Silvopastoral systems with *Tithonia diversifolia* (Hemsl.) A. Gray reduce N_2O-N and CH_4 emissions from cattle manure deposited on grasslands in the Amazon piedmont

J. E. Rivera[1*] · G. Villegas[1] · J. Chará[1] · S. Durango[2] · M. Romero[2] · L. Verchot[2]

[1]Centre for Research on Sustainable Agriculture — CIPAV. Cali– Colombia; [2] Alliance Bioversity International - International Center for Tropical Agriculture — CIAT. Palmira– Colombia.

[*]ORCID ID: https://orcid.org/0000-0002-1207-1485; e-mail: jerivera@fun.cipav.org.co

Author contributions

JR, JC, SD, MR and LV contributed to the study design. JR and GV developed the field experiments, collected the samples and analyzed the results with JC. SD, MR and LV reviewed the manuscript, and contributed to the discussion. All authors read and approved the submitted version.

Abstract

Cattle manure deposited in pastures is an important source of nitrous oxide (N_2O-N) and methane (CH_4) emissions. Environmental conditions and soil characteristics affect emissions of these two gases, and therefore, it is important to conduct studies in local conditions to generate emission factors to improve greenhouse gas (GHG) estimates, as well as to identify mitigation strategies. N_2O-N and CH_4 fluxes from soil, feces and urine were determined for two cattle production systems during two seasons, and emission factors (EFs) were calculated. The static closed chambers technique was used in three conventional systems (CSs) and three silvopastoral systems (SPSs) with *Tithonia diversifolia* in the Colombian Amazon piedmont. SPSs presented lower emission factors than CSs for N_2O-N from urine patches in both seasons (2.64 *vs.*1.49% and 1.69 *vs.* 0.89% of nitrogen (N) deposited for the transition and rainy season, respectively) (p = 0.004), N_2O-N from feces in the rainy season (0.17 *vs.* 0.13% of N deposited for CSs and SPSs) (p=0.046), and CH_4 in the transition rainy season (1.08 *vs.* 0.83 g of CH_4/kg of dry matter of feces for CSs and SPSs, respectively) (p=0.005); with the EFs determined, the cumulative emissions for each system were estimated in 176.8 and 145.3 kg of CO_2 equivalent per hectare per year in the CSs and SPSs. We concluded that SPSs can emit lower amounts of CH_4 and N_2O-N from manure and provide an alternative for mitigation of these gases generated by bovine manure under tropical humid conditions.

Key words: climate change, emission factor, grazing livestock, greenhouse gases, Mexican sunflower, mitigation.

Introduction

The Agriculture, Forestry and Other Land Use (AFOLU) sector is responsible for approximately 22% of global greenhouse gas (GHG) emissions (Lamb et al., 2021), and it is estimated that half of these emissions are associated with livestock (Gerber et al. 2013a; Laborde et al., 2021). The global cattle population, estimated at 1.5 billion, produces an enormous amount of manure and approximately 50% of this is deposited on grasslands (Dangal et al. 2019).

In tropical and subtropical areas, 73% of agricultural land is devoted to livestock grazing (Figueroa et al., 2022). A large portion of the nutrients consumed by animals is excreted and deposited on the soils in the form of urine and manure (Vendramini et al. 2014), providing substrate for soil microbes to produce methane (CH_4) and nitrous oxide (N_2O) (Wu et al. 2020). Livestock manure deposited on rangelands drives GHG production through microbial transformations of carbon (C) and nitrogen (N) contained in feces and urine (Wu et al. 2020).

Grasslands, which cover approximately 55 million km^2 equivalent to 42.5% of the land area, emit about 2.2 Tg of N_2O-N, of which 75% is derived from anthropogenic sources (Gerber et al. 2013b; Dangal et al. 2019). Deposition of animal feces and urine is the largest source of annual N_2O emissions in grasslands (54%), followed by manure application (13%) and nitrogen fertilizer (7%) (Dangal et al. 2019). On the other hand, ruminants contribute 109 million tons of CH_4 from manure (2% of total ruminant emissions, of which 86% comes from cattle) (Opio et al. 2013).

Fresh manure contains abundant rumen methanogens that potentially convert soluble C to CH_4 under anaerobic conditions (Hahn et al. 2018). Decomposition of organic matter can also deplete oxygen within the manure or in the soil, creating a favorable environment for the activity of methanogenic bacteria responsible for CH_4 production (Saggar et al. 2004). On the other hand, organic N in manure is mineralized to ammonium (NH_4^+) and subsequently transformed to nitrate (NO_3^+) by the activity of nitrifiers. Nitrates can be further converted to dinitrogen (N_2) by denitrifying bacteria (Butterbach-Bahl et al. 2013). N_2O-N is produced as a by-product during nitrification and an intermediate product in the denitrification process (Cai et al. 2017).
Since N_2O and CH_4 are potent GHGs linked to animal production, multiple approaches have been explored to reduce their emissions from manure deposited in pastures. The main strategies include application of nitrification or urease inhibitors, use of biochar or lime, change of animal diet, and the use of forage species with biological nitrification inhibition (BNI), among others (Cardenas et al. 2016; Rivera and Chará 2021; Lombardi et al. 2022). The research on these processes has been mostly carried out in temperate regions and therefore there is a need to generate information for tropical humid conditions and to establish local emission factors in order to reduce the uncertainty of GHG estimates and thus improve countries' emission inventories.

In Colombia, the Amazon region has a cattle population of 3,045,089 heads that represent around 10% of the national inventory and are distributed in 35,058 farms (ICA, 2022). Cattle population in the region increased considerably in recent years mainly in the department of Caquetá (Enciso et al., 2018). Unfortunately, during the last decade this region also concentrated the greatest deforestation rates in the country and Caquetá alone contributed with 22% of the deforested area in 2021 (IDEAM et al. 2021; 2022; González-González et al. 2021).
Conventional cattle production in the region is based on extensive grazing systems with pasture monocultures (mainly of *Brachiaria* and *Urochloa*) with little tree cover and pasture degradation. These systems are also less efficient due to low pasture quality, suboptimal management of resources, hence associated with high carbon footprints (Carvalho et al., 2020), but are relevant in socioeconomic terms as they are deeply rooted in the culture and their derived products are still in high demand at local and national levels (Mauricio et al. 2018, Torrijos et al. 2022).

