

Cattle intensification based on silvopastoral systems with *Leucaena leucocephala* (Lam.) de Wit as a strategy to increase cattle production and mitigate greenhouse gas emissions in the Caribbean region of Colombia

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Abstract

Different cattle production interventions have been proposed to reduce greenhouse gas (GHG) emissions and increase animal productivity, but few studies have identified their real potential under grazing conditions and at the whole system level. The aim of this study was to determine the effect of silvopastoral systems (SPS) with *Leucaena leucocephala* on total GHG emissions, emission intensity, GHG balance and cattle productivity in a series of production scenarios in northern Colombia. A life cycle analysis (LCA) approach was used to evaluate one baseline system (BL) based on pastures and four SPS intervention scenarios. For this analysis, the emissions from enteric fermentation and manure were determined *in situ*. Methane emissions from enteric fermentation were 9.7% lower in the SPS with leucaena than in BL systems ($p = 0.0369$). Emission factors for manure were higher in the BL systems ($p < 0.05$) as were emission intensities to produce one kg of fat and protein corrected milk (FPCM) and one kg of live weight gain (LWG). For animal production and GHG balance, it was found that the inclusion of leucaena increased animal production up to four times compared to the BL system and mitigate GHG emissions per hectare up to 86% due to carbon sequestration. In conclusion, leucaena SPS are an alternative to mitigate climate change under grazing conditions, as they reduce GHG emissions and increase animal productivity.

Introduction

The cattle sector is a major source of greenhouse gas (GHG) emissions, especially in the form of enteric methane (CH_4) which has a major impact on climate change and short-term global warming (Arango et al. 2020; Mehrabi et al. 2020). Globally, it is estimated that livestock and agricultural activities contribute between 12 and 17% of GHG emissions and are considered a major source of anthropogenic emissions (Mbow et al. 2019). In Latin America, cattle activities generate about 1,889 Gt of CO_2 eq/year, which represent about 35% of global GHGs from the Agriculture, Forestry and Other Land Use (AFOLU) sector (FAO 2019; Arango et al. 2020).

In developed countries, cattle production has increased per animal and per unit area, but at the same time increasing the dependence on external resources (Gerssen-Gondelach et al. 2017). However, in countries where grazing systems predominate, the increases in cattle production have occurred mainly through the expansion of the agricultural frontier (Maranhão et al. 2019), which has led to negative environmental impacts such as deforestation, land degradation and biodiversity loss (Smith et al. 2013). However, there is significant potential in tropical and subtropical regions to increase cattle yields and reduce environmental burdens through sustainable intensification of the cattle production model, as well as through the adoption of better management practices (González-Quintero et al. 2022).

Adequate grassland management, the association of multiple plant species and the implementation of different silvopastoral systems (SPS) have been proposed as sustainable strategies to solve the problem caused by systems based on pasture monocultures (Koscheck et al. 2020; Cardoso et al. 2020; González-Quintero et al. 2022). These systems can integrate both leguminous shrubs and grasses in order to increase forage production and quality while providing extra N to the system from biological N_2 fixation (Sarabia-Salgado et al. 2020).

In tropical regions, the incorporation of the legume *Leucaena leucocephala* (Lam.) de Wit., often referred to as Leucaena, has been a tool to intensify animal production in grazing systems with a significant potential to reduce enteric CH₄ emissions from cattle systems as the proportion of leucaena in tropical grass mixtures increases (Piñeiro-Vázquez et al. 2018; Montoya-Flores et al. 2020).

Most previous studies on methane mitigation have focused on emissions from individual animals (Piñeiro-Vázquez et al. 2019; Montoya-Flores et al. 2020). Less information exists on the effects of leucaena on the emissions intensity of milk and beef production at the whole level system, especially when animals consume representative amounts of leucaena, and when animals are considered in realistic cattle systems and trade scenarios (Harrison et al. 2015; Stifkens et al. 2022). In addition to enteric CH₄, whole-system level analyses include other GHGs that can represent a significant proportion of total emissions. This is especially important in the case of legume forages such as leucaena, which protein contents above 25% (Piñeiro-Vázquez et al. 2019; Montoya-Flores et al. 2020) that can generate higher nitrous oxide (N₂O) emissions in the soil resulting from nitrogen excretion (Rivera and Chará 2021).

The aim of this study was to determine the effects of leucaena inclusion through SPS on GHG emissions, emission intensity, GHG balance and animal productivity in a series of commercial scenarios for a typical dual-purpose livestock system in the Colombian Dry Caribbean region.

Materials and methods

Location

The study was carried out in the department of Cesar, located in northern Colombia (10°29'0" N, 73°15'0" W) with an average temperature of 28.4°C, a relative humidity of 69.8%, an average annual rainfall of 960 mm and an average solar radiation of 217.3 W/m²/h. The life zone according to Holdridge corresponds to Tropical Dry Forest (Df-T).

Cattle systems and scenarios evaluated

Two reference systems were evaluated, a conventional baseline system (BL) and a SPS with leucaena, both oriented to beef and milk production (dual purpose). The BL system was characterized by the low presence of trees in the grazing areas, extensive grazing areas with *Megathyrsus maximus* (Jacq.) B.K. Simon & S.W.L. Jacobs and *Bothriochloa pertusa* (L.) A. Camus, partially degraded. On the other hand, the SPS had the presence of the shrub *L. leucocephala* at an approximate density of 15,000 shrubs/ha associated with *M. maximus* and *B. pertusa* and native scattered trees. Table 1 shows the main characteristics used in each system based on a representative farm of 70 hectares. This information served as the basis for the estimates for each scenario.

