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 Colombia's greenhouse gas emissions (GHGE). In the department of Cundinamarca, specialized dairy farms located in the high tropics contribute 14% of the national milk production, and 94% of them are small-scale producers. Therefore, mitigation strategies for dairy farms are needed to achieve national GHGE reduction targets. This study aims to quantify the carbon footprint (CF), through a Life cycle Assessment Methodology, of 82 specialized dairy farms at the farm gate in 3 regions of Cundinamarca: Central Savannah, West Savannah and Ubate Valley; and to identify the contribution of *Acacia decurrens*, *Baccharis latifolia*, and *Sambucus peruviana* to milk production increases and GHGE mitigation potential. The comparison of the effect of the tree species on the measured variables was carried out by analysis of variance under a completely random design. GHGE were calculated using the 2019 Refinement to 2006 IPCC guidelines and impact factors from databases. The functional units were 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, enteric fermentation and manure left on pasture were the main on-farm sources of GHGE, and feed manufacturing was the main off-farm source. Milk CFs ranged from 1.5 to 2.2 kgCO_2-eq kgFPCM^{-1}. The inclusion *Acacia decurrens*, *Baccharis latifolia*, and *Sambucus peruviana* in cattle diets reduced the milk CF by 13% to 26% and increased milk yield by 20% to 37% in the three regions. Therefore, the inclusion of locally available forages in dairy cattle diets is a sustainable GHG mitigation option.

Keywords: Global Warming Potential, Greenhouse Gas Emissions, Life Cycle Assessment, Mitigation Potential, Smallholder dairy farms.

1. Introduction

Global milk production is projected to increase by 1.7% per year between 2019 and 2028, with this growth driven by developing countries that currently have low milk yields. Global per capita milk consumption is expected to increase by about 1.1% per year to 2028, driven by higher per capita incomes, population growth, and dietary shifts, particularly in developing countries (OCDE/FAO, 2019). In response to this demand, milk production has increased in Latin America as a result of a 3% increase in animal numbers (Williams and Anderson, 2019), with a consequent increase in environmental pressures such as deforestation, land degradation, and greenhouse gas emissions (GHGE) (Cederberg et al., 2011). Livestock activities contribute to about 10-12% of global GHGE (Mbow et al., 2019), of which about 30% comes from dairy systems (Herrero et al., 2016). The Latin American and Caribbean region accounts for 28% of the world's cattle population, making it the region with the highest GHG emissions from the livestock sector (FAO, 2018). Therefore, it is necessary to adopt sustainable GHG mitigation strategies to address the impact of the Latin American livestock sector on climate change.

In Colombia, ruminant livestock is an important economic activity, accounting for 1.9% of national GDP and 24% of agricultural GDP (DANE, 2020). The cattle sector corresponds to pasture-based systems and its geographical coverage is about 31 million hectares with about 28.8 million heads of cattle. 45% of the animals correspond to dairy production systems such as specialized dairy (6%) and dual-purpose (39%), and the remaining 55% is allocated to the beef production chain (Astaíza-Martínez et al., 2017; Fedegan, 2018b; ICA, 2020a; Rodriguez, J.; Llano, M.; Fonseca, 2018; UPRA, 2020a). Dairy farms (specialized and dual-purpose) generate 7.9 jobs per 100 animals and produce approximately 7,393 million liters of milk per year (UPRA, 2020b). Thirty-two percent of the milk is produced on farms located in the high tropics (above 2,000 m.a.s.l.) of the departments of Antioquia, Boyacá, Cundinamarca, and Nariño. The current national per capita milk consumption (156 L hab^{-1} yr^{-1}) is adequately met by Colombian dairy farms. However, as population growth rates in Colombia are expected to increase in the coming years, the national demand for dairy products is also projected to increase (UPRA, 2020b). As a result, improvements in the milk yields of Colombian dairy farms are needed to meet the country's future milk demand.

The department of Cundinamarca has an area of 22,663 km2, which represents 2% of the Colombian territory. This department has a cattle activity vocation, with an animal stock of about 1.5 million heads distributed in 59,179 farms, which contributes to 15% of the national milk production, making it the second milk-producing department at the national level (Fedegan, 2014; ICA, 2020b; Ministerio de Agricultura y Desarrollo Rural, 2021). In Cundinamarca, 94% of specialized dairy farms correspond to small producers with less than 50 cattle (ICA, 2020b), farm areas range between 6 and 24 ha, stocking rates between 1 and 2 cows per hectare, and milk yields between 12 and 14 L cow^{-1} day^{-1} (Carulla and Ortega, 2016). The most common dairy breeds correspond to Holstein, Jersey, Normande, and their crosses, and considering the herd structure, productive and dry cows reach about 59 to 63% of the total livestock (Carulla and Ortega, 2016). The most common grass species *Cenchrus clandestinus* (Kikuyo grass), and *Lolium sp*. (Ryegrass) in a lower proportion, mixed with clovers (*Trifolium repens* and *Trifolium pratense*) and other legumes. It is possible to find areas with some shrubs *Sambucus nigra* and *Sambucus peruviana*, and tree species such as *Salix sp.*, *Alnus acuminata*, *Acacia sp.*, and *Eucalyptus sp.* (Avellaneda, 2013; Pulido, 2005). Thus, it is expected that the national milk production figures will be a key player in meeting the future demand for dairy products in Colombia. The Colombian government is committed to a reduction of 51% of the national GHGE by 2030 (Ministry of Environment and Sustainable Development, 2020). Considering the number of cattle, dairy systems play an important role in achieving the national GHGE reduction targets for the livestock sector in Colombia by 2030. Therefore, it is necessary to quantify the GHGE generated by these systems and identify the main emission hotspots in order to define appropriate GHG mitigation measures.

