.256) \times \text{NDF} + 16.1 (1.39) \times \text{MF} + 0.148 (0.0143) \times \text{BW}$$

- Where DMI is the dry matter intake (kg/day), EE is the dietary ether extract concentration (% of DM), NDF is dietary neutral detergent fiber concentration (% of DM), MF is milk fat concentration (%), and BW is body weight (kg). DMI was estimated by using the equation from the National Research Council (National Research Council 2001), EE and NDF values for grass and shrub species were obtained from AlimenTro (Ariza-Nieto et al. 2020), while MF and BW were obtained from on-farm measurements. The compositions of experimental diets are shown in Table 4. For the 3 evaluated farms, potential reductions in enteric CH₄ emissions and milk yields were calculated as the difference between the baseline estimations and estimations after offering diets.
- Table 4 displays the percentages of reduction of enteric CH₄ emissions and increases in milk yields calculated in each of the 3 evaluated farms. Consequently, for calculating the CFs for the rest of the farms in the mitigation measure scenario, each farm assumed the potential percentages of reduction of enteric CH₄ emissions and increases of milk yields measured in the farms of the region where they belong. For each farm, the size and structure of the herd, and farm characteristics were kept constant corresponding to the baseline scenario. The allocation method used in this scenario corresponds to the biophysical one.

Table 4
Composition of the experimental diets, reductions in enteric CH₄ emissions, and increases of milk yields in each region of Cundinamarca

Evaluated diets			
<i>Cenchrus clandestinus</i> plus:			
	<i>Acacia decurrens</i>	<i>Baccharis latifolia</i>	<i>Sambucus peruviana</i>
Ether extract concentration, % DM	2,1	2	2
Neutral Detergent Fiber (NDF), % DM	56,6	57,7	57
Crude protein	17,7	17,7	17,9
Center savanna			
Milk fat	5,1	5,1	5,1
Body weight, kg	471,4	471,4	471,4
Reductions of enteric methane emissions, %	1,6	0,8	1,1
West savanna			
Milk fat	3,3	3,3	3,3
Body weight, kg	556,1	556,1	556,1
Reductions of enteric methane emissions, %	1,6	0,8	1,1
Ubaté Valley			
Milk fat	4,7	4,7	4,7
Body weight, kg	541,7	541,7	541,7
Reductions of enteric methane emissions, %	1,6	0,8	1,1

2.3 Statistical analyses

The comparison of the effect of the simulated scenarios with the tree species on the measured variables was carried out by analysis of variance under a completely random design, according to the following model:

$$y_{ij} = \mu + \tau_j + \epsilon_{ij}$$

Where y_{ij} are the response variables evaluated, μ is the general average, τ_j is the effect of simulated scenarios, and ϵ_{ij} is the experimental error.

When the means comparisons were significative, were analyzed by Dunnett test, taking as control group the baseline scenario. The analysis had a confidence level of 95%, using software SAS 8.3 procedures.

3. Results and discussion

3.1 Nitrogen balance

Nitrogen surpluses and emissions of $\text{N}_2\text{O-N}$ and $\text{NH}_3\text{-N}$ are displayed in Table 5. The average N surplus ($301.6 \text{ kgN ha}^{-1} \text{ year}^{-1}$) at the farm gate was higher than N surplus reported for dual-purpose dairy farms ($14.7 \text{ kgN ha}^{-1} \text{ year}^{-1}$) in Colombia, which are low input systems with low stocking rates (González-Quintero et al. 2021b). In addition, these figures were in the lower end of the range of N surpluses reported for specialized dairy systems in the most productive dairy basins in Colombia located in the high tropics (219 to $757 \text{ kgN ha}^{-1} \text{ year}^{-1}$) (Benavides-Patiño 2016), and similar to N surpluses informed for conventional dairy systems in Denmark, Italy, Spain, and Sweden (Cederberg and Mattsson 2000b; Nielsen and Kristensen 2005; Penati et al. 2011; Del Prado et al. 2013). The N surpluses computed were high, therefore for all the farms we identified N available for leaching from manure deposited on pastures and fertilizers applied. Considering the above, indirect emissions from $\text{NO}_3\text{-N}$ were included in the calculations of GHGE. N fertilization was the main input of N accounting for 66%, followed by purchased feeds (30%) and atmospheric deposition (4%). This trend was also reported for specialized dairy farms in Mexico and Sweden, where N fertilizer was the main source, with a contribution over 50% of N inputs to the farms (Cederberg and Mattsson 2000b; Cortez-Arriola et al. 2014). Considering N outputs, as the primary product of studied farms is milk, this was the main N sinking (86% of N outputs). However, as specialized dairy farms also produce live weight from cull cows and weaned calves, 14% of N was retained by LW produced.