Table 1
Principal characteristics of the reference systems studied

	BL		Total	SPS		Total
Parameter	Dry season	Rainy season		Dry season	Rainy season	
Milk production (Kg; FPCM)	3.2	3.6	3.33	4.9	5.64	5.15
Live weight gain (kg; LWG)						
Cow production	0.00	0.00	0.00	0.00	0.00	0.00
Heifer	0.26	0.34	0.29	0.47	0.54	0.49
Growing animal (2–3 years)	0.31	0.40	0.34	0.51	0.59	0.54
Steers (+ 3 years)	0.30	0.39	0.33	0.51	0.59	0.54
Heifers (+ 3 years)	0.29	0.38	0.32	0.50	0.58	0.53
Heifers (1–2 years)	0.29	0.38	0.32	0.50	0.58	0.53
Steers (1–2 years)	0.30	0.39	0.33	0.51	0.59	0.54
Bulls	0.00	0.00	0.00	0.00	0.00	0.00
Calves	0.28	0.36	0.31	0.48	0.55	0.50
Dry cow	0.00	0.00	0.00	0.00	0.00	0.00
Milk fat (%)	4.02	4.27	4.10	4.13	4.47	4.24
Milk protein (%)	3.28	3.46	3.34	3.30	3.47	3.36
LU (450 of LW)	0.64	1.00	0.80	2.00	2.7	2.23
Inputs						
Mineral salt 4% (kg/year)	-	-	1,708.2	-	-	5,190.2
Balanced feed (kg/year)	-	-	-	-	-	9,636
Urea (kg/year)	-	-	150.00	-	-	450.00
Fuel (gal/year)	-	-	75.00	-	-	250.00
Electricity (kw/h)	-	-	300.70	-	-	1,400.70

BL: base line / conventional system; SPS: silvopastoral system; FPCM: fat and protein corrected milk; LU: livestock unit – 450 kg of LW; LWG: live weight gain.

Based on the reference systems, we simulated three scenarios with 25 (Scenario 1), 50 (Scenario 2) and 75% (Scenario 3) of intervention of their area with leucaena and estimated the effect of this shrub on total emissions, emission intensity, GHG balance and animal production.

Direct determination of GHG emissions

Emissions of CH₄ from enteric fermentation, and N₂O-N and CH₄ in urine patches and feces deposited on the soil were measured directly in both BL and SPS systems. Emissions from enteric fermentation were determined in lactating cows. Two experiments were conducted, one in the rainy season and the other in the dry season using the polytunnel technique (Murray et al. 2007, FAO 2023); eight lactating cows typical of the area with 388.8 ± 26.4 kg of live weight, 3.5 ± 0.58 parturitions and 104.8 ± 13.12 months of age were included.

The measurements lasted 35 days per season, with two periods of 15 days of adaptation/acclimatization to the diets and polytunnels, and two measurement periods of two days each. Gas samples were taken every 60 minutes for 48 hours and following the recommendations of Gaviria-Urbe et al (2021); gas samples were taken by individual extractors at an extraction rate of 0.9 m³/s installed in each compartment of the polytunnel, and an environmental sample was also taken every hour (inlet gas) to correct the outlet gas samples. In each hour, after the gas sample was taken, the polytunnel was opened to release the accumulated gas before starting a new measurement. According to Lockyer and Jarvis (1995), polyethylene structures such as those used in this study have gas recoveries of 95.5 to 97.9%.

Two diets were included in the experiment: Diet 1 (BL): composed of *M. maximus* and *B. pertusa* and Diet 2 (SPS): *M. maximus* and *B. pertusa* with inclusion of leucaena at 17 and 24% of the diet on a dry matter (DM) basis for the dry and rainy seasons, respectively. These percentages were established by measuring the biomass available in the SPS plots where the experimental animals were grazing during the dry and rainy seasons.

Total methane emissions were calculated using the ideal gas law according to Lopez and Newbold (2007), based on the CH₄ concentration determined by chromatography (ppm) each hour, the total volume of the polytunnel, temperature and atmospheric pressure. Cumulative methane per day was estimated as the sum of methane production in each hour of the day. Two polytunnels divided into two compartments of 36 m³ each were used to keep the animals separated in individual compartments. The environmental conditions inside and outside the polytunnels were continuously monitored during the experimental period to ensure that the temperature and humidity inside the chambers did not generate thermal stress in the animals and thus ensure normal forage intake. Methane concentration was measured with a gas chromatograph (Shimadzu GC-2014, Shimadzu®, Japan) (International Center for Tropical Agriculture -CIAT).

Emissions were compared between systems by means of a cross-over experimental design, and each diet was assigned to animals during the first experimental period and then exchanged between groups for the second period of each season. The individual cow was the experimental unit for each variable using animal weight as a covariate. Multiple comparisons were evaluated by Tukey's HSD test, using RStudio tool (RStudio Team 2023). The variables measured were g of CH₄/animal/day, g of CH₄/kg of dry matter intake

(DMI), g of CH₄/kg of degraded DM (DMD), DM intake/animal/day as percentage of live weight and Y_m (methane conversion factor as percentage of gross energy (GE) consumed that is converted to CH₄).

The emission of CH₄ per kg of DMI (g) was estimated by dividing the cumulative CH₄ emissions (g of CH₄/animal/day) by the animal intake per day (kg of DMI/day); the amount of CH₄ per kg of DMD was calculated with the emissions of g CH₄/kg DMI adjusted by the degradability of each of the diets (Table 3), and Y_m was calculated from the energy contained in each diet, the g of CH₄/kg DMI and the mass energy of CH₄ (13.3006839 kcal/kg). As for emissions from the other age groups present in the systems (calves, growing animals, dry cows, and bulls), these were estimated using Tier 2 methodology according to IPCC (2019).