Life cycle assessment is a methodology that allows the estimation of GHGE along the milk production chain, 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 environmental impact category known as the global warming potential evaluated in a time horizon of 100 years (GWP100), which is commonly used in LCA studies of livestock systems to quantify the GHGE and interpret them in terms of climate change (Bartl et al., 2011; de Léis et al., 2015; Gerber et al., 2013; González-Quintero et al., 2021b; Lizarralde et al., 2014; Mazzetto et al., 2020). In Latin America, it has been reported that the reduction of GHGE intensities in dairy systems should focus on intensification by improving the quality of diets with the inclusion of higher proportions of seeded pastures and concentrates (de Léis et al., 2015; Gerssen-Gondelach et al., 2017; González-Quintero et al., 2021b; Lizarralde et al., 2014). To our knowledge, the inclusion of local feed sources (such as trees and shrubs available on the farm) in animal diets has not yet been evaluated as a possible mitigation option in LCA studies for specialized dairy systems in the high tropics. Therefore, the present study has two objectives. First, to estimate the CF and the main sources of GHGE from specialized dairy farms in the department of Cundinamarca, Colombia, using primary data collected directly from the farms. Second, to generate environmental and productive development scenarios to identify the contribution of local shrubs to the GHGE mitigation potential and possible increases in milk yields.

2. Methodology

2.1 Sources of information and study area

The information used in this study was collected between the years 2020 and 2021 through semi-structured surveys applied to 132 farms distributed in 29 municipalities in the provinces of Central Savannah, West Savannah and Ubate Valley, located in the department of Cundinamarca - Colombia. Central Savannah is made up of 11 municipalities: Cajicá, Chía, Cogua, Cota, Gachancipá, Nemocón, Sopó, Tabio, Tenjo, Tocancipá, Zipaquirá; West Savannah 8 municipalities: Bojacá, El Rosal, Facatativá, Funza, Madrid, Mosquera, Subachoque, Zipacon: and Ubate Valley 10 municipalities: Carmen de Carupa, Cucunubá, Fúquene, Guachetá, Lenguazaque, Simijaca, Susa, Sutatausa, Tausa, Ubaté (Figure 1). 82 specialized dairy farms were identified, corresponding to the sample for this study. Of these, 32 farms were located in the Central Savannah, 17 in the Western Savannah, and 33 in the Ubate Valley. The study area - Central Savannah, West Savannah, and Ubate Valley - has an average annual temperature of 14°C and an average annual rainfall of 800 mm, which, according to Holdridge, corresponds to the ecological life zone of the lower montane humid forest.

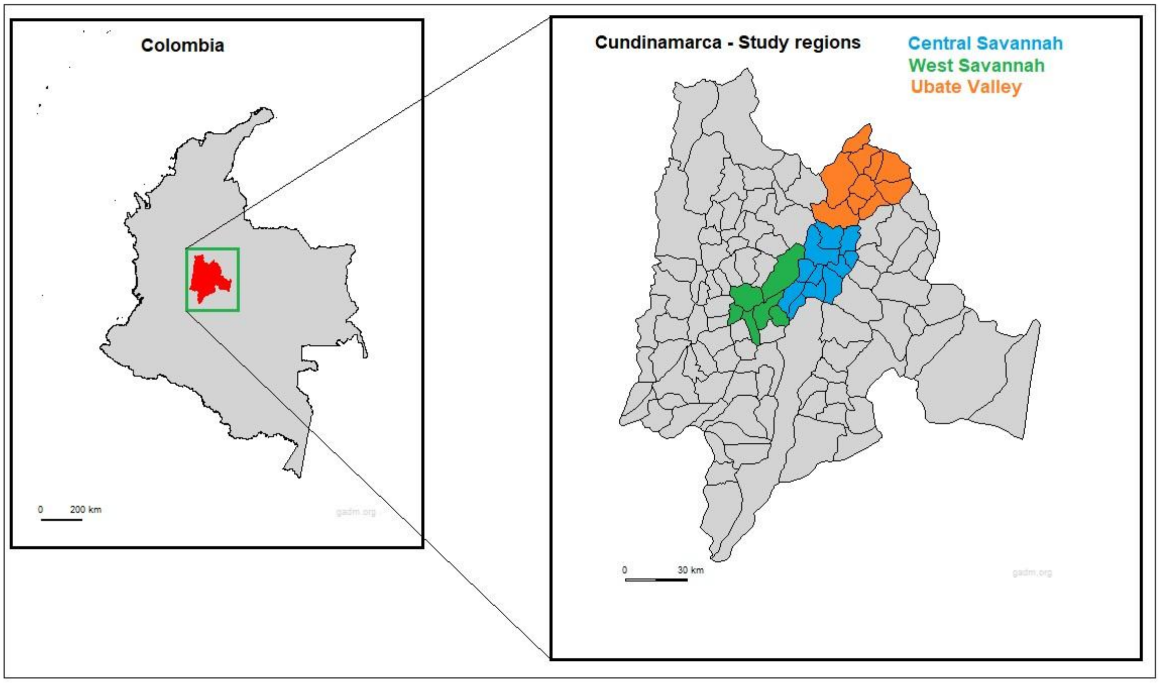

Figure 1. Location of the provinces Central Savannah, West Savannah, and Ubate Valley were studied farms were located.

2.2 Life cycle assessment (LCA)

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

2.2.1 Goal and scope

2.2.1.1 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 (Figure 2).