Several institutions in the region have promoted silvopastoral systems (SPSs) in order to improve productivity and reduce the negative environmental impacts generated by conventional grazing models. Silvopastoral systems are a form of agroforestry that combines trees, shrubs, forage production and animal grazing in an integrated manner on the same land (Jose and Dollinger 2019; Chará et al. 2018). SPS promoted in the region are mainly live fences, tree alleys, fodder banks and intensive silvopastoral systems (iSPS) (Rivera et al. 2015). One shrub that has been used in in fodder banks and iSPS arrangements in the region is *Tithonia diversifolia* (Hemsl.) A. Gray, due to the adaptation to the region and its capacity to improve nutrient supply in the diet (Rivera et al. 2022).
Although SPS with *Tithonia diversifolia* are considered a good alternative to improve productivity in the region, there is little information about the contribution of these systems to the reduction of GHG emissions by cattle manure (Rivera et al. 2022).

The objective of this study was to determine the fluxes and emission factors for N_2O-N and CH_4 from feces and urine deposited in pastures both in conventional and in silvopastoral systems with *Tithonia diversifolia*

for cattle production, and thus outline possible mitigation alternatives in grazing conditions with SPS and generate new knowledge that can improve GHG estimates at the local and regional levels.

Materials and methods

Location and land uses evaluated

Measurements of CH_4 and N_2O-N fluxes from soil, urine and bovine feces were carried out in three locations in the Amazon piedmont (Caquetá - Colombia). Each site had a conventional system of the zone (CSs) and a silvopastoral system (SPSs) based on *T. diversifolia* shrub consumed directly by grazing animals. The CSs were characterized by the low presence of trees (<5 trees/ha), extensive grazing areas (paddocks with an area larger than 5 hectares) with an average stocking rate of 1 animal unit (AU) per ha (large stock units = 450 kg of live weight) and partially degraded grasslands of *Brachiaria humidicola* (Rendle) Schweick; these systems were over 40 years old and were the result of deforestation processes developed in the region due to the expansion of the agricultural frontier. The SPSs had the presence of the shrub *T. diversifolia* (2,000 shrubs/ha), associated with *B. humidicola* and trees (>25 trees/ha; *Gmelina arborea*, *Erythrina poeppigiana*, *Tectona grandis*, and *Cariniana pyriformis*) under rotational grazing that provided a new grazing area each day with rest periods of approximately 40 days. The stocking rate in these systems was 1.4 AU/ha and had an average age of 7 years established in areas previously covered by conventional grazing systems.

The animals grazing these systems were lactating cows typical of the region with various degrees of crossbreeding between *Bos Taurus* and *Bos Indicus*, with a mean production of 5.1 (±0.59) kg of milk/animal/day, a mean weight of 409 (±23) kg and with no offer of supplement feeds. The characteristics of each site are presented in Table 1.

Table 1 Mean characteristics of experimental sites

	Site A		Site B		Site C	
	CS	**SPS**	**CS**	**SPS**	**CS**	**SPS**
m.a.s.l. (m)	337	347	291	297	330	341
Coordinates	N 01°44'29.44" W 075°15'52.44"	N 01°44'34.12" W 075°15'49.67"	N 01°50'52.01" W 075°11'12.88"	N 01°51'52.01" W 075°11'12.32"	N 01°44'13.22" W 075°15'34.11"	N 01°44'18.90" W 075°15'20.13"
Atmospheric pressure (mm.Hg.)	758.2	756	758.3	759.3	762.1	761.1
Municipality	El Doncello		Puerto Rico		El Doncello	

m.a.s.l: meters above sea level; CS: conventional systems; SPS: silvopastoral systems; mm.Hg: millimeters of mercury

The regional climate classification of the study sites is Af type (Koppen classification) tropical rainforest, with a mean annual temperature of 25.5° C, precipitation of 3,800 mm/year and a relative humidity of 85%. Soils in the region are highly weathered and classified as Dystrudepts and Hapludox and originated from fine alluvial sediments, forming a sequence of horizons Ap-Bo. (Olaya-Montes et al. 2020).

Soil analysis

The following variables were measured in each plot: pH according to NTC 5264 (ICONTEC 2008a), saturated paste electrical conductivity and cation exchange capacity (CEC) by Ammonium Acetate, organic matter (NTC 5403-ICONTEC 2008b), total nitrogen (N), ammonium ($N\text{-}NH_4$) and nitrate ($N\text{-}NO_3$) by the extraction method with KCl 1 M (1: 10 w/v), and bulk density (DA), porosity (macro, meso and micropores) (pycnometer) and texture according IGAC (2006). The analyses were carried out at the Analytical Services and Soil Physics laboratories of the International Center for Tropical Agriculture. Soil temperature and volumetric water content (%VWC) were determined in the field at each gas sampling time using a TBT-12H HALTHEN® thermometer and a TEROS 12 soil moisture sensor (Meter Group Inc.), respectively.

Gas flux-rate determination

Manual closed static chambers were used for GHG monitoring (Parkin and Venterea 2010). In this study, 144 cylindrical PVC chamber bases (10 cm height, 25 cm internal diameter; area 0.049 m^2) distributed in 12 plots were inserted 5 cm into the ground where soil and forage characteristics were uniform. Chamber bases were kept 2 m apart to prevent cross-contamination and left in place for the entire monitoring period; a lid of 26 cm height and with the same diameter as the base that was adjusted during gas sampling with an airtight rubber band. The lid had a sampling port and a digital thermometer to record the internal air temperature.