On the other hand, for the measurement of emissions from feces and urine deposited on the soil, manual closed static chambers were used as described by Byrnes et al (2017). Twelve plots were established in three different sites that had the BL and the SPS systems, and each plot had four chambers with feces, four with urine and four without manure application that served as controls. A total of 2,000 g and 1,000 ml of feces and urine were deposited in each chamber, respectively, according to the experimental design. Measurements lasted 35 days in each season with 8 gas collection times (days 1, 2, 3, 7, 11, 18, 24 and 35 after feces and urine application). On each day samples were collected at 0, 10, 20 and 30 minutes after chamber closure following the recommendations of Pelster et al (2016). Gases were collected using the pooling method described by Arias-Navarro et al (2013).

The gas samples were taken simultaneously at each site between 9:30 am and 11:30 am and nitrogen content was determined in feces and urine samples deposited in each plot by the Kjeldahl method according to NTC 4657 (1999). Gas samples were analyzed for CO₂, CH₄ and N₂O using a gas chromatograph (GC-2014, Shimadzu, Kyoto, Japan). Gas fluxes were estimated by calculating the rate of change of concentration over time using a linear approach corrected with chamber volume, internal temperature and air pressure at the site using the ideal gas law (Parkin and Venterea 2010), and following the equations detailed in Lombardi et al (2021). All flow data were checked for linearity and validated by examining CO₂ concentrations.

The comparison between systems was made by means of a randomized complete block design in which the block was each of the sites where the plots were installed for both systems. From the measurement of the accumulated gas flux and the amount of N applied, an emission factor (EF) was determined for each type of excretion and type of system (Sordi et al. 2014). The EF determined were percentage of N emitted as N₂O-N in urine and feces, and g of CH₄ per kg dry matter of feces.

Life Cycle Assessment (LCA)

The Publicly Available Specification standard (PAS, 2050: 2011) (BSI and Carbon Trust 2011) was used to estimate the different sources of GHG emissions based on an LCA approach. The LCA was applied to each reference system and scenario to quantify the emission intensities for each condition for both the rainy and dry seasons (Table 1) and the emission factors determined *in situ*. The "*cradle to farm gate*" system

boundary was defined to determine and calculate GHG emissions that include sources upstream and downstream of the production system (farm) and within the farm.

The functional units for expressing GHG intensities were kg of fat and protein corrected milk (FPCM), kg of total protein and kg of live weight gain (LWG) at the farm gate. As these were dual purpose systems the GHG emissions were divided between the products generated (beef and milk) using an economic allocation based on the commercial price of milk and beef (BSI and Carbon Trust 2011; Rice et al. 2017). Using the fat and protein contents in each reference system, milk production was standardized at 3.7% and 3.3% fat and protein, respectively (Thomassen and Boer 2005). Liveweight gain was calculated for the animals raised, assuming no change in herd size. Liveweight gain was calculated from all animals considering the daily weight gains recorded by the systems and the inventory of animals in each livestock category.

For the animal categories that were not assessed *in vivo* for CH₄ emissions (calves, growing animals, dry cows, and bulls) gross energy intake (GE) was calculated using the IPCC Tier 2 equations, including daily gross energy intake, and taking into account diet degradability and daily net energy requirements for gestation, lactation, growth, activity and maintenance (Gavrilova et al. 2019), and Y_m was estimated according to Ellis et al (2007). Dry matter intake (DMI) was quantified by dividing herd-specific gross energy intake values by 18.45 MJ of metabolizable energy per kg of dry matter, which corresponds to the energy density of the feed (Gavrilova et al. 2019). Table S1 shows the EFs obtained and the age distribution for each reference system and scenario.

To estimate the EF, the diets offered in each reference system were evaluated for dry matter (DM), organic matter (OM), neutral detergent fiber (NDF), acid detergent fiber (ADF), crude protein (CP), dry matter degradability (DMD), ether extract (EE), calcium (Ca), phosphorus (P), gross energy (GE) and ash. DM content was determined in a forced air oven at 105°C until constant weight was reached (ISO 6496), the percentage of N and CP was determined by the Kjeldahl method according to the Colombian Technical Standard (NTC 4657 1999), NDF and ADF were determined by the sequential technique described by Van Soest et al (1991) according to the Association of Official Analytical Chemists (AOAC) 2002.04 and 973.18 and (AOAC 2005) respectively, and EE by Soxhlet extraction by immersion (Colombian Technical Standard - NTC 668 1973). Ash content was obtained by direct combustion in a muffle furnace at 500°C according to AOAC 942.05 (AOAC 2005), P (Phosphorus) and Ca (Calcium) by spectrometry, and GE by calorimetry based on ISO 9831 (ISO 1998) and *in vitro* DM digestibility (IVDMD) according to Tilley and Terry (1963); OM content was estimated from the difference between total DM and ash-free DM.

On-farm GHG calculations were performed using the Tier 2 equations from the 2019 refinement of IPCC 2006 Chaps. 10 and 11 (Gavrilova et al. 2019; Hergoualc'h et al. 2019). These GHGs included methane (CH₄) from enteric fermentation and excretions left on pasture, nitrous oxide (N₂O) from excretions deposited on pasture and from fertilizer application, and carbon dioxide (CO₂) from lime and urea application and fossil fuel burning. CO₂ emissions from feed and other imported raw materials, fertilizers and amendments were calculated with emission factors obtained from databases, as shown in Table S2.

Finally, under a C_{GWP} approach (conventional use of GWP100), the equivalent CO_2 emissions of a given GHG were calculated as follows:

$$E_{CO_2e} = E_{GHG} \times GWP_H$$

Where: E_{CO_2e} : total CO_2 equivalent; E_{GHG} are the emissions of a specific GHG; GWP_H pollutants over a 100-year time horizon, 28 for CH_4 ; 265 for N_2O ; and 1 for CO_2 (IPCC, 2014). Consequently, the C_{GWP} was calculated using the following equation:

$$C_{GWP} = E_{CO_2e} - CO_2 \text{ sequestered}$$

Biomass carbon sinks (sequestered CO_2)

Carbon sequestration was calculated for those areas on the farm that changed their use, i.e., from BL to SPS. The values of carbon stored per hectare in areas with silvopastoral systems allowed obtaining the carbon sequestration factors in the aerial biomass during conversion from traditional pastures. For pastures with leucaena and trees, C sequestration of 1.47 t of C ha/year (5.4 t CO_2 ha/year) was used (Pulido et al. 2019). In addition, since the pastures were established more than 20 years ago, emissions from changes in carbon stocks on the farm were not considered.

