Using silvopastoral systems for the mitigation of greenhouse gas emissions from livestock in the Colombian Amazon

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Abstract Silvopastoral systems (SPS) are strategic in neutralizing greenhouse gases (GHG) emissions in livestock production systems, particularly in the tropics. This research assessed the mitigation potential of SPS on the carbon footprint (CFP) neutralizing in one integrated livestock farm of cow-calf and pig production system in the Colombian Amazon. Annual carbon accumulation rate (ACAR) in $MgCO_2e\ ha^{-1}y^{-1}$, was evaluated on living above-ground biomass including trees and shrubs > 2 cm DBH and pasture, and leaf litter and below-ground biomass including coarse and fine roots, soil organic carbon 0–10 cm deep, and total ACAR adding up all components in live fences (LF), scattered trees (ST), fallows (FW), fodder bank (FB) and pastures (PT). The GHG emissions in $MgCO_2e\ ha^{-1}y^{-1}$ were accounted in CO_2 from liming, urea, fuel, electricity, and supplementation, CH_4 from enteric methane, manure, and organic fertilization and N_2O from urine and manure. The C balance was obtained from the differences between ACAR of SPS on farm and the CFP per surface. Mean total ACAR expressed in $MgC\ ha^{-1}y^{-1}$ were 9.0 ± 4.6 in FW, 7.0 ± 1.2 in LF, 5.5 ± 0.8 in ST, 4.2 ± 0.2 in FB and 2.9 ± 0.1 in PT. Mean CFP was 3.7 $MgCO_2e\ ha^{-1}y^{-1}$, 5.3 $MgCO_2e$ Live Weight $ha^{-1}y^{-1}$, and 23.6 $MgCO_2e$ Live Weight Gain y^{-1}. The CFP (area) can be neutralized with total ACAR value of 2.1 ha^{-1} for LF, 1.6 ha^{-1} for FW, 2.6 ha^{-1} for ST, 3.5 ha^{-1} for FB and 5.1 ha^{-1} for PT. The Silvopastoral systems have a higher potential for neutralizing GHG emissions than pasture-based scenario when considering the ACAR in above-ground biomass.

Abbreviations

ACAR	Annual carbon accumulation rate
LAB	Living above-ground biomass
LBB	Living below-ground biomass
ANOVA	Analysis of variance
AU	Animal units
CFP	Carbon footprint
FB	Fodder bank
FW	Fallow
GHG	Greenhouse
LF	Live fence
LW	Live weight

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LWG	Live weight gain
PT	Pasture
SOC	Soil organic carbon
SPS	Silvopastoral systems
ST	Scattered trees

Introduction

The removal of both above and belowground forest biomass in the Amazon biome between the period 1971–2021 has reached 17%, 14% of which was transformed into agricultural areas (89% grasslands and 10% crops). Such large-scale transformations led to an increase in temperatures and a decrease in precipitation in different parts of the biome, consequently increasing vulnerability to fires and forest degradation (Gatti et al. 2021). In the Colombian context, during the 2001–2018 period, the Amazon region accumulated 38% of national deforestation, mainly driven by livestock production (Ganzenmüller et al. 2022), as well as other socio-economic factors of high complexity such as small-scale agriculture, illicit crops, timber extraction, mining, and oil extraction, among other infrastructure projects (Hoffmann et al. 2018).

On the other hand, Colombia is the fifth country with the largest cattle inventory in the Americas with 29.3 million heads (ICA 2022; FAO 2022), covering 34 million hectares, 78% of the land use (DANE 2020). Livestock is mainly for beef production (58%), followed by dual-purpose (35%) and dairy (7%) cattle (FEDEGAN 2020); these activities are carried out in 0.63 million farms (ICA 2022). In general, livestock farming is extensive, with a stocking rate of 0.7 head/ha (CIPAV et al. 2021) and with indicators below its productive potential (González-Quintero et al. 2022). The Amazon region of Colombia comprised the departments of *Amazonas*, *Caquetá*, *Guainia*, *Guaviare*, *Putumayo*, and *Vaupés*, experienced the highest growth (17%) in the bovine herd between 2018 and 2022, increasing from 2.4 to 3.8 million heads, along with a similar increase in the number of farms (23%), from 29 to 35 thousand livestock farms (ICA 2023). The departments of *Caquetá* and *Putumayo* are part of the national meat industry in the central-southern region of the country. In 2021, they produced 125,995,620 kg of meat, representing 66% of the region's total volume, with 2,335,300 heads of cattle.

Out of these, 70% were used for dual-purpose models, while 30% were dedicated to specialized beef production (MADR, UPRA 2022).