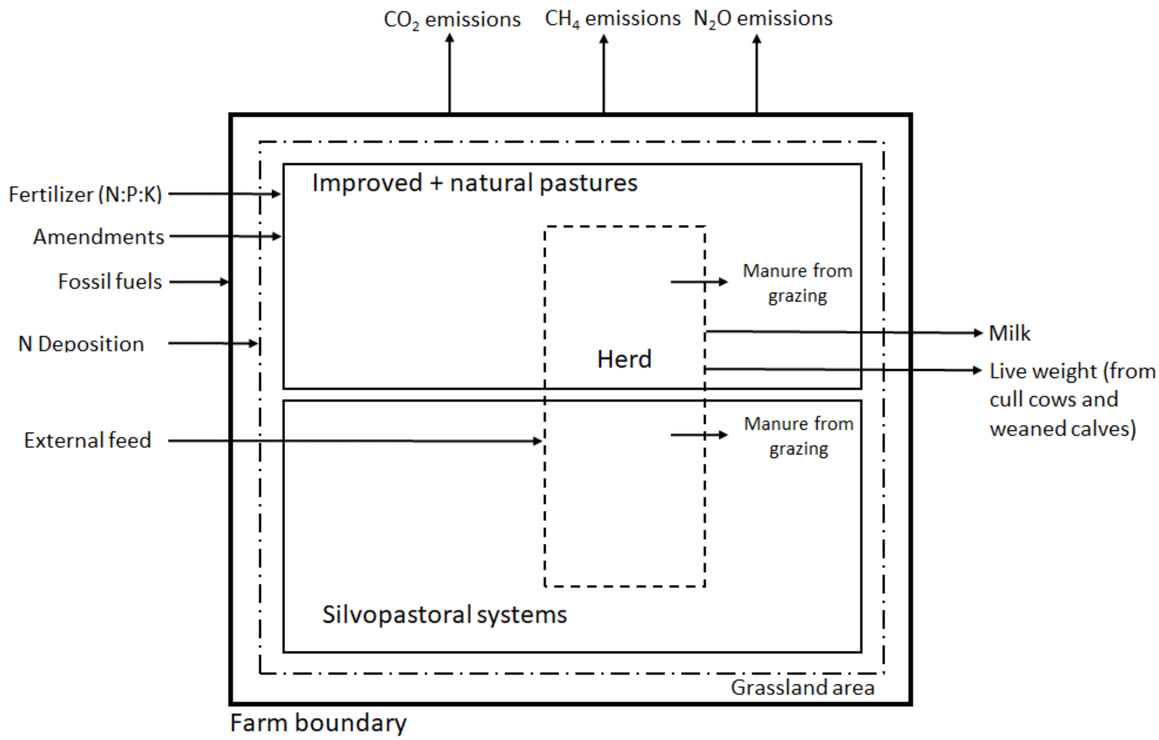

Figure 2. Outline of the specialized dairy farms in Cundinamarca, and the activities included in the "cradle to farm-gate" system boundary – Adapted from González-Quintero et al. (2021).

2.2.1.2 Functional units and handling of co-products

The main output of specialized dairy systems in the highlands of Colombia is milk. However, culled cows and surplus weaned calves are considered as another by-product of the farm. Considering the above, the environmental impacts of dairy farms were expressed as indices using two functional units: for milk, one kg of fat and protein corrected milk (FPCM), and for meat, one kg of live weight gain (LWG). The attributional and consequential modeling approaches were used in the LCA. In the attributional approach, co-product allocation is typically used, while in the consequential LCA, system expansion is used instead. Attributional LCA focuses on capturing the physical flows and allocating emissions between co-products, and consequential LCA examines the consequences of a change (Flysjö et al. 2011a). Below are the five methods used to handling co-products:

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 allocating GHGE between milk and meat in specialized dairy farms was used. This allocation rule was 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 content (MJ).
4) The mass allocation method was estimated considering the total amount of milk (FPCM) and meat (LWG) produced in one year.
5) In the system expansion approach, it was determined that the live weight (LW) produced by the dairy farms substituted an identical amount of LW produced in an

alternative beef farm. Considering the above and applying the system expansion through avoided burden, the environmental burden of the substituted LW was credited to the dairy farms (Marton et al. 2016). Therefore, the total environmental impact of milk would be equal to the total environmental impact generated in the dairy farm, including the rearing of calves until weaning, minus the impact generated in the production of the same amount of LW produced by the dairy farm in the alternative beef system. We determined that the LW from dairy farms would replace the amount of LW produced in a cow-calf system, which was the chosen alternative system. The average CF from Colombian cow-calf systems is equivalent to 15 kgCO_2-eq kgLWG^{-1} (González-Quintero et al. 2021a). This value was used to estimate the avoided GHGE.

2.2.2 Life Cycle Inventory

2.2.2.1 *Description of the specialized dairy cattle farms in Cundinamarca*

Milk production was standardized to a specific 3.7% fat and 3.3% protein-corrected milk (FPCM), following Carulla and Ortega (2016). LWG was quantified as the weight (kg) of animals leaving the farms, such as surplus calves and cull cows. The average and minimum and maximum values of the variables describing herd structure, milk yield, feeding, land use, and N and soil amendment application rates are presented in Table 1.

Table 1.

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)								
	Central Savannah (n=32)			West Savannah (n=17)			Ubate Valley (n=33)		
	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max
Herd									
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}	**5,735**	1,825	14,600	**6,464**	3,650	14,600	**5,422**	2,053	14,600
Milk, kg FPCM[a] cow^{-1} year^{-1}	**5,560**	1,769	14,155	**6,268**	3,539	14,155	**5,257**	1,991	14,155
Commercial concentrate, kg cow^{-1} yr^{-1}	**971**	365	2,190	**1,337**	365	2,920	**968**	365	2,008
Maize silage, kg cow^{-1} yr^{-1}	**304**	29	365	**340**	256	730	**432**	256	3,650
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
Land									

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}									
Farm									
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	1,252.4	**439.0**	35.2	2,052.1	**689.7**	28.7	3,313.4

[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 yr, or 1.3 heifers 2-3 yr, or 1.3 steers 1- 2 yr, or 0.8 bulls)
[c] Urea: 46(N)
[d] Fertilizer: 31(N): 8(P): 8(K)

2.2.3 Impact assessment

2.2.3.1 Estimation of on-farm and off-farm GHGE

The emission factor (EF) for enteric CH_4 from cows (g cow^{-1} day^{-1}) was estimated for each farm by considering the following equation (Niu et al., 2018):

$$\mathrm{CH_4} = -60.5\ (17.56) + 12.4\ (0.37) \times \mathrm{DMI} - 8.78\ (1.342) \times \mathrm{EE} + 2.10\ (0.256) \times \mathrm{NDF} + 16.1\ (1.39) \times \mathrm{MF} + 0.148\ (0.0143) \times \mathrm{BW}$$

Where DMI is dry matter intake (kg day^{-1}), EE is 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 using the National Research Council equation (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. For animal categories other than cows, enteric CH_4 emissions and gross energy concentration were calculated using IPCC Tier 2 equations (Table S1), taking into account the daily gross energy intake (GE) 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). DMI was calculated by dividing herd-specific gross energy intake values by the energy density of the diet (18.45 MJ $kgDM^{-1}$) (Gavrilova et al., 2019; IPCC, 2006). The nutritional quality and pasture productivity (t DM ha^{-1} yr^{-1}) were determined using the "hand plucking" method described by (Bonnet et al., 2011), where grazing was simulated. Nutrient content and digestibility were estimated using the NIRS technology (Ariza-Nieto et al., 2018), to calculate the nutrients offered to the animals in the diet. The use of fertilizers and amendments was expressed as the amount applied to an area (ha) of improved pastures.