Milk and beef productivity of the reference systems.

To determine animal production, historical records of both reference systems (BL and SPS) at three locations were reviewed and both milk production and weight gain were measured at during the dry and rainy seasons for 45 days while polytunnel studies were in progress.

Results

Methane (CH_4) emissions from enteric fermentation

The *in vivo* EFs determined for lactating cows are presented in Table 2. The treatment with inclusion of leucaena generated lower CH_4 emissions in both seasons ($p = 0.0369$) with greater differences during the rainy period ($p = 0.0175$). Also, leucaena intake favored lower emissions of CH_4 per kg of DMI and DMD and lower proportion of EB converted to CH_4 (Y_m).

Table 2
Enteric CH₄ emission factors in the BL and SPS systems in the Caribbean region of Colombia.

g of CH ₄ /animal/day			g of CH ₄ / kg of DMI		g of CH ₄ / kg of DMD		DM intake (% of LW)		Ym (%)	
Dry season										
BL	220.3a	(± 22.6)	27.1a	(± 2.91)	49.2a	(± 3.46)	1.98b	(± 0.05)	9.17a	(± 0.65)
SPS	202.7b	(± 15.8)	22.9b	(± 2.41)	37.3b	(± 3.26)	2.11a	(± 0.08)	7.63b	(± 0.46)
SEM	5.82		0.675		1.688		0.027		0.241	
p-value	0.0369*		0.0004*		0.0005*		0.0103*		0.0002*	
Rainy season										
BL	207.5a	(± 25.3)	25.9a	(± 3.21)	45.9a	(± 5.70)	2.08b	(± 0.06)	7.81	(± 0.91)
SPS	183.7b	(± 27.6)	21.2b	(± 2.43)	35.3b	(± 3.37)	2.2a	(± 0.11)	7.12	(± 0.50)
SEM	7.09		0.85		1.724		0.03		0.272	
p-value	0.0175*		0.0006*		< 0.0001*		0.0238*		0.1131	

DMI: dry matter intake; DMD: dry matter degraded; LW: live weight; Ym: methane conversion factor as percentage of GE consumed that is converted to CH₄; SEM: standard error of the mean. *Values with different letters in the same column denote significant differences (p < 0.05).

On the other hand, Table 3 and Table S1 shows the estimated emission factors for the other animal types, calculated using IPCC Tier 2.

Table 3
Emission factors estimated by IPCC for the other animal types.

Animal type	BL	SPS
Calves (female < 1 year)	12.46	11.79
Calf (male < 1 year)	13.02	11.97
Heifers (1–2 years)	40.14	36.39
Steers (1–2 years)	40.46	36.84
Growing animal (2–3 years)	46.63	49.26
Steers (+ 3 years)	57.93	53.58
Heifers (+ 3 years)	57.23	53.49
Dry cow	74.34	72.23
Bulls	81.81	79.11

Regarding the chemical composition of the diets offered in both systems, Table 4 shows the values found. The diet offered in the BL system presented higher dry matter, ash, NDF and FDA, but for both periods the diet containing leucaena offered higher contents of CP, EE, Ca, GE and presented higher DM degradability.

Table 4
Chemical composition of the diets offered in the BL and SPS systems in rainy and dry seasons.

	DM	OM	Ash	NDF	ADF	CP	IVDMD	EE	Ca	P	GE
	%										kcal/kg
Dry season											
BL	22.58	83.9	16.1	69.28	40.32	7.95	55.22	3.37	0.37	0.22	3893.04
SPS	21.26	84.87	15.13	65.33	38.25	12.73	57.16	4.58	0.69	0.23	3991.28
Rainy season											
BL	21.55	85.85	14.15	68.87	36.99	9.14	60.63	5.47	0.29	0.26	4004.37
SPS	19.55	87.26	12.74	62.63	35.49	15.22	62.18	5.93	0.54	0.27	4212.38

BL: base line/conventional system; SPS: silvopastoral system; DM: dry matter; OM: organic matter; NDF: neutral detergent fiber; ADF: acid detergent fiber; CP: crude protein; IVSMD: *in vitro* degradability of dry matter; EE: ether extract; Ca: calcium; P: phosphorus; GE: gross energy.

CH₄ and N₂O emissions from manure

The (*in situ*) EFs for CH₄ and N₂O-N from manure are presented in Table 5 (for the other types of animals the EFs are presented in Table S1). According to the results, the BL presented higher values of N₂O-N in urine and feces in the dry season, and N₂O-N from urine and CH₄ from feces in the rainy season ($p < 0.05$).

Table 5
Emission factors of CH₄ and N₂O from manure of the BL and SPS systems in the Caribbean Region of Colombia.

N (%) emitted as N ₂ O– N in urine patches			N (%) emitted as N ₂ O– N in feces		Grams of CH ₄ / kg of DM feces	
Dry season						
BL	0.23a	(± 0.11)	0.10a	(± 0.12)	0.30	(± 0.09)
SPS	0.16b	(± 0.09)	0.06b	(± 0.08)	0.27	(± 0.11)
SEM	0.032		0.029		0.028	
p-value	0.0347*		0.0424*		0.3746	
Rainy season						
BL	0.55a	(± 0.29)	0.15	(± 0.07)	0.61a	(± 2.15)
SPS	0.26b	(± 0.22)	0.08	(± 0.04)	0.38b	(± 1.84)
SEM	0.0865		0.0194		0.0656	
p-value	0.0083*		0.1530		0.0057*	

BL: base line/conventional system; SPS: silvopastoral system; N: Nitrogen; DM: dry matter; SEM: standard error of the mean. *Values with different letters in the same column denote significant differences ($p < 0.05$).