Historically, the amazon region has been characterized as one of the main fronts of deforestation in the country and contributes with 20% to the country's global greenhouse gas (GGH) emissions (38.28 Mt CO2e). The departments of Caquetá (49%), Guaviare (27%), and Putumayo (17%) are the major emitters in this region, with over 77% of emissions originating from deforestation in all cases (IDEAM 2016). Colombian population, now at 50 million, is expected to increase by 22% by 2070 which will pose significant challenges to food security in the country. The agriculture, livestock, forestry, and other land uses (AFOLU) contributed with 59% of total emission of CO_2e in the country, whit enteric methane and conversion of forest into pasture with 14 and 20% of total greenhouse gases GHG emissions respectively (IDEAM 2021). Thus, Colombian livestock requires transitioning to low-carbon models, with better productivity and profitability indicators that allow supplying protein demands in a sustainable fashion (Minagriculutura and Minambiente 2022).

Silvopastoral systems (SPS), characterized by the incorporation of woody plants in pastures, have a high potential to mitigate GHG emissions through the Annual Carbon Accumulation Rate (ACAR) in the Living Above-Ground Biomass or LAB (Resende et al. 2020) and other components such as soil organic carbon or SOC, roots, and leaf litter. In Colombia, SPS present an ACAR in LAB that can vary between 4.53 ± 0.26 MgCO$_2$e ha^{-1}y^{-1} in fodder banks and 14.76 ± 1.89 MgCO$_2$e ha^{-1}y^{-1} in intensive SPS. This characteristic broadens the mitigation potential, when compared to improved pasture monocultures with ACAR in LAB 0.296 MgCO$_2$e ha^{-1}y^{-1} (CIPAV et al. 2021). As such, SPS can potentially become carbon sinks capable of neutralizing emissions caused by productive intensification and rendering possible to obtain meat and dairy products with a lower CFP (Carbon Footprint) as defined by Schettini et al. (2021), and Torres et al. (2017).

This study aims to quantify carbon stocks and the ACAR, as well as to determine the C balance and CFP in a small-scale integrated livestock system, representative of the predominant systems in Colombia, particularly in the framework of the incorporation of SPS alternatives such as live fences, scattered trees,

forage bank and fallows. These are part of the agricultural landscape of the Colombian Amazon region and the tropics (Albrecht and Kandji 2003). Results from this research will be useful to support the country's GHG reduction goals, estimated at 51% by 2030 (Min Ambiente et al. 2021) and may likely be extrapolated to other countries in the Andean and Amazonian regions.

Material and methods

Study site

The research site is located in the Amazon region of Colombia at the *Villa Lucero* farm (8.8 ha^{-1}), Municipality of *Puerto Asis*, in the Department of *Putumayo* ($-$ 76°32.2′4.0″W, 0°35′24″N) at 256 m. The mean annual temperature is 25.3 °C, with 85% relative humidity and precipitation is 3100 mm y-^{1}. Precipitation presents an unimodal to non-seasonal distribution. The highest rainfall is concentrated between the months of March to May (34% of the precipitation or 350 mm month) and from June to August (28% if the precipitation or 250 mm month). The least rainy months occur during the periods of September to November (21% of the precipitation or 217 mm month) (Jaramillo and Chavez 2000). The area is located in equatorial tropical rainforest, with a Köppen classification AF climate (Kottek et al. 2006). The soil is classified as Oxic Dystrudepts (IGAC 2022).

Silvopastoral systems and pasture characteristics

Live fences (LF) are linear plantations of trees and shrubs used for farm delimitation with other properties and roads. LF are characterized by the abundance of forage and legume native trees such as *Erythrina poeppigiana* and timber species such as *Miconia caudata*, *Piper aduncum*, and *Cecropia peltata*.

Scattered trees (ST) are natural pastures with trees selected and protected by the farmer because of natural regeneration. The trees provide shade and fruit for both cattle and humans. The most abundant species are guava (*Psidium guajava*) and timber species such as *Bellucia pentamera Naudin* and *Piptocoma discolor*.

Fodder bank (FB) is a system based on the use of resprouting leaves of *E. poeppigiana* with strict pruning at approximately 1.15 m in height. This system also had timber shade trees such as *C. peltata* and *Vernonanthura patens* (Kunth) H. Rob. In this system, cattle enters the fodder bank area to forage for 2 or 3 days according to the availability of forage, with approximately 45 days of recovery.

Fallow (FW) are natural areas of regeneration, where cattle eventually enters to take feed ad libitum on pasture. Timber species such as *Phyllostachys aurea, P. discolor* and *B. pentamera* are the most abundant.

Pasture (PT) are fields with spontaneous occurring grasses, predominantly *Ischaemum ciliare, Brachiadira decumbens* and *Stenotaphrum secundatum*. Pastures in the 5th year were limed and organically fertilized with swine manure. The grazing cycles correspond to 3 days of occupation and 45 days of recovery.