On-farm CH_4 (excreta management), N_2O, and CO_2 emissions were calculated using Chapters 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 EFs are summarized in Table S1. The amount of dry organic matter in manure was determined from herd-specific gross energy intake, digestibility of consumed feed, default values for ash content in dry matter and CH_4 production capacity, and the CH_4 conversion factor. In this study, GHGE from cattle respiration and changes in on-farm soil carbon stocks were not considered because the grasslands were established more than 20 years ago and no land-use changes have occurred since establishment (Steinfeld et al., 2006).

Emission factors (EF) used to calculate off-farm emissions from production and transportation of imported feed, fertilizer, and soil amendments are summarized in Table S2.

2.2.3.2 Nitrogen Balance

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

N inputs were estimated by multiplying the amount of each input (feed and fertilizer) by its N content. The N content of fertilizers and feeds was based on 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 assumed to be zero. N outputs were estimated by multiplying the amount of milk and live weight produced by their N content. The N content of meat and milk was calculated based on their protein content and converted to the N content of milk and meat according to Gavrilova et al. (2019). The N surplus needs to be translated into different emissions, which is done by applying on-farm N emission calculation models. N_2O-N and NH_3-N losses were calculated using emission factors from Hergoualc'h et al. (2019) (Table S1).

2.3 Scenario analysis

Enteric fermentation has been reported as the source that contributes most to total GHGE from dairy cattle production in the Latin American tropics (de Léis et al., 2015; González-Quintero et al., 2022; Mazzetto et al., 2020; Ribeiro-Filho et al., 2020). Therefore, proposing strategies to mitigate enteric CH_4 is an important way to reduce total GHGE from dairy farms and thus the CF of milk from these systems. To assess how changing the diet composition by including locally available shrubs influences enteric CH_4 emissions and milk CF, a scenario analysis was performed comparing the current farm situation (baseline scenario) with modeled mitigation measures of GHGE (mitigation measures scenario). Therefore, the following scenarios were considered:

- Baseline scenario: Total GHGE and milk CFs were estimated using real data describing the current dynamics of the farms. Information was obtained from the surveys conducted on each farm.
- Mitigation scenarios: 3 experimental diets were established. The diets were composed of the grass species currently offered by the farmers plus a locally available shrub. The grass:shrub inclusion ratio on a daily dry matter basis was 90:10. The grass species included was *Cenchrus clandestinus* (Kikuyu grass) and the shrub species were *Acacia decurrens*, *Baccharis latifolia*, and *Sambucus peruviana*. Shrub species in the diets were considered one at a time, resulting in a total of 3 experimental diets. To evaluate the effect of the experimental diets on animal performance, 3 farms located in Central Savannah, West Savannah, and Ubaté Valley were selected, with a total of 7, 10, and 12 animals treated, respectively. For each experimental diet, milk yield and CH_4 emissions were measured for each animal. Table 2 shows the composition of experimental diets, percentages of reductions in enteric CH_4 emissions, and increases in milk yield calculated for each of the three farms evaluated. For each experimental diet, the reductions in enteric CH_4 emissions

and increases in milk yield were calculated as the difference between the baseline and the results after offering the diet.

- Consequently, to model the CFs for the rest of the farms for each experimental diet, each farm assumed reductions in enteric CH_4 emissions and increases in milk yield obtained in the farm of the region to which it belongs. For each farm, the size and structure of the herd and the farm management characteristics remained the same as in the baseline scenario.
- The allocation method used in this scenario analysis corresponds to the biophysical one.

Table 2. Composition of experimental diets, reductions in enteric CH_4 emissions, and increases of milk yields in Central Savannah, West Savannah, and Ubaté Valley.

	Evaluated diets		
	Cenchrus clandestinus plus:		
	Acacia decurrens	*Baccharis latifolia*	*Sambucus peruviana*
Ether extract concentration, % DM	2.1	2	2
Neutral Detergent Fiber (NDF), % DM	56.6	57.7	57
Crude protein, %DM	17.7	17.7	17.9
Central Savannah			
Milk fat	5.1	5.1	5.1
Body weight, kg	471.4	471.4	471.4
Reductions of enteric CH_4 emissions (from baseline), %	1.6	0.8	1.1
Increases in milk yields (from baseline), %	36.9	29.9	19.1
West Savannah			
Milk fat	3.3	3.3	3.3
Body weight, kg	556.1	556.1	556.1
Reductions of enteric CH_4 emissions (from baseline), %	1.6	0.8	1.1
Increases in milk yields (from baseline), %	35.9	30.1	19.6
Ubaté Valley			
Milk fat	4.7	4.7	4.7
Body weight, kg	541.7	541.7	541.7
Reductions of enteric CH_4 emissions (from baseline), %	1.6	0.8	1.1
Increases in milk yields (from baseline), %	37.1	30.8	20.1

2.4 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:

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

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 N_2O-N and NH_3-N are shown in Table 3 (this information is not derived from the analysis of variance). The average N surplus (301.6 kgN ha^{-1} year^{-1}) at the farm gate was higher than the N surplus reported for dual-purpose dairy farms in Colombia (14.7 kgN ha^{-1} year^{-1}), which are low input systems with low stocking rates (González-Quintero et al., 2021b). Furthermore, these figures were at 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 kgN ha^{-1} year^{-1}) (Benavides-Patiño, 2016), and similar to the N surpluses reported for conventional dairy systems in Denmark, Italy, Spain, and Sweden (C. Cederberg and Mattsson, 2000; del Prado et al., 2013; Nielsen and Kristensen, 2005; Penati et al., 2011). The calculated N surpluses were high, so we identified the N available for leaching from manure deposited on pastures and applied fertilizers for all farms. Considering the above, indirect emissions of NO_3-N were included in the calculations of GHGE. On average, N fertilization was the main input of N, accounting for 66%, followed by purchased feed (30%) and atmospheric deposition (4%). This trend has also been reported for specialized dairy farms in Mexico and Sweden, where N fertilization was the main source, contributing more than 50% of N inputs to the farms (C. Cederberg and Mattsson, 2000; Cortez-Arriola et al., 2014). As the main product of the farms studied is milk, this was the main N sink (86% of N outputs). However, as specialized dairy farms also produce LW from cull cows and weaned calves, 14% of N was retained by the LW produced.