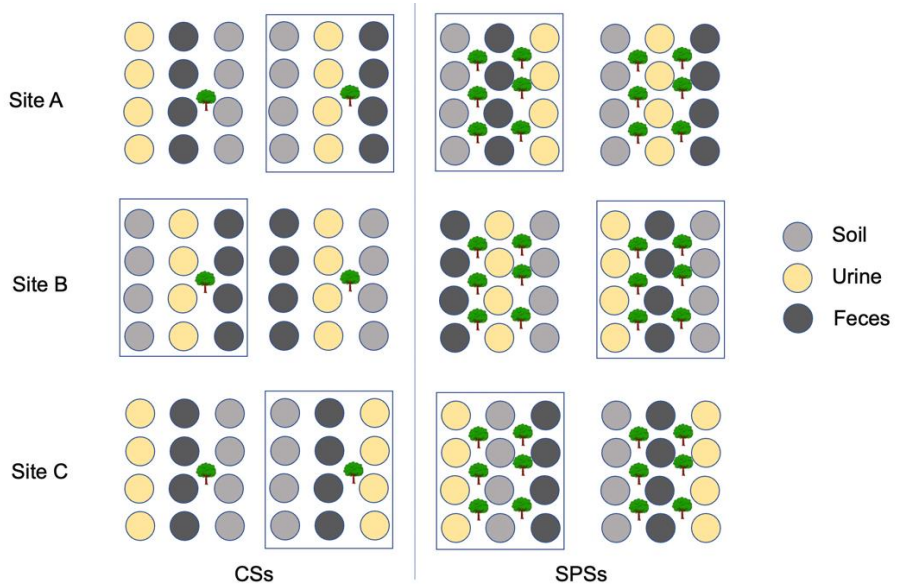


Fig. 1 Distribution of chambers in each experimental plot
CSs: conventional systems; SPSs: silvopastoral systems

A total of 2,000 g and 1,000 ml of feces and urine, respectively, were deposited in each chamber according to the experimental design, and chambers without manure application were used as control (Figure 1). Urine samples were collected through stimulation of the vulva zone from 42 dual-purpose cows, and the feces samples were collected fresh at the time of milking immediately after deposition in the stable.

Measurements lasted 32 days with 8 gas collection times (days 1, 2, 3, 7, 11, 18, 24 and 32 following applications of feces and urine). For each collection time, gas samples were taken 0, 10, 20 and 30 minutes after closing the chambers and immediately transferred to pre-evacuated 5.9 mL Labco Exetainer vials (Pelster et al. 2016). The gases were collected with the pooling method (Arias-Navarro et al. 2013), using four chambers per emission source (soil, feces, or urine) (Figure 1).

Gas sample collections were carried out simultaneously at each site between 9:30 a.m. and 11:30 a.m., and during 2020 transition (May and April) and rainy (October and November) seasons. Throughout the evaluation period, precipitation was recorded at each site using a Davis Vantage Pro2™ station. Nitrogen content was determined in feces and urine samples deposited in each plot using the Kjeldahl method (ICONTEC, 1999), and one 300 g portion of homogenized feces per plot was dried at 105 °C to constant weight, to determine the dry matter (DM) content.
Gas samples were analyzed for CO_2, CH_4 and N_2O using a gas chromatograph (GC-2014, Shimadzu, Kyoto, Japan) equipped with a flame ionization detector and an electron capture detector. Two certified calibration gas standards were analyzed in triplicate along with the samples (2,000 ppm CO_2, 10 ppm CH_4, and 1 ppm

N_2O; and 5,000 ppm CO_2, 2,000 ppm CH_4, and 5 ppm N_2O) that were used to calculate the concentration of the samples assuming a linear response.

Gas fluxes were estimated by calculating the rate of change of concentration over time using a linear approach. Gas concentration (GC) was converted into mass units using the ideal gas law with the internal air temperature (T_{air}) of the chamber at sampling, the atmospheric pressure (P_{air}), the R constant of ideal gas, and the molecular volume (Vm) and weight (Wm) of the corresponding gas (Parkin and Venterea 2010; Lombardi et al 2021). Flow data was tested for linearity and validated by examining CO_2 concentrations; all flux data were checked for linearity by examining the R^2 value, with chambers excluded from the dataset at $R^2<0.8$.

The EF for CH_4 (g CH_4/kg of DM of feces) was calculated as direct CH_4 emissions from the feces patch (CH_{4feces}) minus cumulative CH_4 emissions from the control ($CH_{4control}$). The EF for N_2O-N, expressed as percentage of N emitted per unit of N added, was calculated by subtracting the cumulative N_2O emissions in the control ($N_2O_{control}$) from the cumulative N_2O emissions directly lost from the urine and feces patches ($N_2O_{patches}$), and then dividing by the amount of N applied (N_{app}) inside the chamber (Lombardi et al. 2021).

Experimental design and data analysis

A randomized complete block design was used, where the block was each of the sites where the plots were installed for both systems. Each system in the three sites had two plots composed of 12 chambers each (Figure 1). Comparisons of emission factors and different soil characteristics between systems were evaluated by ANOVA and Tukey's HSD test, using the RStudio tool (RStudio Team 2022). Data were tested for normality using the Shapiro-Wilk test and homogeneity of variance using Levene's test.; system, type of manure and sampling days were the fixed factors, and each plot was considered a random factor.

Finally with the EFs determinate and according to estimates of DM intake based on animal production in each system (8.19 *vs.* 8.23 kg/day), diet degradation (57.8 *vs.* 69.7 %), animal units per hectare (1 *vs.* 1.4 large stock units), total nitrogen intake (138.4 *vs.* 170.1 g/day), milk production (5.23 *vs.* 8.07 kg/day per hectare), crude protein in milk (3.45 *vs.* 3.60 %) and fecal production (3.40 *vs.* 3.64 kg DM per hectare/day), emissions per hectare/year of manure were estimated for each system. The Cornell Net Carbohydrate and Protein System (Tylutki et al. 2008) was used to estimate N excretion as well as animal dry matter consumption, and milk production. It was assumed that 55% of the nitrogen excretion consumed in the diet was excreted in urine and the remaining 45 % in feces (Rivera et al. 2019) and, according to meteorological reports, a transition rainy season of four months and a rainy season of 8 months were assumed. The chemical composition of the diets used in the simulations of each diet in the CNCPS model was determined in a parallel experiment that has not been published; the N supply was estimated at 118.9 (±23.0) and 152.1 (±2.21) g/kg in the CSs and SPSs diets, respectively in the transition season, and in the rainy season the N supply of the diets was 86.4 (±2.8) and 116.7 (±17.1) g/kg DM, respectively. The following warming potential values were used for each GHGs: CO_2=1, CH_4= 28 and N_2O= 265 over a 100 years' time horizon (AR5).