Herd characteristics

Farm operations started in 2013 with a genetic nucleus of 12 heifers of the Colombian Creole breed *Hartón del Valle*, as shown in Fig. 1, and recently described in detail by Asocriollo (2021). It is managed in rotational grazing system with an electric fence with an average stocking rate of 1.8 Animal Units (AU) per ha. The pastures have a water supply system providing water ad libitum. During periods of higher rainfall, cattle is supplemented with balanced minerals and nutritional blocks as sources of minerals, protein and energy. Supplementation corresponds to 1% of dry matter intake; the nutritional block has 12% crude protein, 3.2 megacalories of metabolizable energy/kg, 6% Ca, 12% P and 0.5% mineral premix. In the 2020–2021 season, some of cows were artificially inseminated with red Brahman semen to produce F1 crossed calves. Overall, calves have a live weight (LW) at birth of 38 kg and are sold at 9 to 12 months at 160 to 170 kg. LW gain (LWG) per day averages 0.432 kg/day for purebred *Hartón del Valle* and 0.650 kg/day for F1 calves. In 2020, the farm incorporated a production subsystem of 60 Landrace X *Pietrain* pigs. The pigs are purchased weaned at an average of 7 kg and sold at 90 kg at 5 months of age. They are fed with commercial concentrates. During the first 2 months, the concentrate has 16% crude
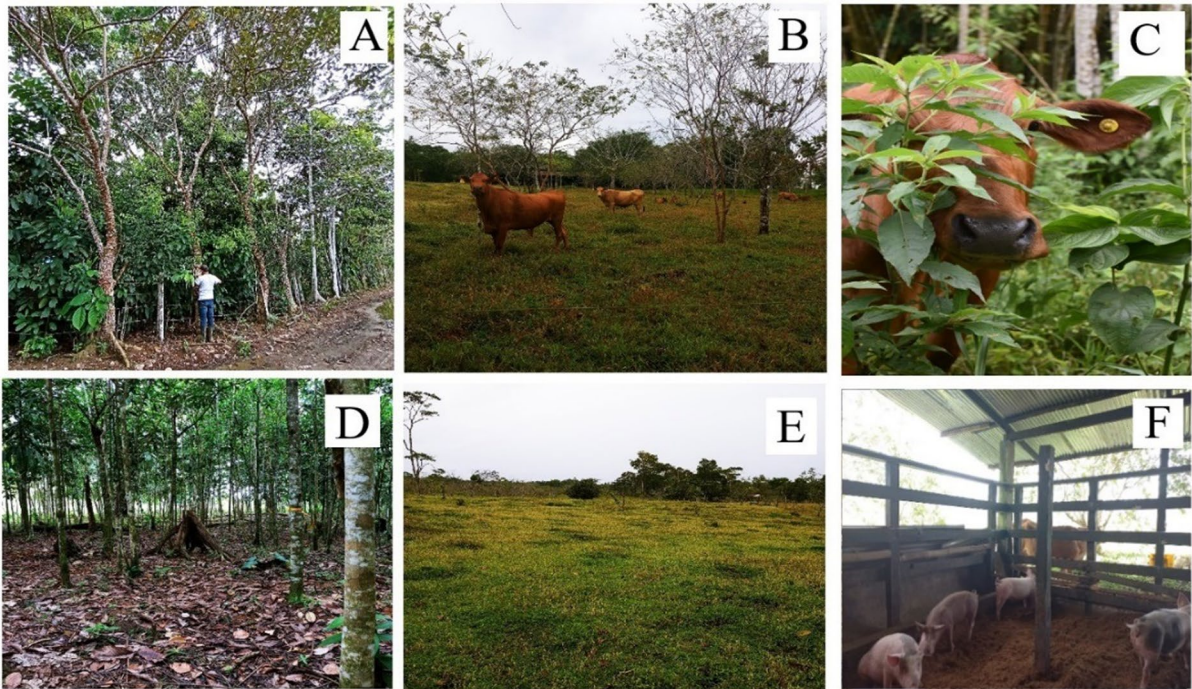
Fig. 1 Silvopastoral Systems, Pasture and pig breeding systems on the farm. **A** LF live fences, **B** ST scattered trees with the predominance of *P. guajava* and Creole breed *Hartón del Valle*, **C** FB fodder bank with a high density of *E. poeppigiana*, **D** FW fallow, **E** PT pasture and **F** Landrace pig breeding system by *Pietrain* meat line

protein, 3.0 mega calories of digestible energy. In the remaining 3 months, the concentrate has 12% crude protein and 3.2 metabolizable energy per kg. Figure 1 shows several aspects of the farm, particularly the *Hartón del Valle* cattle production silvopastoral systems and the pig production facilities.