Distribution of greenhouse gases and LCA approach

According to the LCA approach, the largest emissions are generated on-farm and more than 90% of the total emissions correspond to CH₄ as CO₂ eq (Fig. 1). Also comparing the BL and SPS, the proportion of CO₂ and N₂O in the total emissions increases in the SPS as well as the emissions generated off-farm.

The higher percentage of off-farm emissions in the SPS can be explained by the greater use of fuels for the transport of inputs and products, and for carrying out farm activities (CO₂); the greater percentage of N₂O-N in the SPS is due to the excretion of nitrogen in feces and urine, since there are more animals per unit area and the diets offered in these systems have a higher nitrogen content even when the percentage of N excreted with relation with the N in the diet is reduced.

Figure 2 shows the main emission sources found in each system. The most important source of emissions is enteric fermentation that represents 92.3 and 87.7% of the total emissions for the BL and SPS respectively. In turn, SPS have relatively higher emissions for input manufacturing and manure. The transport of inputs and their manufacture represent less than 6% of the emissions. More than 95% of manure emissions come from excreta deposited in the field, since for this study it was assumed that only 3% of the manure is managed.

The emission intensity for each functional unit (FU) is presented in Table 6. The economic allocation for beef and milk production was 36.5 and 63.5% for BL and 36.9 and 63.1% for SPS, respectively. For all the FU calculated, the implementation of areas with leucaena decreased the emission intensities with greater reductions in scenario 3 where there was higher cover of this shrub. On average, it was found that for each 25% replacement of the BL by SPSs, the emissions were reduced a 15% for each FUs, with a maximum reduction of 76.4% when all the grazing area was covered by SPS.

Table 6
Emission intensity per unit of product in five land cover scenarios with leucaena silvopastoral systems in Colombia

	BL	Scenario1	Scenario2	Scenario3	SPS
Kg of CO ₂ eq/kg of FPCM	3.04	2.71	2.38	2.05	1.73
Kg CO ₂ eq/kg of total protein	80.0	67.1	54.2	41.3	28.4
Kg of CO ₂ eq/kg of LWG	15.2	13.6	11.9	10.3	8.6

FPCM: fat and protein corrected milk; LWG: live weight gain; BL: baseline with 0% of leucaena; Scenario 1: 75% BL and 25% SPS; Scenario 2: 50% BL and 50% SPS; Scenario 3: 25% BL and 75% SPS; SPS: silvopastoral system with 100% of leucaena cover.

Finally, it was estimated that the production of milk and beef was 400.5 l and 50.05 kg per ha/year for BL and 2330 l and 272.9 kg per ha/year for the SPS respectively. The total emissions per hectare were estimated at 2,194 and 6,372 kg of CO₂ eq/year for BL and SPS, respectively. The GHG balance is presented in Fig. 3.

According to Fig. 3, the scenarios with the implementation of leucaena-based systems show more favorable GHG balance. While in the BL scenario there are no carbon removals that can offset emissions, the inclusion of leucaena in 25, 50, 75 and 100% of the area produced as result that 42, 64, 77% and 86% of the gases emitted in the system can be mitigated, respectively.

Discussion

The use of leucaena in ruminant nutrition has been widely implemented due to its high CP content, low fiber (NDF and ADF) and presence of some phytochemical compounds that can modulate ruminal fermentation

(Montoya-Flores et al. 2020). In this study, the diets offered in both seasons in the SPS were able to increase CP, DM degradability, and GE, and to decreased NDF and ADF content in comparison with the BL diet (Table 4), with greater differences in the rainy season due to the higher supply of leucaena that reached 24% of the DM offer. According to Sarabia-Salgado et al (2020) diets containing leucaena increase animal production both individually and per unit area due to the N fixed by this legume that improves both the productivity and the chemical composition of the diet.

One of the main limitations to increasing the productivity of cattle grazing in low quality tropical forages is the limited supply of fermentable nitrogen ($\text{NH}_3\text{-N}$) for microbial growth in the rumen, particularly during the dry season (Leng 1990). The main supply of $\text{NH}_3\text{-N}$ comes from the degradation of dietary crude protein in the rumen. CP in leucaena forage is rapidly fermented in the rumen, producing NH_3 for microbial protein synthesis (Sarabia-Salgado et al. 2020). Nitrogen intake in cows grazing SPS with leucaena is increased by combining a high-quality legume foliage with a tropical pasture, that improves the N uptake efficiency by rumen bacteria (Paciullo et al. 2011; De Angelis et al. 2021). from which amino acids are absorbed from the small intestine, which in turn are available for milk protein synthesis (Calsamiglia et al. 2010).

The effect of *L. leucocephala* in reducing enteric CH_4 is associated with its condensed tannin (CT) content, which forms complexes with protein (CT-P) and polysaccharides and reduces nutrient degradation in the rumen (Schofield et al. 2001; Stifkens et al. 2022). In addition, some studies propose that CTs promote changes in microbial populations due to their bacteriostatic, bactericidal and enzyme inhibitory effects that modify ruminal fermentation (Harun et al. 2017). In this study, the inclusion of 17 and 24% of leucaena in the BL diet generated a reduction of 7.66 and 11.47% of CH_4 emissions for the dry and rainy seasons respectively. Other authors such as Montoya-Flores et al (2020), Piñeiro-Vázquez et al (2018) and Stifkens et al (2022) in Colombia, Mexico, and Australia respectively in *in vivo* conditions obtained reductions close to 15% of total CH_4 emissions when leucaena was included above 18% in diets based on tropical pastures. According to Piñeiro-Vázquez et al (2018), the intake of tropical foliage containing CT in low concentrations (3–6% of DM) improves nutrient intake of ruminant rations, particularly DM, OM, and CP, so moderate intakes of leucaena as given in this study do not affect nutrient intake and degradability. On the other hand, it has been pointed out that doses lower than 2% of CT do not affect DM intake (Beauchemin et al. 2007) and that the molecular weight and structure of *L. leucocephala* CT are also adequate characteristics that do not affect the degradability of the diet (Barahona et al. 2006).