Results

The chemical and physical characteristics of the soils are presented in Table 2. The parameters found are typical of Hapludox soils with low pH, clay loam texture, and moderate OM and N. Soils presented similar characteristics in both systems, except for NO_3-N content that was higher in SPSs, and macropore percentage that was lower in these systems.

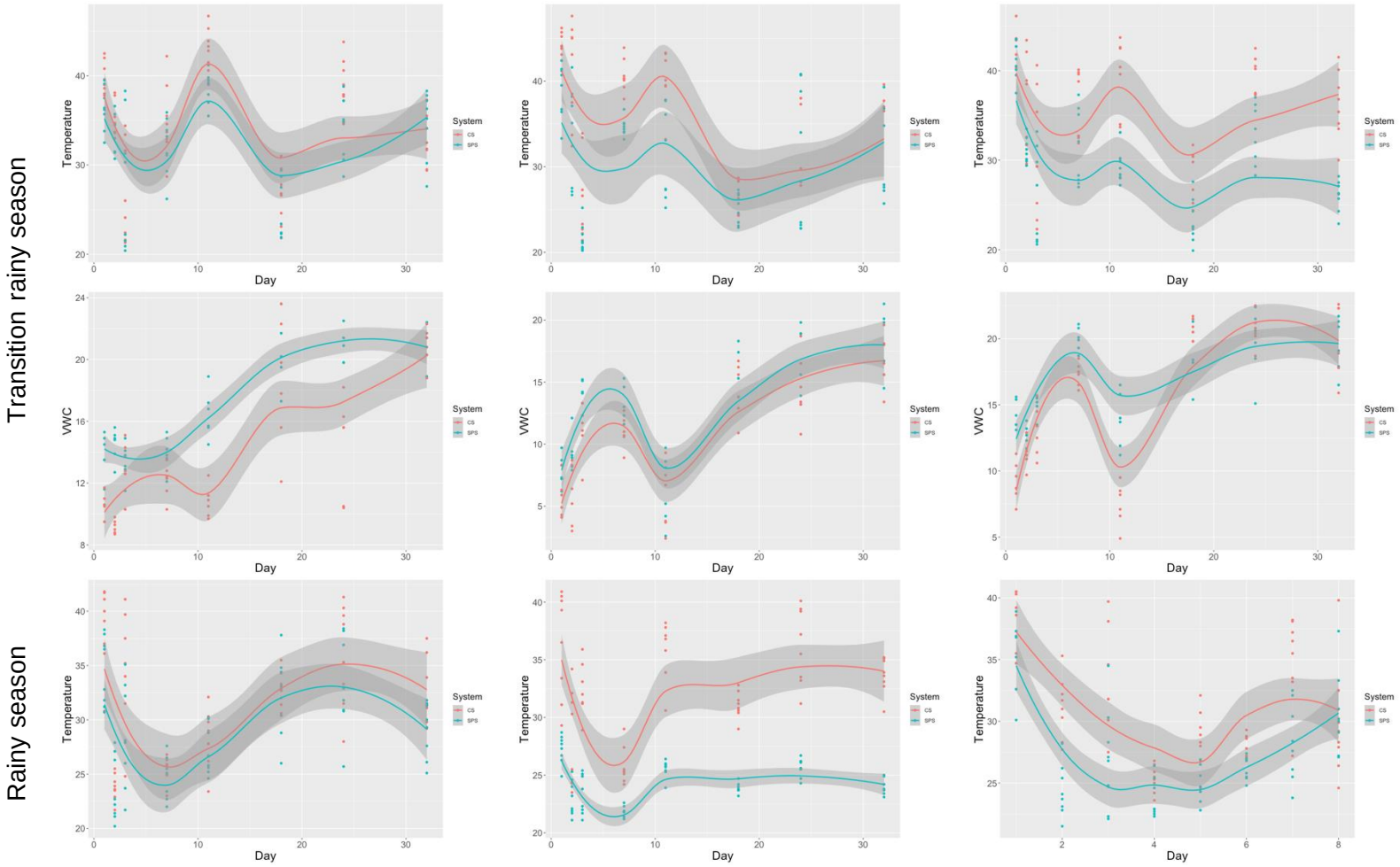
Table 2 Physical and chemical characteristics of soils for conventional and silvopastoral systems

Characteristic	CSs			SPSs			*p-value*	SEM
	Site A	Site B	Site C	Site A	Site B	Site C		

pH	5.89	5.57	5.50	±0.21	5.45	6.04	4.83	±0.6	0.516	0.13
EC (mS/cm)	0.16	0.08	0.12	±0.04	0.48	0.79	0.34	±0.23	0.06	0.11
CEC (cmol/kg)	12.10	9.57	15.35	±2.9	14.1	9.25	15.20	±3.16	0.793	0.92
OM (g/kg)	51.07	36.64	48.24	±7.65	51.57	36.16	53.41	±9.47	0.721	2.24
Total N (mg/kg)	1,860	1,699	2,256	±287	2,895	1,556	2,599	±704	0.24	169
NH_4-N(mg/kg)	22.20	7.08	11.72	±7.75	15.31	7.36	17.08	±5.18	0.913	2.26
NO_3-N (mg/kg)	6.70	1.23	2.09	±2.94	21.83	2.5965	18.44	±10.3	0.019*	10.8
RD	2.52	2.52	2.52	0	2.55	2.54	2.50	±0.03	0.437	0.01
BD	0.96	1.11	0.87	±0.12	0.98	1.25	0.94	±0.17	0.437	0.05
Sand (%)	49.79	42.97	44.64	±3.56	44.62	40.35	45.12	±2.62	0.246	1
Silt (%)	14.87	19.88	16.72	±2.53	21.23	18.94	15.11	±3.09	0.525	0.95
Clay (%)	35.35	37.16	38.65	±1.65	34.15	40.71	39.77	±3.55	0.645	1.16
Macropores (%)	13.98	13.46	14.92	±0.74	9.45	9.74	11.91	±1.35	0.021*	0.87
Mesopores (%)	3.22	2.95	3.43	±0.24	2.90	2.33	2.44	±0.30	0.074	0.18
Micropores (%)	44.79	39.56	47.05	±3.84	49.19	38.78	48.17	±5.74	0.602	1.42
Total porosity (%)	61.98	55.98	65.40	±4.77	61.53	50.84	62.51	±6.47	0.47	1.84

CSs: Conventional systems; SPSs: Silvopastoral systems; EC: electric conductivity; CEC: cation exchange capacity; OM: organic matter; N: nitrogen; NH_4-N: ammonium; NO_3-N: nitrate; RD: real density, BD: bulk density; SEM: standard error of the mean. *Different letters in the same row denote significant differences ($p<0.05$).