Table 5
Calculated N inputs, N outputs, N surplus, and N-losses

Dairy cattle farms (n = 82)			
	Mean	Min	Max
<i>Inputs ($\text{kg N ha}^{-1} \text{ year}^{-1}$)</i>			
Purchased feeds	116,9	7,2	847,5
Purchased fertilizer (urea + fertilizer)	269,4	175,4	400,5
Atmospheric deposition ^a	15,0	15,0	15,0
Total	407,8	197,6	1387,4
<i>Outputs ($\text{kg N ha}^{-1} \text{ year}^{-1}$)</i>			
N in milk	80,8	3,2	478,1
N in meat (LWG)	13,7	0,3	145,1
Total	94,5	3,5	623,2
Total N surplus ($\text{kg N ha}^{-1} \text{ year}^{-1}$)	313,3	194,1	764,2
<i>Emissions ($\text{kg N ha}^{-1} \text{ year}^{-1}$)</i>			
Direct $\text{N}_2\text{O-N}$ (excretions)	2,4	0,1	23,8
Direct $\text{N}_2\text{O-N}$ (Urea + fertilizer)	2,7	1,8	4,0
$\text{NH}_3\text{-N}$ (excretions)	127,5	7,5	1249,7
$\text{NH}_3\text{-N}$ (Urea + fertilizer)	21,6	14,0	32,0
Total emissions	154,2	23,5	1309,6

3.2 Handling of co-products: allocation of GHGE between milk and live weight gain

LCA studies for specialized dairy systems developed in various regions in the globe have applied different allocation rules. Some of them, carried out in Italy, Peru, and Uruguay, have used the biophysical approach (Bartl et al. 2011; Lizarralde et al. 2014; Battini et al. 2016; Tichenor et al. 2017; Ribeiro-Filho et al. 2020). Other studies carried out in Costa Rica, Denmark, New Zealand, Sweden, and Switzerland applied the system expansion approach (Flysjö et al. 2011b, 2012; Kristensen et al. 2011; Marton et al. 2016; Mazzetto et al. 2020), while studies developed in Brazil and Nicaragua did not use any allocation method (de Léis et al. 2015; Gaitán et al. 2016). According to our findings (Table 6), the method for allocating the GHGE between co-

products, milk, and meat, plays an important role in the outcome of the CFs. Considering the 3 regions in Cundinamarca, the allocation factors for milk ranged from 78–98%, with the mass production method assigned the higher proportion, followed by energy content, economic, biophysical, and finally the system expansion approach (Table 6). Several studies have reported a similar tendency as our findings about the share of GHGE allocated to milk according to the allocation method applied (Cederberg and Stadig 2003; Gerber et al. 2010; Kristensen et al. 2011; Flysjö et al. 2011a; Marton et al. 2016; Rice et al. 2017). Therefore, the percentages assigned to milk influenced the final results of the CF, e.g, as the system expansion approach assigned the lower percentage to milk, the CF obtained with this approach was the lowest when compared to any of the other allocation alternatives.

Table 6
Percentages of GHGE assigned to milk by using different co-product allocation methods, and carbon footprints of milk and meat GHGE.