Regarding emissions from manure, one of the main concerns when using Leucaena is the increase of N_2O -N emissions due to the relatively high CP content (> 20%) and the increased cycling of nitrogen through the animals. Since ruminants excrete 75–95% of ingested nitrogen, a high CP diet often leads to increased urinary nitrogen concentration and, under conditions that favor denitrification and nitrification, this can result in increased N_2O emissions (de Klein and Eckard 2008). According to the results of this study, although it was a higher offer on N via CP in the SPS diet, the EFs were significantly lower in urine and feces patches for both seasons in this system when compared with the BL. However, due to the higher offer of N and stocking density and the consequent higher total excretion in the SPS, the total N_2O -N emissions were higher in this system (Fig. 1). Higher nitrogen concentration in urine leads to increased ammonia

volatilization, which further increases N_2O emissions (Harrison et al. 2015). Changes in N_2O production had minimal effects on whole-farm emissions, as enteric methane emissions were higher and accounted for over 90% of total emissions. These observations are consistent with previous studies documenting emissions from other livestock systems (Alcock et al. 2014; Harrison et al. 2015) and highlight the importance of focusing on enteric methane in mitigation strategies, as enteric methane dominates the emissions profile in a livestock system.

N_2O EFs in SPS systems (percentage of N excreted via feces and urine that is converted to N_2O -N) were lower probably due to better soil conditions. Chirinda et al (2019) found lower urine patch emission factors at seven sites in South America (0.42 vs. 0.18%) when pastures had higher vegetation cover compared to areas with low cover or degraded pastures. According to these authors, higher emissions in soils with low cover are due to pasture degradation that can stimulate or restrict N losses. For example, low vegetation cover can reduce N sinks for deposited excreta and thus increase vulnerability and N loss through microbial soil and leaching processes (Chirinda et al. 2019). However, low vegetation cover may also be associated with fewer excreted plant roots that decrease microbial activity and N_2O emissions (Henry et al. 2008).

Improved soil cover and pasture management also contribute to maintaining or increasing soil organic matter (SOM) (Aryal et al. 2018), which plays a key role in determining the response of N_2O emissions to urea deposition. Increasing SOM increases cation exchange capacity, reducing the concentration of NH_4^+ in the soil solution which, in turn, reduces NH_3 in the soil solution and the associated inhibition of NO_2^- oxidation, thereby reducing urea-derived N_2O emissions (Breuillin-Sessoms et al. 2017). The SPS studied in this evaluation had adequate grazing managements ensuring greater soil cover.

Similarly, the lower CH_4 -C emissions from manure in SPS are possibly due to a higher diversity of microorganisms in the soil, a higher soil structure due to the presence of trees and shrubs in the grasslands, and a higher soil cover. Cubillos et al (2016) reported in a study that included SPS of different ages, that these arrangements have a significantly lower potential for anaerobic processes (between 15 and 20%) compared to monoculture systems, and similar those observed in forested areas. Rivera et al (2018) found that some silvopastoral systems can present negative CH_4 fluxes and similar to those presented in forests. On the other hand, overgrazing without time for grass recovery increases the risk of soil compaction. Compaction in turn reduces soil porosity and pore continuity, decreases aeration, restricts plant growth, and increases soil CH_4 emissions, characteristics usually found in conventional systems (van Groenigen et al. 2005).

On the other hand, SPS can modify emissions in feces due to the presence of dung beetles that limit the interactions of manure with mineral soil, restricting substrates for nitrification and denitrification processes (Slade et al. 2016). Studies in the same region of the Cesar River Valley have shown that SPS have higher abundance, diversity, and activity of beetles than treeless pastures (Montoya-Molina et al. 2016). According to Slade et al (2016) the presence of beetles in livestock systems reduces N_2O emissions by 14.7% and CH_4 emissions by 17%.

Finally, in terms of GHG emission intensities and balance, the results of this study coincide with those reported by Gonzales-Quintero et al (2021) and González -Quintero et al (2022) in systems with different levels of intensification and orientation in Colombia. These authors found that intensification generates lower emissions per unit of product and that CH₄ emissions from enteric fermentation represent more than 90% of total emissions in systems with low use of external inputs such as fertilization and feed. The inverse correlation between GHG intensity and productivity of beef and dairy cattle production systems has been documented by several studies in Latin America (de Léis et al. 2015; Gaitán et al. 2016; González-Quintero et al. 2021), indicating the strong influence of increased beef and milk production on GHG dilution. This study contributes to these findings, as considerable GHG mitigation potentials were found to be achievable by less productive systems when they increase their productivity via implementation of more complex and efficient systems.

The contribution of animal sources, such as enteric fermentation and excretions deposited on pasture, to total GHGs was high, a common finding reported for grazing livestock systems where CH₄ and N₂O are the most critical GHGs requiring mitigation actions (González-Quintero et al. 2021). The results found in this study also coincide with those reported by González-Quintero et al (2022) who concluded that the contribution to total GHGs from off-farm emissions from the manufacture and transport of inputs is low in systems with limited productivity compared to more intensive cattle systems.

The emission intensities found in this work are in the range of values reported by González-Quintero et al (2021), who in an analysis of 1,313 farms found emissions between 2.1 and 4.2 kg CO₂ eq per kg of FPCM, and between 9.0 and 18.3 kg CO₂ eq per kg of LWG exported. These authors associate the lower emission intensities in dual-purpose systems to practices such as: the use of improved pastures and implementation of SPS, use of pasture rotation and electric fences, weed control and adequate fertilization management.