The total average rainfall during the 32 days of the evaluation period in the three sites was 318 and 442 mm in the transition and rainy season, respectively. During the two evaluation periods SPSs presented higher moisture and lower temperature (Figure 2).



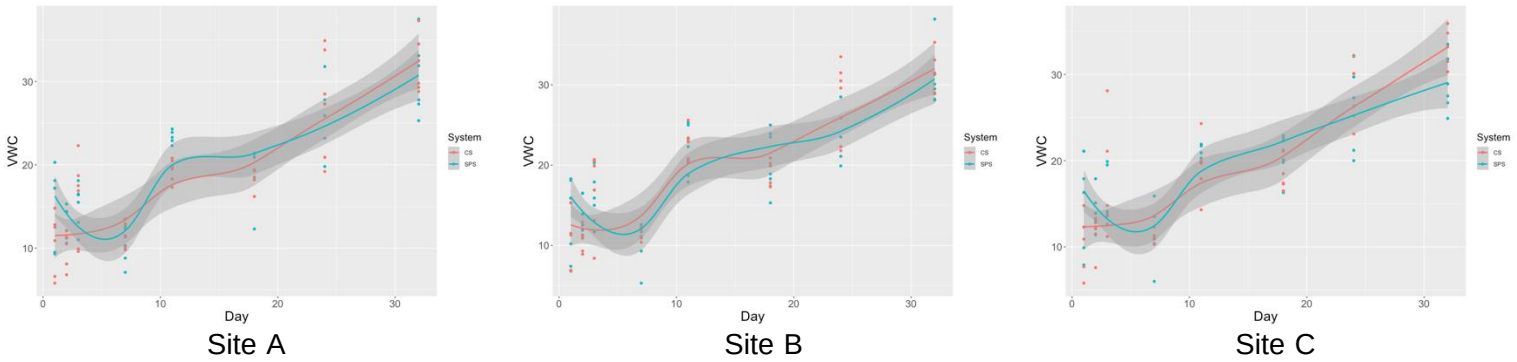
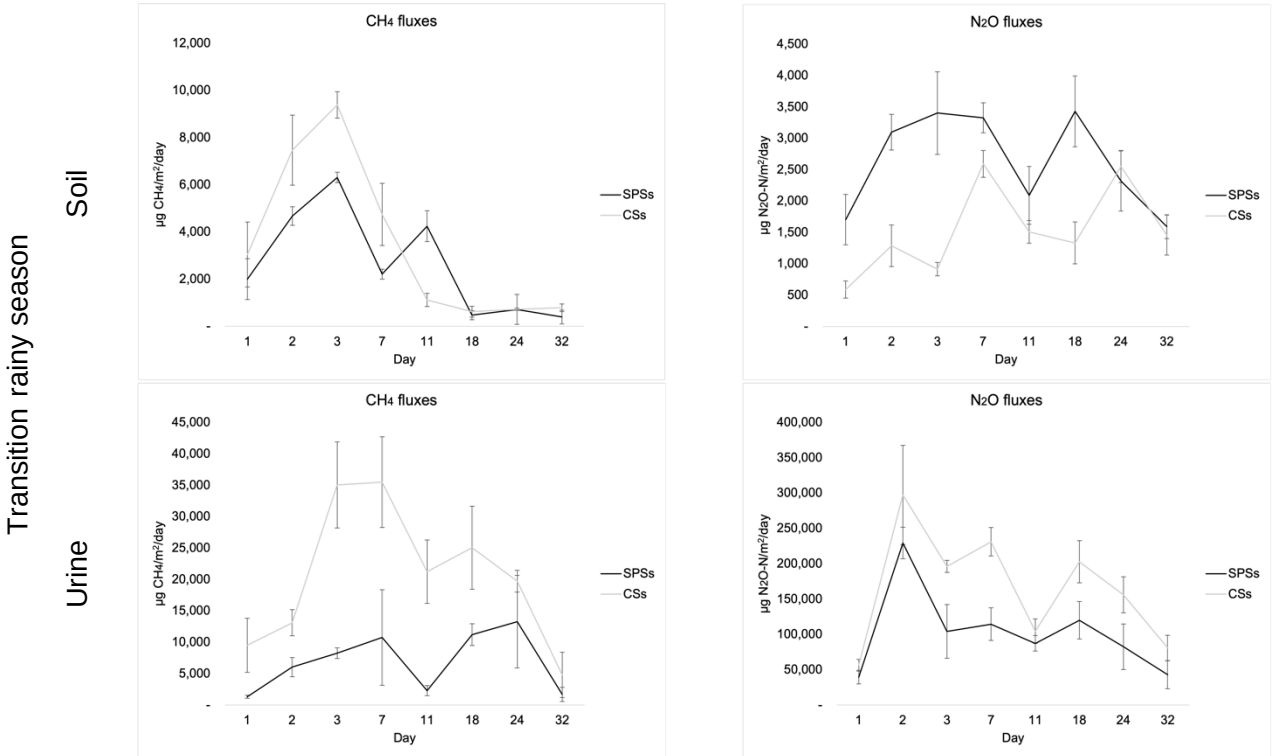


Fig. 2 Temperature (°C) (top) and volumetric water content (%VWC) (bottom) for each site during the evaluation period.
CSs: conventional systems; SPSs: silvopastoral systems

The N contents in urine and feces were 5.69 (±0.53) g/l and 1.75 (± 0.23) % in the transition season and 4.91 (±0.55) g/l and 1.85 (± 0.053) % in the rainy season respectively. On the other hand, the dry matter of feces was 15.43 (± 0.84) % and 13.83 (± 0.77) % for the transition and rainy season, respectively.