Dairy cattle farms (n = 82)									
	Center savanna (n = 32)			West savanna (n = 17)			Ubaté Valley (n = 33)		
	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max
Milk CO ₂ -eq, % of total									
Biological ^a	82	43	94	86	70	95	81	42	95
Economic ^b	89	72	96	91	83	97	89	71	97
Energy ^c	91	77	97	93	86	97	91	76	97
Mass	97	91	99	98	95	99	97	91	99
System expansion ^d	78	62	88	80	67	96	76	61	90
Emission after allocation, kg CO ₂ -eq per kg FPCM									
Biological	1,6	0,7	3,5	1,9	0,5	8,0	1,5	0,5	5,3
Economic	1,8	0,7	5,6	2,0	0,5	8,6	1,7	0,5	6,4
Energy	1,9	0,7	6,0	2,1	0,5	8,8	1,8	0,5	6,7
Mass	2,1	0,7	7,2	2,2	0,6	9,3	1,9	0,5	7,4
System expansion	1,7	0,6	6,4	1,9	0,4	9,1	1,5	0,4	7,0
Emission after allocation, kg CO ₂ -eq per kg LWG									
Biological	13,3	4,2	47,3	13,5	3,4	57,8	12,0	3,3	47,2
Economic	7,7	2,8	23,4	8,4	2,2	35,8	7,2	2,2	26,7
Energy	6,1	2,2	19,3	6,6	1,7	28,2	5,7	1,7	21,5
Mass	2,1	0,7	7,2	2,2	0,6	9,3	1,9	0,5	7,4
System expansion	15,0	15,0	15,0	15,0	15,0	15,0	15	15	15
^a $AF_{milk} = 1 - 6,04 \times BMR$ (IDF 2015)									
^b 1 kg FPCM = 1175 COP; 1 kg live weight gain = 4903 COP									
^c Energy value of milk = 2.9 MJ kg ⁻¹ ; energy value of carcass meat = 9.25 MJ kg ⁻¹									
^d 1 kg live weight gain = 15 kg CO ₂ eq. in avoided emission (González-Quintero et al 2021)									

Substitution by system expansion is an alternative to bypass allocation (ISO 2006), also called the “avoided burden method” because the potentially avoided emissions within the expanded system (cow-calf farms) are subtracted from the primary system of interest (specialized dairy systems). A consequential model was built to account for the potential climate impact that weaned calves and cull cows might have by satisfying some of the demand arising in fattening farms, which is usually met by the cow-calf farms. In Colombia, it has been reported an increasing beef production over the last 30 years (FAO 2018). This means that it would be plausible that LW produced as a co-product from specialized dairy systems, might be introduced (sold) in the primary beef production chain and contribute to fulfilling the national beef demand, and/or replace some LW produced by the cow-calf systems. Considering this scenario, by each kg of LW leaving the dairy farms, a reduction of 15 kgCO₂-eq in all their GHGE in one year period is expected, which leads to a lower CF per kg milk produced when compared with that resulting from the “attributional approaches” (Table 6). Therefore, results obtained with this approach may be a proxy indicator of the potential climate impact reductions of dairy farms in Cundinamarca beyond the farm gate, when considering the inclusion of LW produced in the Colombian beef market.

It is important to remark that there is no agreement among LCA practitioners about which method for handling co-products is better to apply, as the application of different methods can result in different CF outcomes of products of a system. For instance, the Livestock Environmental Assessment and Performance Partnership (LEAP) guidelines explicitly excludes the substitution by system expansion arguing that the focus shall be only on the studied system (FAO 2016), meanwhile under the hierarchy of ISO 14044:2006 the use of system expansion would be the first option (ISO 2006). Considering the above, and the fact that most attributional LCA studies of dairy systems have applied the biological approach adopted by the IDF (IDF 2015), the CFs of milk and meat resulting from this allocation rule will be used for the discussion and analysis in the rest of the paper.

3.3 Annual emissions of CH₄, N₂O, and CO₂

Considering CH₄ on-farm emissions in the three regions of Cundinamarca, enteric fermentation contributed the most, followed by emissions from excreta left in paddocks that contributed to a lesser extent (Table 7). The greater contribution of enteric fermentation to total CH₄ emissions has been also reported by LCA studies of pasture-based dairy systems in Brazil, Colombia, and Costa Rica, mainly because manure management is not performed, which reflects the dominance of all-year-round grazing (Rivera et al. 2014; de Léis et al. 2015; Mazzetto et al. 2020; González-Quintero et al. 2022).

For the three regions of Cundinamarca, direct emissions from fertilization and excreta left in pastures were the main contributors to total N₂O emissions (Table 7). Because of the high N surplus calculated in all the farms, the contribution of indirect emissions from leaching of nitrate (NO₃), from excreta and fertilizers, corresponded to the second contributor to total N₂O emissions, while volatilization of ammonia (NH₃) contributed to the remaining emissions (Table 7).