The above analysis provides insights into possible technological changes and management options that can increase productivity parameters and improve the environmental performance of dual-purpose systems. For the correct establishment of policies aimed at supporting mitigation and adaptation actions for the livestock sector in tropical conditions and under grazing, it is important to know the relative profitability for the implementation of SPS systems as a mitigation measure. It is also important to advance in the determination of carbon sequestration in bovine systems since their potential could be underestimated.

In a meta-analysis, Feliciano et al (2018) found that systems using controlled grazing practices and appropriate grass species can increase average aboveground carbon sequestration between 2.29 to 6.54 Mg/ha/year. Likewise, López-Santiago et al (2018) reported that systems with *L. leucocephala* associated with *M. maximus* contain higher aboveground C (19.6 ± 1.6 Mg/ha) and belowground biomass (7.7 ± 0.90 Mg/ha) compared to tropical deciduous forest and monoculture pastures in Mexico. With these values, negative carbon systems could be raised, since for this study an emission of 2,194.1 and 6,372.4 kg of CO₂ eq/year was estimated for the BL and SPS systems, respectively. Another aspect to consider could be the evaluation of scenarios with the release of areas where the most suitable areas for cattle ranching could be intensified and other areas could be released for conservation; this approach would bring greater

environmental benefits such as carbon sequestration, connectivity, conservation of water sources and increased biodiversity, among others (Calle et al. 2014; Calle 2023).

Conclusions

Systems that implement leucaena in their grazing areas can reduce the emission intensity for beef and milk production and improve the carbon balance at the farm level in a typical dual-purpose system, becoming an alternative with high potential to mitigate climate change under grazing conditions. SPS reduce CH₄ emissions from enteric fermentation, which is important in grazing systems because this is the main GHG emitted in cattle systems. Finally, to complement the analysis, it is important to measure the economic viability of these systems at different scales and to advance in landscape level analyses including carbon sequestration determinations to establish gas balances more adjusted to real production conditions. Also, the results found in this study can provide information on specific EFs for regions such as the Colombian dry Caribbean that could improve GHG estimates in regional or national inventories.

Declarations

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Conflicts of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest. The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The study was reviewed and approved by Ethics Committee of the Centre for Research on Sustainable Agriculture— CIPAV and following protocols of the Colombian law No. 84/1989.

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Figures

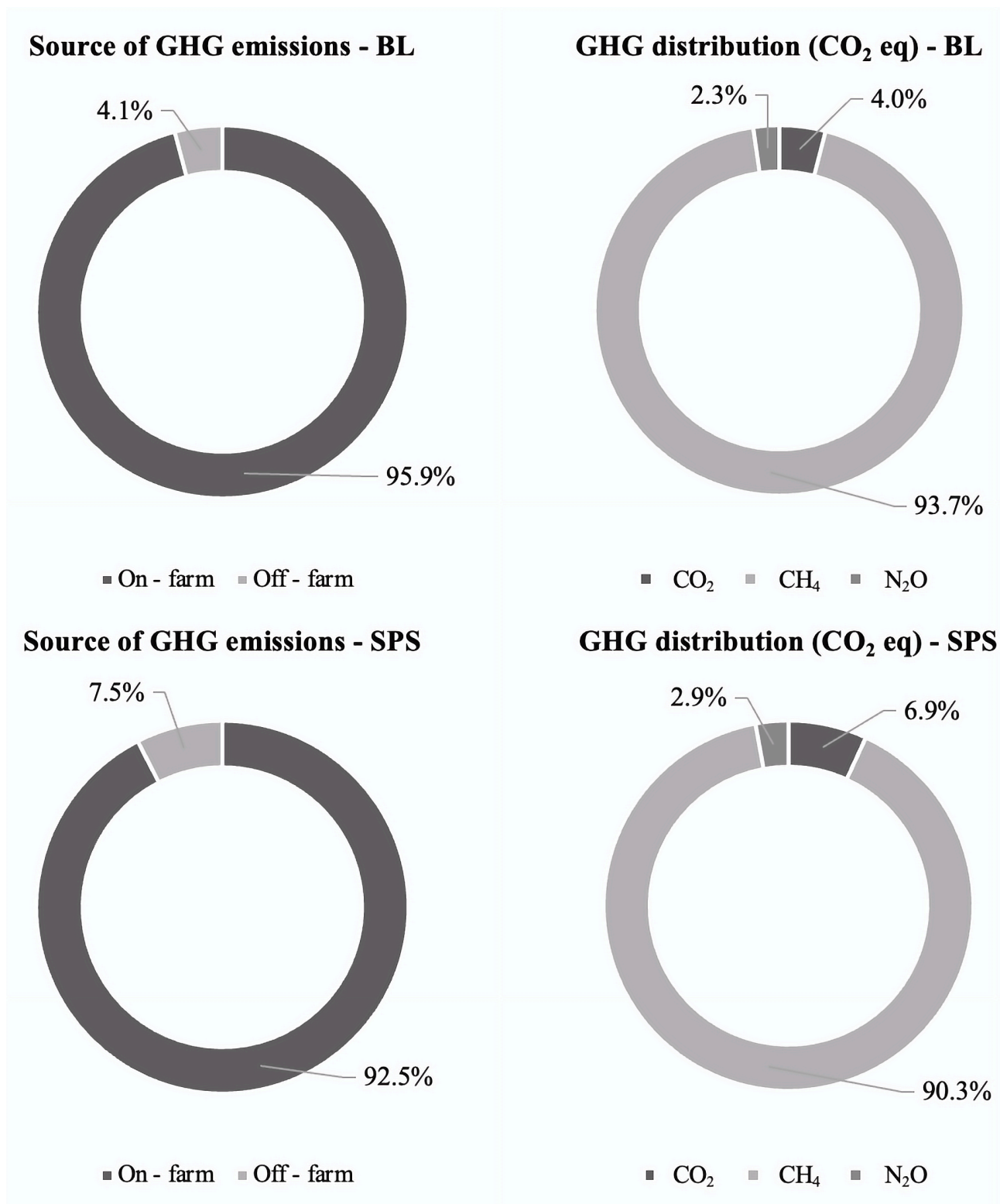


Figure 1

Sources of GHG emissions and their distribution in the BL and SPS systems.