Gas fluxes for soil, urine and feces are shown in Figure 3. Methane soil emissions were higher ($p<0.0001$) for CSs (15,953 µg/m^2/day) than for SPSs (5,213 µg/m^2/day), and N_2O-N emissions were higher for SPSs than for CSs (6,338 *vs.* 1,477 µg/m^2/day, respectively) ($p<0.0001$). When comparing the two evaluation periods, SPSs emitted 2.4 times more CH_4 in the rainy season (7,375 *vs.* 3,083 µg/m^2/day) and CSs emitted six times more CH_4 during the transition season (27,353 *vs.* 4,554 µg/m^2/day). For N_2O-N emissions, during the rainy season there were higher fluxes than in the transition season in both systems; soils emitted 4,856 *vs.* 7,821 µg/m^2/day of N_2O-N ($p=0.0234$) in the SPSs, and ted 1,318 *vs.* 1,636 µg/m^2/day ($p=0.543$) in the CSs during the transition and rainy seasons, respectively.



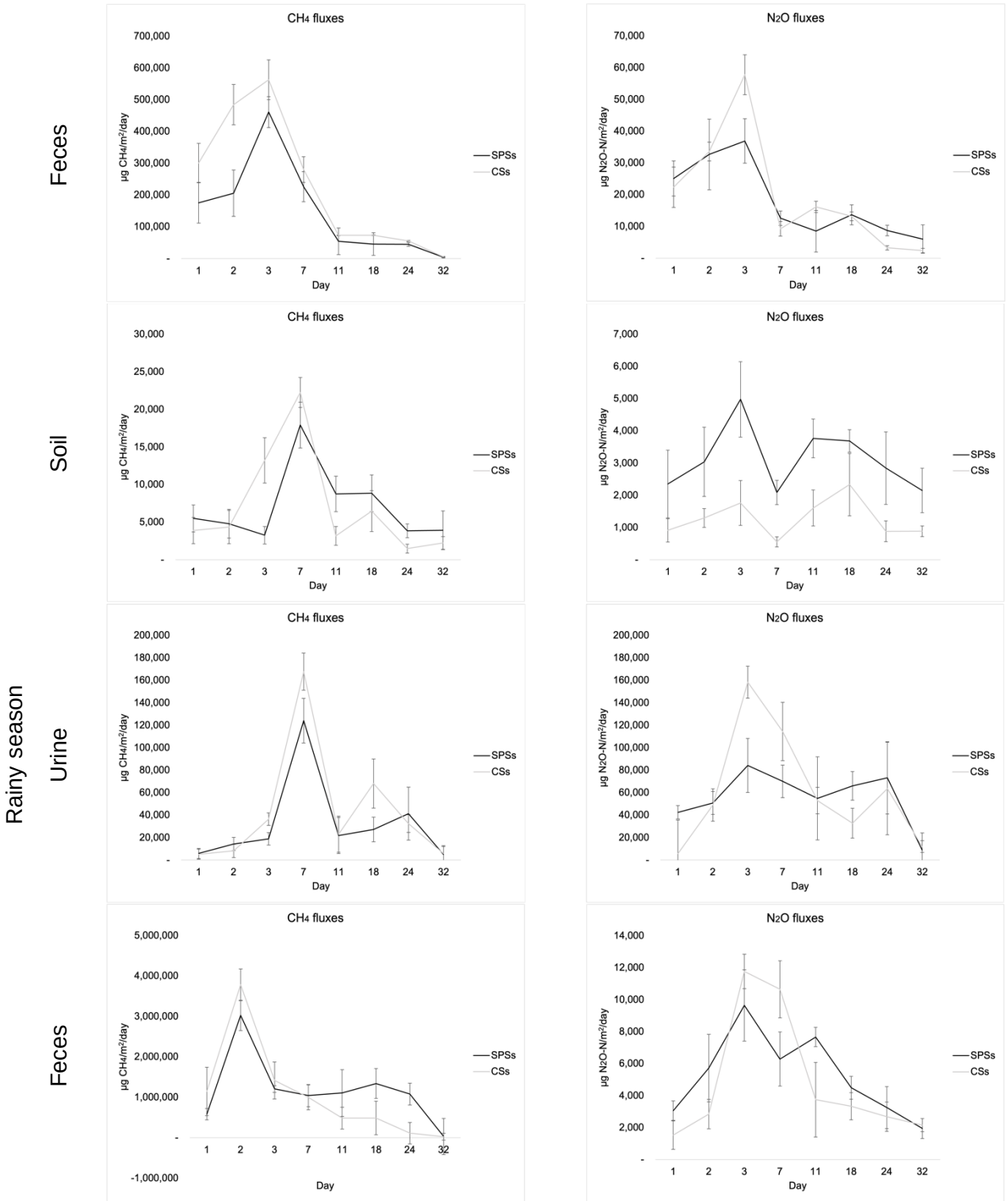


Fig. 3 Gas fluxes during the evaluation period per day for conventional (CSs) and silvopastoral (SSPs) systems

Table 3 shows the emission factors determined for feces and urine. SPSs presented lower emission factors than CSs (p=0.004) for N_2O-N from urine patches in both seasons, N_2O-N from feces in the rainy season

and CH_4 in the transition season. The season had influence on gas fluxes, with higher emission factors in the transition season for N_2O-N in urine patches, and for N_2O-N and CH_4 from feces in the rainy season.

Table 3 Emission factors (EFs) for feces and urine deposited in conventional and silvopastoral systems

	N (%) emitted as N_2O-N in urine patches	N (%) emitted as N_2O-N in feces	Grams of CH_4/kg of DM feces
		Transition season	
CSs	2.64a (±0.22)	0.13 (±0.02)	1.08a (±0.23)
SPSs	1.49b (±0.25)	0.11 (±0.04)	0.833b (±0.21)
SEM	0.040	0.003	0.020
p-value	0.007*	0.133	0.005*
		Rainy season	
CSs	1.69a (±0.22)	0.17a (±0.04)	2.46 (±1.04)
SPSs	0.89b (±0.25)	0.13b (±0.02)	1.99 (±0.55)
SEM	0.074	0.002	0.069
p-value	0.004*	0.046*	0.406

CS: conventional systems; SPS: silvopastoral systems; SEM: standard error of the mean; N: nitrogen; DM: dry matter. *Value in the same column with different letter denotes significant difference ($p < 0.05$).