The burning of fossil fuels on-farm, which is mostly used in the operation of mechanical milking (performed twice a day), chainsaws, and motor pumps, was the main source of direct CO₂ emissions for all the 3 regions of Cundinamarca (Table 7). Urea application, which is widely used by the farmers, ranked as the second source of direct CO₂ on-farm emissions (18%), and the contribution of direct CO₂ emissions from liming corresponded to 2% because of the little use of this soil amendment by farmers.

Table 7
Annual GHGE from the farm processes

Dairy cattle farms (n = 82)									
	Center savanna (n = 32)			West savanna (n = 17)			Ubate Valley (n = 33)		
	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max
Methane emissions, kg CH₄ per AU^a									
Enteric Fermentation – Herd	119,6 (99%)	93,3	145,2	120,8 (99%)	100,1	136,6	119,0 (99%)	99,8	135,6
Manure over pastures	1,2 (1%)	0,8	1,9	1,2 (1%)	0,9	1,4	1,2 (1%)	0,8	1,8
Total	120,7	94,1	147,1	121,9	101,0	138,0	120,1	100,6	137,3
Nitrous oxide emissions, kg N₂O-N per ha									
Directly									
Manure (pasture)	2,3 (26.8%)	0,3	9,0	1,7 (21.9%)	0,3	7,1	2,9 (28.8%)	0,1	23,8
Fertilizer	2,6 (29.9%)	1,8	4,0	3,0 (37.7%)	2,5	3,3	2,7 (26.7%)	2,4	3,4
Indirectly									
NH ₃ (excretions)	1,2 (14.1%)	0,2	4,7	0,9 (11.5%)	0,2	3,7	1,5 (15.1%)	0,1	12,5
NH ₃ (fertilizer)	0,3 (3.6%)	0,2	0,4	0,3 (4.4%)	0,3	0,4	0,3 (3.2%)	0,3	0,4
Leaching (excretions)	1,5 (17.7%)	0,2	5,9	1,1 (14.5%)	0,2	4,7	1,9 (19%)	0,1	15,7
Leaching (fertilizer)	0,7 (7.9%)	0,5	1,1	0,8 (10.0%)	0,7	0,9	0,7 (7%)	0,6	0,9
Total, kg N ₂ O-N per ha	8,6	3,1	25,2	7,9	4,1	20,1	10,0	3,7	56,7
Carbon dioxide emissions, kg CO₂ per ha									
Directly, kg CO ₂ per ha									
Urea application	235,8 (28.4%)	220,0	256,7	239,5 (19.6%)	220,0	256,7	241,1 (13.1%)	220,0	330,0
Liming	11,3 (1.4%)	0,0	329,0	4,5 (0.4%)	0,0	71,5	55,2 (3%)	0,0	880,0
Fossil fuels	582,3 (70.2%)	19,8	2792,8	979,1 (80.1%)	78,6	4576,1	1538,1 (83.8%)	64,0	7388,8
Total, kg C ₂ O per ha	829,5	239,8	3378,5	1223,0	298,6	4904,3	1834,4	284,0	8598,8
^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 year, or 1.3 heifers 2–3 year, or 1.3 steers 1–2 year, or 0.8 bulls)									