Table 3. Calculated N inputs, N outputs, N surplus, and N-losses

	Dairy cattle farms (n = 82)	
	Mean	Standard error
Inputs (kg N ha^{-1} year^{-1})		
Purchased feeds	116.9	13.7
Purchased fertilizer (urea + fertilizer)	269.4	3.4
Atmospheric deposition[a]	15.0	0.0
Total	401.3	---
Outputs (kg N ha^{-1} year^{-1})		
N in milk	80.8	8.2
N in meat (LWG)	13.7	2.2
Total	94.5	---
Total N surplus (kg N ha^{-1} year^{-1})	306.8	---
Emissions (kg N ha^{-1} year^{-1})		
Direct N_2O-N (excretions)	2.4	0.3
Direct N_2O-N (Urea + fertilizer)	2.7	0.0
NH_3-N (excretions)	127.5	17.5
NH_3-N (Urea + fertilizer)	21.6	0.3
Total emissions	154.2	---

[a]Data take from Bobbink et al. (2010).

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

LCA studies for specialized dairy systems developed in different regions of the world have applied different allocation rules. Some of them, carried out in Italy, Peru, and Uruguay, used the biophysical approach (Bartl et al., 2011; Battini et al., 2016; Lizarralde et al., 2014; Ribeiro-Filho et al., 2020; Tichenor et al., 2017). Other studies conducted in Costa Rica, Denmark, New Zealand, Sweden, and Switzerland applied the system expansion approach (Flysjö et al., 2012, 2011b; Kristensen et al., 2011; Marton et al., 2016; Mazzetto et al., 2020), while studies conducted in Brazil and Nicaragua did not use any allocation method (de Léis et al., 2015; Gaitán et al., 2016). According to our results (Table 4), the method used to allocate GHGE between co-products, milk and meat, plays an important role in the outcome of CFs. Considering the three regions of Cundinamarca, the allocation factors for milk ranged from 78% to 98%, with the mass production method assigning the higher proportion, followed by energy content, economic, biophysical, and finally the system expansion approach (Table 4). Several studies have reported a trend similar to our findings regarding the proportion of GHGE assigned to milk according to the allocation method applied (Cederberg and Stadig, 2003; Flysjö et al., 2011a; Gerber et al., 2010; Kristensen et al., 2011; Marton et al., 2016; Rice et al., 2017). Therefore, the percentages allocated to milk influenced the final results of the CF, e.g., because the system expansion approach allocated the lower percentage to milk, the CF obtained with this approach was the lowest compared to all other allocation alternatives.

Table 4. Percentages of GHGE assigned to milk by using different co-product allocation methods, and milk and meat CFs.

	Dairy cattle farms (n = 82)					
	Central Savannah (n=32)		West Savannah (n=17)		Ubaté Valley (n=33)	
	Mean	Standard error	Mean	Standard error	Mean	Standard error
Milk CO_2-eq, % of total						
Biological [a]	82	1.1	86	0.5	81	1.0
Economic [b]	89	0.5	91	0.3	89	0.5
Energy [c]	91	0.4	93	0.2	91	0.4
Mass	97	0.2	98	0.1	97	0.2
System expansion [d]	78	0.1	80	0.1	76	0.1
Milk carbon footprints, kg CO_2-eq $kgFPCM^{-1}$						
Biological	1.6	0.2	1.9	0.4	1.5	0.2
Economic	1.9	0.2	2.0	0.5	1.7	0.2
Energy	2.0	0.2	2.1	0.5	1.8	0.2
Mass	2.1	0.3	2.2	0.5	1.9	0.2
System expansion	1.8	0.3	1.9	0.5	1.5	0.2
Meat carbon footprints, kg CO_2-eq $kgLWG^{-1}$						
Biological	13.3	1.8	13.5	3.2	12.0	1.5
Economic	7.9	0.9	8.4	2.0	7.2	0.8
Energy	6.3	0.7	6.6	1.5	5.7	0.6
Mass	2.1	0.3	2.2	0.5	1.9	0.2
System expansion	15.0	0.0	15.0	0.0	15	0

[a] AF_{milk}= 1 – 6.04 x BMR (IDF 2015)

[b] 1 kg FPCM = 1,175 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 bypassing allocation, also known as the "avoided burden method." This approach subtracts potentially avoided emissions from the expanded system (cow-calf farms) from the primary system of interest (specialized dairy systems). The method is described in ISO (2006), A consequential model has been developed to consider the potential climate impact of weaned calves and cull cows meeting some of the demand in fattening farms, which is typically fulfilled by cow-calf farms. The FAO (2018) reports rising beef production in Colombia over the past three decades. It is feasible for co-product LW produced by specialized dairy systems to be introduced (sold) into the primary beef production chain. This can aid in fulfilling the national beef demand and potentially replace some of the LW produced by cow-calf systems. In this scenario, for each kilogram of LW leaving the dairy farms, a reduction of 15 kgCO_2-eq in all of their GHGE can be expected over a one-year period. This in turn leads to a decrease in CF per kilogram of milk produced when compared to the "attributional approaches" (see Table 4). Therefore, the results obtained through this approach may serve as a proxy indicator of the potential reduction of climate impact by dairy farms in Cundinamarca beyond the farm gate, taking into account the inclusion of LW produced in the Colombian beef market.