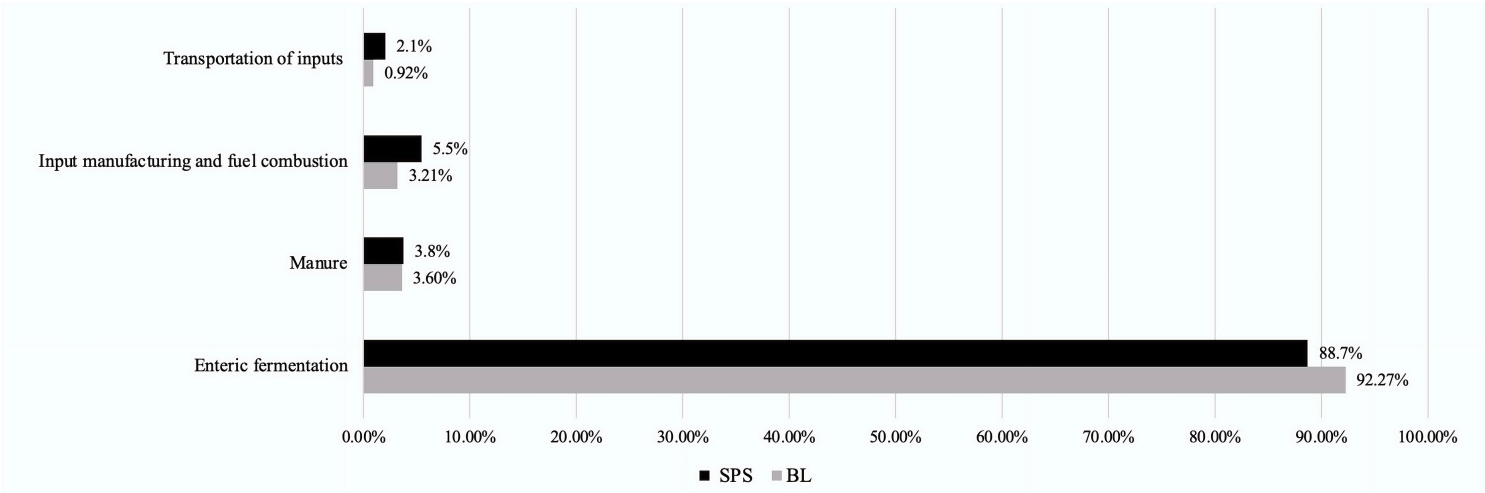


Figure 2

GHG emission sources in the reference BL and SPS systems.

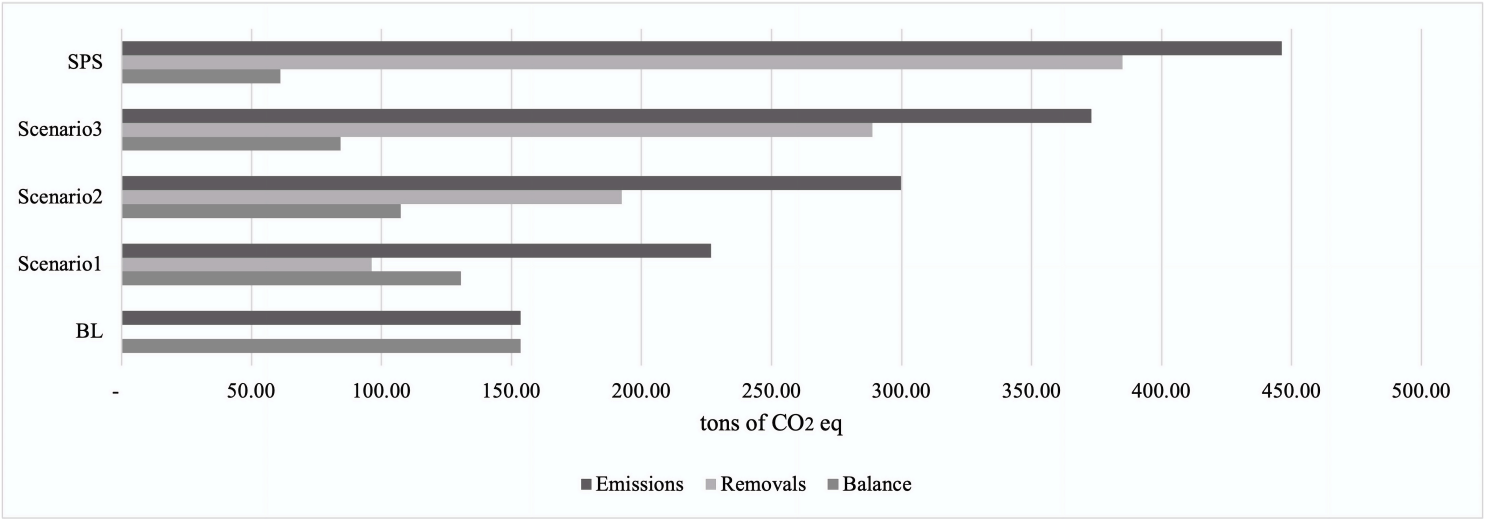


Figure 3

GHG balance at the farm level for BL and four land cover scenarios of leucaena silvopastoral systems in Colombia.

Supplementary Files

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- [TablesS1andS2.SupplementaryTables.xlsx](#)