3.4 Contribution of primary and secondary activities to total GHGE

Figure 2 shows the contribution of on-farm and off-farm emissions sources to total GHGE for the 3 regions of Cundinamarca. As a general trend, the ranking of overall emissions by pollutant was led by CH₄, followed by CO₂, and last NO₂ (Fig. 2). Most of GHGE were generated by on-farm sources, which contributed to 74 and 79% of total GHGE in the 3 regions (Fig. 2). Enteric fermentation was the source that contributed the most to total GHGE, as is typically found in previous studies of milk CF of dairy systems in Latin America (Bartl et al. 2011; Rivera et al. 2014; de Léis et al. 2015; Ribeiro-Filho et al. 2020; Mazzetto et al. 2020). Fertilizer application and excreta left in pastures were important on-farm emission sources, contributing between 18 and 21% of the overall GHGE. In addition, the main sources of direct on-farm CO₂ emissions corresponded to the burning of fossil fuels, and lime and urea application. The contribution of the burning of fossil fuels on-farm to total GHGE varied between 3 and 6% in the 3 regions, which depended on the level use of machinery and equipment by the farms. Off-farm emissions represented between 21 and 26% of total GHGE in the 3 regions, and the ranking of these emissions by source was led by the manufacture of feed, followed by agrochemicals production, and transport (Fig. 2). A similar GHGE pattern to our findings was reported in LCA studies for specialized dairy pasture-based systems in Brazil, Colombia, Costa Rica, and Peru (de Léis et al. 2015; Mazzetto et al. 2020; González-Quintero et al. 2022), which used the same scope used in this paper “from the cradle to farm gate”. These studies reported a trend in which CH₄ was the main pollutant emitted being enteric fermentation the most important source, followed by CO₂ from the use of agrochemicals and fossil fuels, and N₂O emissions from excretions and the use of fertilizers. Given the share of CH₄ in total

GHGE from the farms, it would be advisable to assess intervention scenarios considering changes in diets to mitigate enteric methane emissions, which would be a key in the overall reduction of the CF of dairy systems.

3.5 Reductions in milk CF after the inclusion of local feedstuffs in animal diets

In pasture-based systems, there is a wider window for the reduction of GHGE by the sustainable intensification and improvements in diet quality composition than in intensive/confined systems (Gerber et al. 2013; Gerssen-Gondelach et al. 2017). In dairy farms, intensification is defined as the increase of outputs per hectare and can be achieved through different strategies (Bava et al. 2014) including the introduction of high-quality feed ingredients, increased use of fertilizer to satisfy the nutritional requirements of pastures, good pasture management practices, and supplementation with silages and concentrate (Nguyen et al. 2013). With intensification, milk yields usually increase, contributing to the reduction of GHGE intensities, which is based on enhancing dairy efficiency by diluting the environmental cost associated with maintenance (Bava et al. 2014). It has been reported that silvopastoral systems can be a real alternative to achieve GHGE intensities reductions up to 50% when compare with traditional systems, thanks to the inclusion of shrubs in animal feeding, optimization of fertilization, appropriate concentrate feed offers and balancing of diet for reducing the N excretion (Rivera et al. 2015). Some LCA studies for dairy systems in Latin American have assessed the inclusion of improved pastures as well as different high-quality ingredients in diets to increase milk yields and reduce GHGE from the farms. However, to our knowledge, there are not LCA studies in Latin America that have evaluated the inclusion of locally produced feedstuffs, such as shrubs, in animal diets and their influence on the environmental and productive behavior of dairy farms. Therefore, this is a first attempt to simulate how the inclusion of local feedstuffs in dairy cattle diets influence the milk CF and milk productivities of Colombian dairy systems located in the high tropics of Cundinamarca.

According to our findings, the inclusion of locally available shrubs, such as *Acacia decurrens*, *Sambucus peruviana*, and *Baccharis latifolia* in animal diets had two important effects, the increasing of milk production per cow and a slightly reduction in enteric methane emissions and nitrous oxide emissions from excreta left in field, when compared to the baseline scenario. Milk yield increases corresponded to 37, 19, and 30% which mean an average milk production of 6916.4, 6235.5 and 6651.6 kg FPCM cow⁻¹ yr⁻¹ for diets including *Acacia decurrens*, *Sambucus peruviana*, and *Baccharis latifolia*, respectively. These potential milk production figures achieved are like the milk yields reported for the best performing specialized dairy farms in Colombia (González-Quintero et al. 2022), and higher than the average milk production figures reported for traditional dairy systems located in West savanna (4270 L cow⁻¹ yr⁻¹), Center savanna (4880 L cow⁻¹ yr⁻¹), and Ubaté Valley (2745 L cow⁻¹ yr⁻¹) (EVA 2018). Like our results, a study performed by Guadron and Padilla (2007) in the high tropics of Cundinamarca, found that the milk yields of cows grazing in silvopastoral plots, which included *Acacia decurrens* and *Alnus acuminata* associated with kikuyu grass, were higher at 12% than the control treatment. In addition, in a study carried out by Carvajal et al. (2012) in Cundinamarca, when *Acacia decurrens* was included as a supplement for dairy cows, the milk yields were similar as those obtained by the traditional diets based on concentrates. The above points out that the inclusion of locally shrubs in cows' diet would help to reduce the yield gap of milk productivity among dairy systems in the high tropics of Cundinamarca.