It is noteworthy that there is disagreement among LCA professionals regarding the optimal co-product handling method to use. The application of various methods may result in differing CF outcomes for a system's products. For example, the LEAP guidelines for Livestock Environmental Assessment and Performance Partnership state that substitution by system expansion is explicitly excluded and the focus is solely on the studied system (FAO, 2016). In contrast, the hierarchy of ISO 14044:2006 prioritizes the use of system expansion (ISO, 2006). Given the aforementioned information and the prevalence of dairy system attributional LCA studies utilizing the biological approach adopted by the IDF (2015), the CFs obtained from this allocation method will be utilized for the remainder of the paper's discussion and analysis.

3.3 Annual emissions of CH_4, N_2O, and CO_2

In the three regions of Cundinamarca, CH_4 on-farm emissions analysis shows enteric fermentation as the major contributor to total CH_4 emissions. This is followed by emissions from excreta that were left in paddocks, which made a comparatively smaller contribution (Table 5). LCA studies of pasture-based dairy systems in Brazil, Colombia, and Costa Rica have also reported a greater contribution of enteric fermentation to total CH_4 emissions. This is primarily due to the lack of manure management, which reflects the prevalence of all-year-round grazing (de Léis et al., 2015; González-Quintero et al., 2022; Mazzetto et al., 2020; Rivera et al., 2014).

Direct emissions from fertilization and excreta left in pastures were the primary sources of total N_2O emissions in the three regions of Cundinamarca, as illustrated in Table 5. Indirect emissions resulting from leaching of nitrate (NO_3) from excreta and fertilizers were the second contributor to total N_2O emissions, due to the high N surplus calculated in all the farms. The remaining emissions were due to volatilization of ammonia (NH_3), as shown in Table 5.

Fossil fuel combustion on farms, mainly for operating machinery such as milkers (used twice daily), chainsaws, and motor pumps, was the primary source of direct CO_2 emissions for all three regions

(Table 5). The second leading cause of direct on-farm CO_2 emissions (18%) was urea application, which farmers widely use. Due to the minimal use of this soil amendment, direct CO_2 emissions from liming corresponded to only 2%.

Table 5.

Annual GHGE from the farm processes

	Dairy cattle farms (n = 82)					
	Central Savannah (n=32)		West Savannah (n=17)		Ubaté Valley (n=33)	
	Mean	Standard error	Mean	Standard error	Mean	Standard error
Methane emissions, kg CH_4 per AU[a]						
Enteric Fermentation - Herd	119.6	2.0	120.8	2.4	119.0	1.3
Manure over pastures	1.2	0.0	1.2	0.0	1.2	0.0
Total	120.7	---	121.9	---	120.1	---
Nitrous oxide emissions, kg N_2O-N per ha						
Directly						
Manure (pasture)	2.3	0.4	1.7	0.4	2.9	0.7
Fertilizer	2.6	0.1	3.0	0.0	2.7	0.0
Indirectly						
NH_3 (excretions)	1.2	0.2	0.9	0.2	1.5	0.4
NH_3 (fertilizer)	0.3	0.0	0.4	0.0	0.3	0.0
Leaching (excretions)	1.5	0.3	1.1	0.3	1.9	0.5
Leaching (fertilizer)	0.7	0.0	0.8	0.0	0.7	0.0
Total, kg N_2O-N per ha	8.6	---	7.9	---	10.0	---
Carbon dioxide emissions, kg CO_2 per ha						
Directly, kg CO_2 per ha						
Urea application	235.8	2.8	239.5	3.9	241.1	3.9
Liming	11.3	11.3	4.5	4.5	55.2	31.0
Fossil fuels	582.4	127.3	979.1	315.1	1,538.1	342.6
Total, kg C_2O per ha	829.5	---	1,223	---	1,834.4	---

[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)

3.4 Contribution of primary and secondary activities to total GHGE

Figure 3 displays the proportion of emissions from on-farm and off-farm sources contributing to the total GHGE for the three regions in Cundinamarca. The data indicates that CH_4 is the leading pollutant, followed by CO_2, and NO_2. Furthermore, on-farm sources were responsible for the majority of GHGE, with a range of 74 to 79% in all three regions. Enteric fermentation was the primary contributor to total GHGE, consistent with earlier studies of milk CF in Latin American dairy systems (Bartl et al., 2011; de Léis et al., 2015; Mazzetto et al., 2020; Ribeiro-Filho et al., 2020; Rivera et al., 2014). On-farm emissions from fertilizer application and excreta left in pastures also played a significant role, accounting for 18-21% of overall GHGE. Additionally, direct on-farm CO_2 emissions were primarily generated through the burning of fossil fuels, as well as the application of lime and urea. The proportion of on-farm GHGE resulting from burning fossil fuels varied between 3% and 6% in the three regions, depending on the degree to which farms utilized machinery and equipment. Off-farm emissions accounted for 21-26% of total GHGE in the three regions examined. Among these emissions, the manufacture of feed was the largest source, followed by agrochemicals and transport (Figure 3). Our findings aligned with similar GHGE patterns observed in LCA studies of specialized dairy pasture-based systems in Brazil, Colombia, Costa Rica, and Peru (Bartl et al., 2011; de Léis et al., 2015; González-Quintero et al., 2022; Mazzetto et al., 2020). The studies indicate a trend of CH_4 as the primary pollutant emitted from farms, with enteric fermentation being the major source, followed by CO_2 from inputs transportation, manufacturing, and on-farm inputs use, and N_2O emissions from excretions and fertilizer use. Considering the share of CH_4 in total GHGE from farms, it is advisable to evaluate intervention scenarios that involve dietary changes to reduce enteric CH_4 emissions. This would be a crucial factor in decreasing the CF of dairy systems overall.