Finally, according to the CNCPS model the estimated N extraction for CSs and SPSs was 98.4 and 156.3 g per hectare per day for CSs and SPSs, respectively. Based on these values and the emission factors calculated, the estimated annual emissions were 176.8 and 145.3 kg CO_2-eq./ha in the CSs and SPSs, respectively (Figure 5).

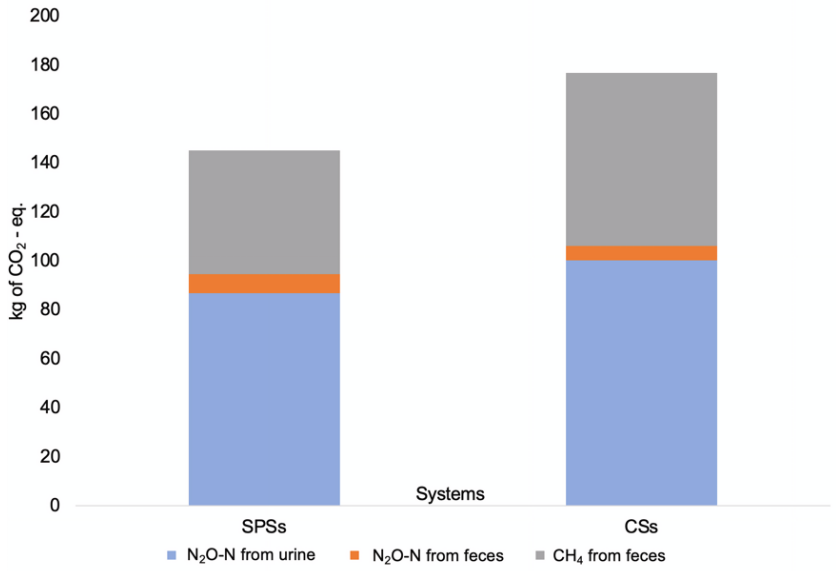


Fig. 4 Total emissions per ha/year from manure (CO_2 – eq) for conventional (CSs) and silvopastoral (SPSs) systems

Discussion

Soil emissions

The two main processes that generate N_2O-N: nitrification and denitrification, are strongly influenced by climatic and edaphic factors (Chen et al. 2008). The higher N_2O-N fluxes in the SPSs were probably due to

the higher amount of N and the higher moisture present in the soil under these systems. N_2O-N production depends on the availability of substrates for both processes, i.e., NH_4^+ for nitrification and NO_3^- for denitrification (Zaman et al. 2007).

Among the factors affecting N_2O-N emissions, the availability of C and N is critical, especially when these elements are in labile organic form (van Groenigen et al. 2005). There is a linear relationship between N input, either through fertilizer or manure, and N_2O emission (Zebarth et al. 2008). SPSs based on *T. diversifolia* offer greater amounts of N than CSs (Rivera et al 2021) and due to the low utilization that ruminants can make of this nutrient, their excretions in feces and urine are expected to be higher providing a greater amount of substrate to generate nitrification and denitrification processes (Luo et al. 2010). According to Rivera et al (2021), *T. diversifolia* offers up to three times more nitrogen than Brachiaria grasses and, when this shrub is mixed with Brachiaria, the total diet has 35% more nitrogen when compared to a diet of only grasses (80:20 ratio pastures:shrub on a dry basis) (Rivera et al. 2022).

Regarding the difference in emissions between seasons, Chirinda et al. (2019) studied the response of dry and wet soils to N_2O-N emissions and established that when the soil is dry there are no emissions, while when water is applied, N_2O production begins immediately, since soil water content influences diffusion conditions by determining the amount of available oxygen. Saturation values of 60-70% soil moisture promote N_2O generation because they limit O_2 diffusion, leading to denitrification processes (Saggar et al. 2004). According to the results found in this study, N_2O emissions were similar in both periods because there was considerable precipitation during the two study periods that maintained soil moisture (Figure 2). Although SPSs presented higher soil moisture in both seasons, N_2O emissions were lower than CS during the rainy season (p=0.046) and did not present differences in the transition rainy season.

For CH_4 emissions, different microbial processes determine their fluxes to the atmosphere and are conditioned by factors such as redox potential, pH, temperature, and soil organic carbon and nitrogen content. These factors can affect the proliferation of some soil microorganisms and, in turn, favor or limit bacterial metabolism through their impact on enzyme synthesis and activity (Towprayoon et al. 2005). The lower CH_4 emissions in SPSs are possibly due to a greater diversity of microorganisms in the soil, a greater soil structure due to the presence of trees and shrubs in the grasslands, and a greater 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 to those observed in forested areas. Rivera et al. (2019) found that some silvopastoral systems can present negative CH_4 fluxes similar to those presented in adjacent forests.

Manure emissions

The amounts of N in the deposited manure varied slightly between seasons even though the excreta were generated by the same animals and with the same feed; this is consistent with the findings of Zhu et al. (2018) and Lombardi et al. (2022), who reported differences in the quality of excreted manure between seasons. Variations in manure N and moisture content between seasons could affect the magnitude of GHG emissions in feces and urine, which rose several days after application and then returned to baseline levels within 32 days. N_2O-N fluxes increased three days after urine and feces application in both seasons; this trend is consistent with studies on manure patches conducted in tropical systems where a similar delay in GHG flux increase is reported (Lombardi et al. 2022). Similarly, it has been observed that the highest emission peaks occur later in feces than in urine due to the type of N that both excretions have. During the first seven days after feces deposition, feces were major points of CH_4 emissions, probably due to the high methanogenic activity due to the available substrate in the soil to carry out this process (Hahn et al. 2018). Several studies previously conducted in tropical conditions report that approximately 80% of total CH_4 emissions occur during the first week after manure deposition (Zhu et al. 2018). In this study, emissions also occurred later probably due to rainfall that could generate anaerobic environments in the soil.

The EFs found in this study were calculated over a relatively short period (32 days) compared to the recommended time for monitoring GHG emissions to develop robust EFs from manure depositions (IPCC, 2019), but due to the environmental conditions of humidity and temperature in the study area, and the rate of decomposition and volatilization of manure, the gas fluxes are expected to occur for shorter periods than in temperate zones (Durango et al. 2020; Lombardi et al. 2022). In addition, the determination of emission factors in both transition and rainy seasons allows achieving robust information under the conditions presented during this study.