Reductions in emission factors for enteric methane ranged between 0.8 to 1.6% among the 3 evaluated diets scenarios. Keeping constant or reducing GHGE while increasing milk yields has been reported as an important mitigation measure as it can lower the GHGE intensities from dairy systems (Gerber et al. 2011). The milk and meat CFs of the studied farms were calculated again considering the increases in milk yields and reductions of enteric methane emissions obtained in the mitigation measure scenario (Table 8). CFs were highly sensitive to this scenario conditions reaching reductions which ranged between 13 to 26% for milk, and from 18 to 28% for meat (Table 8). Reductions in CFs were mainly driven by increases in milk yields, as CH₄ emissions diminishes were low. Additionally, keeping methane emissions constant while increasing productivities has been reported as a real challenge for cattle systems in the Latin American tropics (Arango et al. 2020). For dairy systems in Cundinamarca, the above seems to be achievable by the inclusion of locally available *Acacia decurrens*, *Sambucus peruviana*, and *Baccharis latifolia* in diets.

Table 8

Carbon footprint and reductions achieved after the inclusion of local feedstuffs in animal diets of dairy cattle farms in Cundinamarca.

Carbon footprint and reductions achieved after the inclusion of local feedstuffs in animal diets of dairy cattle farms in Cundinamarca.								
	Baseline scenario		Mitigation measure scenario					
	<i>Cenchrus clandestinus</i> (100%)		<i>Cenchrus clandestinus</i> (90%) plus (10% of):					
			<i>Acacia decurrens</i>		<i>Sambucus peruviana</i>		<i>Baccharis latifolia</i>	
Carbon footprint (% variation with baseline), kg CO ₂ eq kgFPCM ⁻¹								
Center savanna	1.6	a	1,3 (-19%)	a	1,4 (-13%)	a	1,4 (-13%)	a
West savanna	1.9	a	1,4 (-26%)	a	1,6 (-16%)	a	1,5 (-21%)	a
Ubate Valley	1.5	a	1,2 (-20%)	a	1,3 (-13%)	a	1,2 (20%)	a
Carbon footprint (% variation with baseline), kg CO ₂ eq kgLWG ⁻¹								
Center savanna	13.3	a	9,7 (28%)	a	11,1 (18%)	a	10,2 (24%)	a
West savanna	13.5	a	9,7 (28%)	a	11,1 (18%)	a	10,2 (24%)	a
Ubate Valley	12	a	8,6 (28%)	a	9,9 (18%)	a	9,1 (24%)	a
Variable means with different letters across columns are not significantly different								

Considering the three regions, the CFs of milk reached after reductions were close to CF values informed by more intensify milk production systems from Denmark, Italy, New Zealand, and Sweden (Flysjö et al. 2011a; Bava et al. 2014; Dalgaard et al. 2014; Salvador et al. 2017; Ribeiro-Filho et al. 2020). The above points out the opportunity of dairy farms in the high tropics of Cundinamarca to achieve better environmental performance, regarding GHGE, with the inclusion of shrubs which are locally available. Therefore, this would be a feasible mitigation measure for scaling up to the dairy cattle systems located in the Colombian high tropics, and by this contribute to the commitments of Colombian Government towards 2030 regarding cutting the 51% of GE of the country (Ministry of Environment and Sustainable Development 2020).

4. Conclusions

The largest on-farm greenhouse gas emissions (GHGE) sources in dairy systems in Cundinamarca arise from animals, where methane from enteric fermentation and nitrous oxide from excretions over pastures are the main contributors. In addition, the manufacturing of inputs corresponded to the largest off-farm GHGE source. Considering this, the carbon footprint (CF) of milk and live weight produced by dairy farms are highly sensitive to changes in methane and nitrous oxide emissions, as well as the level of inputs used.