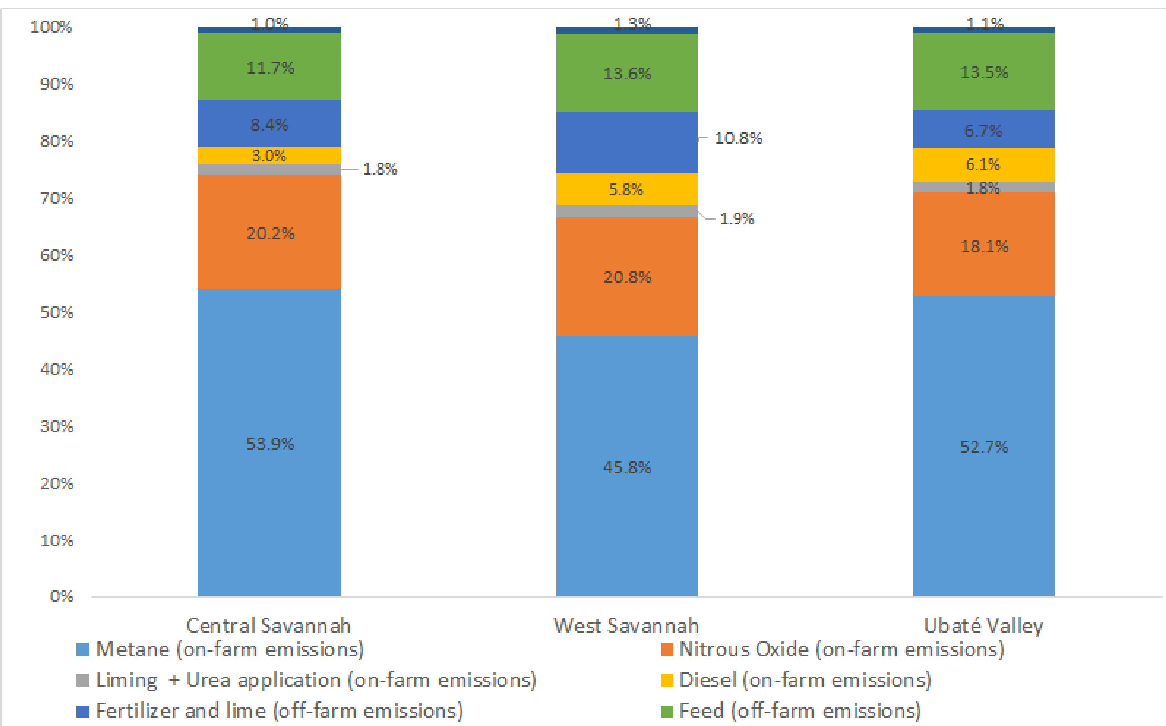

Figure 3. Contributions primary and secondary sources to total GHGE from specialized dairy farms in Cundinamarca.

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

In pasture-based systems, sustainable intensification and improvements in diet quality composition offer a greater opportunity for reducing GHGE compared to intensive/confined systems. This has been shown by Gerber et al. (2013) and Gerssen-Gondelach et al. (2017). Intensification in dairy farms refers to the increase of outputs per hectare and can be achieved via various strategies (Bava et al., 2014), such as introducing high-quality feed ingredients, increasing the use of fertilizers to meet the nutritional needs of pastures, implementing good pasture management practices, and supplementing with silages and concentrates (Nguyen et al., 2013). It is a crucial aspect of modern dairy farming practices. Increasing milk yields through intensification typically reduces GHGE intensities by enhancing dairy efficiency and diluting the environmental cost of maintenance (Bava et al., 2014). Silvopastoral systems have demonstrated the potential to achieve significant reductions in GHGE intensities - up to 50% when compared to traditional systems. This is attributed to the inclusion of shrubs in animal feeding, optimization of fertilization, appropriate concentrate feed offers, and the balancing of diets to reduce N excretion (Rivera et al., 2015). Some LCA studies in Latin America have evaluated the inclusion of improved pastures and high-quality ingredients in dairy systems to boost milk yields and reduce GHGE. Nonetheless, no research has assessed the impact of locally produced feedstuffs, like shrubs, on the environmental and productive behavior of dairy farms in the region. Therefore, this study aims to simulate the impact of incorporating locally sourced feed into dairy cattle diets on milk CF and productivity in Colombian dairy systems situated in the high tropics of Cundinamarca.

Based on our findings, incorporating locally available shrubs, including *Acacia decurrens*, *Baccharis latifolia, and Sambucus peruviana* into animal diets yields two important outcomes: enhanced milk production per cow and a modest decrease in enteric CH_4 and N_2O emissions resulting from excreta left in the field (Table 2). Average milk yield increased by 37%, 30%, and 20% for diets containing *Acacia decurrens*, *Baccharis latifolia, and Sambucus peruviana*, respectively. This resulted in an average milk production of 6916.4, 6651.6, and 6235.5 kg FPCM cow^{-1} yr^{-1} for diets including *Acacia decurrens*, *Baccharis latifolia, and Sambucus peruviana*, respectively. The attained milk production figures are comparable to the milk yields reported by the top-performing specialized dairy farms in Colombia (González-Quintero et al., 2022), and exceed the average milk production figures reported by conventional dairy systems in West Savannah (4270 L cow^{-1} yr^{-1}), Central Savannah (4880 L cow^{-1} yr^{-1}), and Ubaté Valley (2745 L cow^{-1} yr^{-1}) in Cundinamarca (EVA, 2018). Similar to our findings, a study conducted by Guadron and Padilla (2007) in the high tropics of Cundinamarca demonstrated that cows grazing in silvopastoral plots containing *Acacia decurrens* and *Alnus acuminata* along with kikuyu grass had a 12% higher milk yield compared to the control treatment. Furthermore, Carvajal et al. (2012) conducted a study in Cundinamarca, indicating that when dairy cows were supplemented with *Acacia decurrens*, milk yields were comparable to those obtained from concentrates-based traditional diets. Cárdenas et al., (2011) reported that *Sambucus nigra* and *Sambucus peruviana* are promising nutritional alternatives for enhancing animal performance. These plants contain high protein content while having low amounts of fiber, providing palatability and digestibility benefits. Hernández (2011) also found that supplementing Holstein cows with *Sambucus nigra* led to a significant increase in milk production from 18 L cow^{-1} day^{-1} to 23 L cow^{-1} day^{-1}. In the same study, it was reported that in a silvopastoral system with *Alnus acuminata*, *Sambucus nigra*, and *Cenchrus clandestinus* (kikuyu grass), higher milk production was found (9 L cow^{-1} day^{-1}) when compared to pure pasture-based diets (7.5 L cow^{-1} day^{-1}). The above points out that the inclusion of local shrubs in cows' diets would help to reduce the yield gap of milk productivity among dairy systems, but also has the potential to reduce the use of external concentrate feed, which can be reflected in economic benefits for farmers (Carvajal et al., 2012).