Although one month after feces and urine deposition, N_2O-N and CH_4 fluxes measured in the manure patches were similar to those in the control soils (Figure 3), there may be a possibility that more GHG emissions occurred. While longer GHG monitoring campaigns may allow capturing the remaining manure based GHG emissions, short-term studies provide important insights into the major GHG emissions following livestock manure depositions (Lombardi et al. 2022).

The results found for the EFs presented higher N_2O-N values in urine than in feces. Most studies comparing feces and urine N_2O-N emission factors suggest higher values for urine (López-Aizpún et al. 2020). According to Sordi et al. (2014), the fraction of N lost as N_2O-N in urine is higher than that in feces because only a relatively small fraction of N in manure is in an unstable condition and this depends on the diet of the animals. In a study in New Zealand, Luo et al. (2008) reported EFs for urine applications between 0.2 and 1.59%, depending on the season; this range of emission factors agrees with what was determined in this evaluation. On the other hand, the EF of N_2O-N from feces obtained in the present study ranged between 0.11 and 0.17%, corroborating other studies conducted in tropical conditions (Cardoso et al. 2016; Lombardi et al. 2022).

This variability in EFs highlights the importance of determining specific emissions for each country or climate region. Some studies have found that this value can be considerably lower to such an extent that for the year 2019 in IPCC has modified that value to 0.4% for estimating direct emissions and another 0.27% approximately for indirect emissions by leaching and volatilization (IPCC 2019).

Currently in New Zealand, efforts have been made to disaggregate EFs by type of livestock (cattle and sheep), type of excreta (feces and urine) and climate (wet and dry). In this country, the EFs for urine and feces are 1% and 0.25%, respectively (van der Weerden et al. 2020). The New Zealand values, applied to all major livestock classes are similar to those found by Chadwick et al. (2018) in studies in the United Kingdom (urine and feces average of 0.69% and 0.19%, respectively). Similarly, Rivera et al. (2019) in Colombia found EF for systems under tropical conditions between 1.37 and 1.77% for feces, and between 1.3 and 3.47% for urine, which are higher than those reported by Sordi et al. (2014) in Brazil who found values of 0.19 to 0.33% and 0.12 to 0.19% for urine and feces, respectively.

The N_2O-N EFs obtained in the present study for urine are above those reported in other studies developed under tropical conditions in unfertilized grasslands in Colombia (0.0002-0.471% EF, Chirinda et al. 2019) and Brazil (0.1-1.93% EF, Lessa et al. 2014), probably due to the rainfall regime. For example, Chrinda et al. (2019) reported an average rainfall close to 110 mm in a 30-day period, and Lessa et al. (2014) reported rainfall averages of 60 and 160 mm per month in the dry and rainy season respectively.

Regarding CH_4 emissions from feces, the results of this assessment are above recent IPCC estimates, which broadly estimate on average 0.49 ±0.43 g CH_4/kg DM of manure (IPCC 2019). The diversity of conditions that modify CH_4 emissions has generated great dispersion in the results (Andueza et al. 2017), as there are reports of up to 1 g of CH_4 per kg DM of manure generated, a value that can be up to five times higher when manure is improperly stored under anaerobic conditions (Rivera and Chará 2021). According to Chadwick et al (2018), manure emissions can range from 0.4 to 9.7% of the total C content deposited in manure.

Finally, it is highlighted that although SPSs excrete more N and produce more feces, due to a greater supply of N in the diet and a higher animal carrying capacity (1 *vs.* 1.4 AU per hectare in the CSs and SPSs, respectively), annual emissions are 17.8% lower compared to CSs (Figure 5). This main reason for this is

that on average SPS had 45, 20 and 20.3 % lower EFs of N_2O-N from urine patches, N_2O-N from feces, and CH_4 from feces than the CSs, respectively (Table 3). The results found in this research provide evidence of the ability of SPSs with *T. diversifolia* to reduce GHG emissions from manure under the conditions of this study, which added to the potential to reduce CH_4 emissions by enteric fermentation (Rivera et al. 2022) postulate this type of SPSs as an effective tool to mitigate climate change in the region.

According to Rivera and Chará (2021) SPSs can have lower soil GHG emissions compared to conventional systems due to the following factors: i) SPSs improve soil cover and biological integrity which is associated with reduced N loss through microbial soil and leaching processes; ii) SPSs have demonstrated effects on the physical, chemical and microbiological properties of the soil, both by the provision of shade and higher amount of heterogeneous biomass that is deposited on the soil in the form of leaves, branches, fruits and exudates, and by improving the root microbiome allowing the modification of microorganism populations that can regulate nitrification and oxidation processes; iii) SPS have greater abundance diversity and activity of dung beetles than treeless pastures (Montoya-Molina et al. 2016) and they limit the interactions of manure with mineral soil, restricting substrates for nitrification and denitrification processes. According to Slade et al. (2016) the presence of beetles in livestock systems can reduce N_2O emissions by 14.7% and CH_4 emissions by 17%.

Given the capacity of the SPSs studied to reduce GHG emissions in the Amazon region of Colombia, these systems hold a great potential to improve production efficiency and reduce GHG emissions from cattle manure and will contribute to meet Colombia's commitments in its Nationally Determined Contributions (NDC). For the Caquetá department in Colombia, the adoption of SPS in 10 % of the 1.5 million hectares already in pastures, would reduce GHG emissions in 4,725 tons of CO_2eq per year.

Conclusions

The SPSs have the capacity to generate lower EFs from urine (N_2O-N) and feces (CH_4) deposited in the pastures under conditions of the Colombian Amazonian piedmont, so they can be systems that mitigate the emissions of these gases in the manure deposited on pastureland grazed by cattle. The results found in this study can contribute new information to GHG inventory calculations at both local and regional levels by reporting gas fluxes in both rainy and transition seasons. Our study provides further evidence for the need to determine site- and system-specific EF, as N_2O-N and CH_4 emissions are affected by multiple biotic and abiotic factors. However, it is recommended to further study gas fluxes in the soil without manure and to make more integral estimates including emissions from enteric fermentation and carbon sequestration.

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