It was determined that, for LCA studies, more attention should be paid to beef as a co-product when allocating environmental burdens associated with specialized dairy farms. The methodology for handling co-products is fundamental for the outcome of the CF of milk. By the system expansion, the greenhouse gas emissions per kg milk was lower than other analyzed allocation methods. Therefore, the alternative meat system that is replaced by beef from dairy farms highly influences the result of the CF. There is no consensus among LCA practitioners on which coproduct handling method is more suitable to apply when calculating the CF of coproducts from specialized dairy farms, although the biophysical method is the most widely used.

Improving the milk yields by the inclusion of locally available feedstuffs such as *Acacia decurrens*, *Sambucus peruviana*, and *Baccharis latifolia* in animal diets would lead to a reduction in the milk and meat CFs of dairy farms located in the high tropics of Cundinamarca. Thereby, this would help to achieve the Nationally Determined Contribution which aims to mitigate 51% GHGE by 2030 compared to the BAU scenario (Ministry of Environment and Sustainable Development 2020), as well as to close the existing yield gaps of milk production of the dairy systems from the Colombian high tropics.

Our findings support the understanding current productive and environmental performance, in terms of GHGE, of the dairy farms of Cundinamarca Department. In addition, this study identified the main hotspots of GHGE of these systems and give insights on how milk and meat CFs can be reduced with the inclusion of locally available feedstuffs in cattle diets. This study will inform practitioners and policy makers in the path to propose policies and programs for improving productivity indicators and GHGE mitigation in dairy cattle systems of Colombia.