The implementation of local forage species in cattle diets may encounter several obstacles. Variations in the availability of local forage species by season and cropping capacity can be a hindrance to their adoption. Certain species may be insufficient to meet cattle energy needs, and hence, not available throughout the year making their adoption challenging. Moreover, the nutritional and economic advantages of incorporating local forage species into livestock feeding may not be known to farmers. A lack of education and awareness regarding available options can serve as a significant obstacle. Additionally, the acceptance and digestibility of local forage species by cattle can vary, leading to some species being poorly accepted or digested, ultimately impacting their adoption. A comprehensive approach to overcoming these barriers should involve investments in education, technology, research to identify suitable forage species, and adaptation to local conditions. Collaboration among farmers, researchers, and authorities can significantly promote the incorporation of native forage species in cattle diets.

Reductions in emission factors for enteric CH_4 ranged from 0.8% to 1.6% among the three evaluated diet scenarios. Increasing milk yields while maintaining or reducing GHGE has been identified as a crucial mitigation measure, as it can lower the GHGE intensities in dairy systems (Gerber et al., 2011). The dairy and beef CFs of the analyzed farms were recalculated to factor in the increases in milk production and reductions in enteric CH_4 emissions obtained in the mitigation measure scenario (Table 6). The CFs proved highly responsive to these conditions, with reductions between 13-26% for milk and 18-28% for beef, as denoted in Table 6. The primary driver behind the decrease in CFs was the boost in milk production, as the reduction in CH_4 emissions was low. Keeping CH_4 emissions constant while increasing productivity has been identified as a significant challenge for cattle systems in the Latin American tropics (Arango et al., 2020). However, for dairy systems in Cundinamarca, it appears attainable through the incorporation of locally available *Acacia decurrens*, *Baccharis latifolia, and Sambucus peruviana* in their diets.

Table 6. 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					
	Cenchrus clandestinus (100%)		*Cenchrus clandestinus* (90%) plus (10% of):					
			Acacia decurrens		*Baccharis latifolia*		*Sambucus peruviana*	
	Mean	Standard error	Mean	Standard error	Mean	Standard error	Mean	Standard error
Carbon footprint (% variation with baseline), kg CO_2eq kgFPCM^{-1}								
Central Savannah	1.6 a	0.2	1.3 (-19%) a	0.1	1.4 (-13%) a	0.1	1.4 (-13%) a	0.2
West Savannah	1.9 a	0.4	1.4 (-26%) a	0.3	1.5 (-21%) a	0.4	1.6 (-16%) a	0.4
Ubate Valley	1.5 a	0.2	1.2 (-20%) a	0.1	1.2 (20%) a	0.1	1.3 (-13%) a	0.1
Carbon footprint (% variation with baseline), kg CO_2eq kgLWG^{-1}								
Central Savannah	13.3 a	1.8	9.7 (-28%) a	1.3	10.2 (-24%) a	1.4	11.1 (-18%) a	1.5
West Savannah	13.5 a	3.2	9.7 (-28%) a	2.4	10.2 (-24%) a	2.5	11.1 (-18%) a	2.7
Ubate Valley	12.0 a	1.5	8.6 (-28%) a	1.1	9.1 (-24%) a	1.13	9.9 (-18%) a	1.2

Variable means with different letters across columns are not significantly different

Considering the three regions, the milk CFs approached the values of CFs from more intensive milk production systems in Denmark, Italy, New Zealand, and Sweden, after reductions were made (Bava et al., 2014; Dalgaard et al., 2014; Flysjö et al., 2011a; Ribeiro-Filho et al., 2020; Salvador et al., 2017). The above highlights the significant potential for dairy farms in the high tropics of Cundinamarca to enhance their environmental performance concerning GHGE by incorporating locally available shrubs. Therefore, this would be a feasible mitigation measure for scaling up to the dairy cattle systems located in the Colombian high tropics, contributing to the commitments of the Colombian Government towards 2030 regarding cutting off 51% of GHGE of the country (Ministry of Environment and Sustainable Development, 2020).

4. Conclusions

The primary GHGE from on-farm dairy systems in Cundinamarca originate from animals, specifically from CH_4 due to enteric fermentation and N_2O from excretions on pastures. Moreover, the manufacturing of inputs accounts for the highest off-farm greenhouse gas emissions. Therefore, any change in CH_4 and N_2O emissions and the level of inputs used have a significant impact on the CF of milk and LW produced by dairy farms.

It has been found in LCA studies that greater emphasis should be placed on beef as a co-product when allocating environmental burdens in specialized dairy farms. It is crucial to the outcome of the milk CF to have a solid methodology for dealing with co-products. GHGE per kg milk were lower than other evaluated allocation methods through the system expansion. Thus, the result of the CF is significantly affected by the alternative meat system that is replaced by beef from dairy farms. There is no agreement among LCA researchers as to which method for handling coproducts is more fitting when determining the CF of coproducts derived from specialized dairy farms, even though the biophysical approach is the most frequently employed.

Including locally available feedstuffs, namely *Acacia decurrens*, *Baccharis latifolia*, and *Sambucus peruviana* in animal diets could increase milk yields and reduce meat and milk CFs of dairy farms in the high tropics of Cundinamarca. This would assist in attaining the Nationally Determined Contribution of reducing 51% of GHGE by 2030 (Ministry of Environment and Sustainable Development, 2020) as and closing the milk yield gaps in dairy systems located in the high tropics of Colombia.

Our findings enhance comprehension of productivity and environmental performance regarding GHGE within dairy farms across the Cundinamarca Department. Additionally, this study has identified the primary GHGE hotspots of these systems and provides insights on how to reduce milk and meat CFs by including locally available feedstuffs in cattle diets. The findings of this study will inform practitioners and policymakers on developing policies and programs for improving productivity indicators and mitigating GHGE in dairy cattle systems in Colombia.

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