Declarations

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Figures

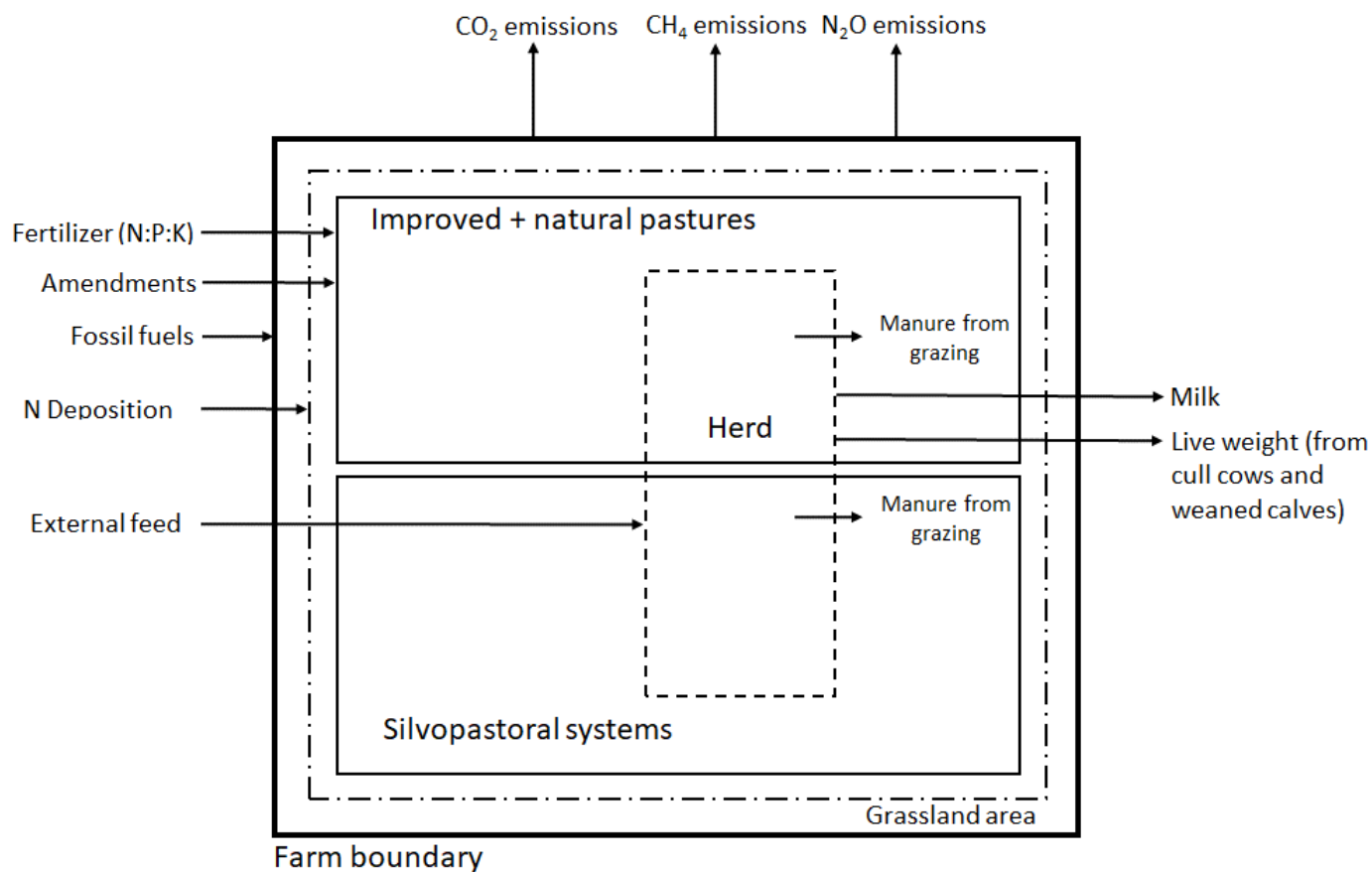


Figure 1

Outline of the specialized dairy farms in Cundinamarca, and the activities included in the "cradle to farm gate" system boundary – Adapted from González-Quintero et al. (2021).

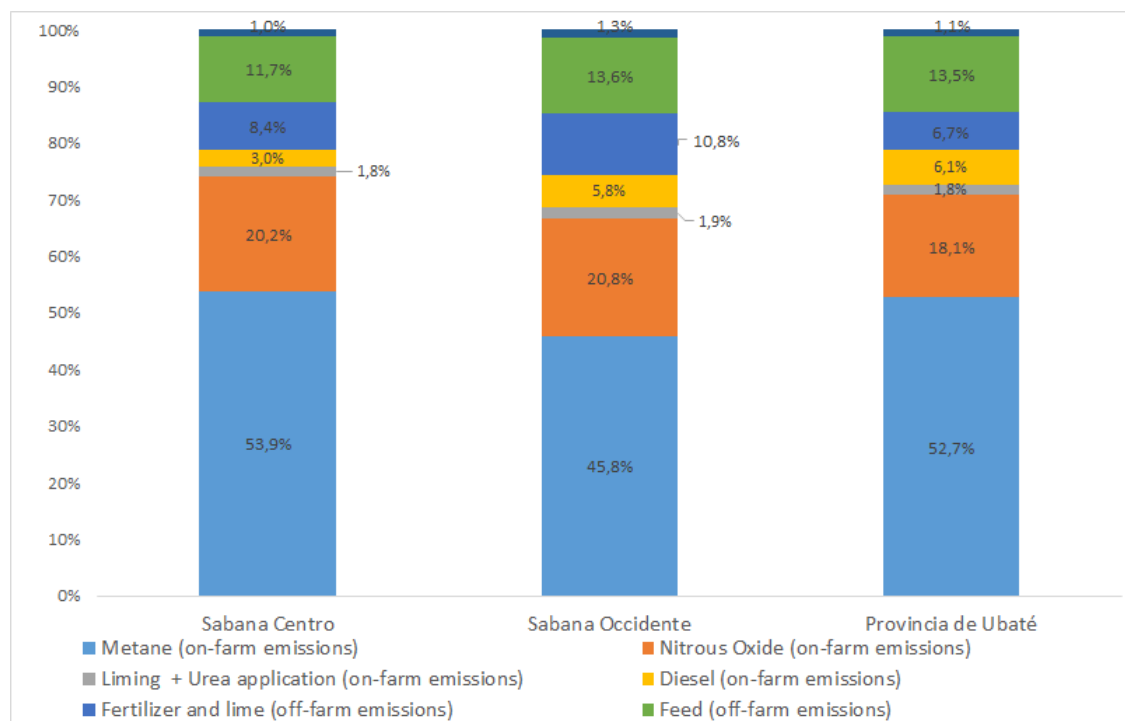


Figure 2

Contributions primary and secondary sources to total GHGE from specialized dairy farms in Cundinamarca.