Field measurements and analysis

Three temporary sampling plots were randomly established in each system. Circular plots (314 m^2) in FW, ST, PT and FB and rectangular plots (600 m^2) in LF with three sub-transects of 20×10 m according to methodological adaptations in previous studies Villanueva-López et al. (2015); Gómez Cardozo et al. (2018); Aryal et al. (2019), and TNC and ACT (2019). The C fractions assessed in each plot are described in the Fig. 2.

Table 1 Allometric equations used for Living Above Ground Biomass (LAB, kg) and Living Below Ground Biomass (LBB kg) estimation

Type of vegetation	Formula	Source
Trees > 10 cm DBH	Ln(LAB) = 2.406–1.289*Ln(DBH) + 1.169*[Ln(DBH)]^2– 0.122*[Ln(DBH)]^3 + 0.445*[Ln (ρ)]	Alvarez et al. (2012)
Shrubs 1 < 10 cm DBH	LAB = 0.18598*DBH$^{2.31155}$	Ducey et al. (2009)
Pruned trees of *E. poeppigiana*	LAB = 0.613Ln (PH) + 0.3072 (r^2 = 0.7)	This research
Trees and shrubs > 1 cm DBH coarse roots	LBB = EXP (− 1.805 + 0.926Ln (LAB))	Cairns et al. (1997)
Grass roots	LBB = 1.8887*LAB Grass	Mokany et al.(2006)

DBH diameter at breast height (cm); *PH* pruned height (m), ρ: wood density (g cm^{-3})

Fig. 2 Sampling plots of C inventory for (**a**) FW, ST, PT, FB and (**b**) LF
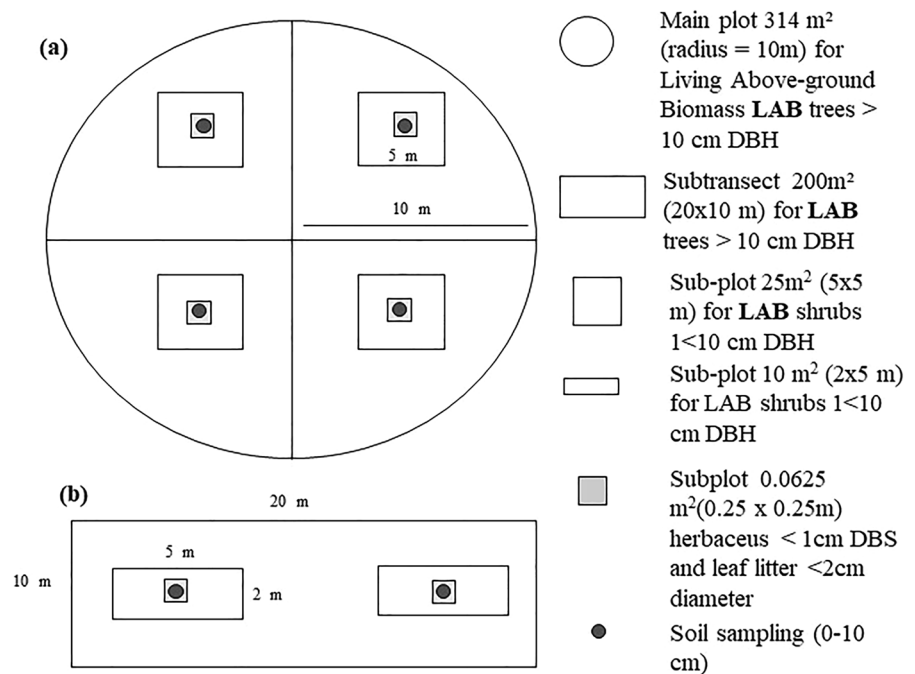
Table 2 Specific emission factors of CH$_4$ and N$_2$O adjusted for the southwestern region of Colombia used for the bovine GHG inventory on farm

Pollutant	Unit	Breeding cows (a)	Pre-weaning calves (b)	Fattening cattle (c)	Reference
CH$_4$ enteric fermentation	kg CH$_4$ head y^{-1}	69.94	16.64	56.27	Moreno et al. (2021)
CH$_4$ manure management	kg CH$_4$ head y^{-1}	0.64	0.18	0.45	Moreno et al. (2021)
N$_2$O from urine and manure from grazing animals (direct)	kg N$_2$O–N head y^{-1}	0.45	0.14	0.31	Torres et al. (2021)
N$_2$O from urine and manure grazing animals (indirect)	kg N2O–N (kg N leaching/runoff) head y^{-1}	0.20	0.06	0.14	Torres et al. (2021)

(a) females over 3 years old, (b) females and males under 1 year old, (c) males and females 1–3 years old

Tree biomass was estimated using multispecies allometric equations (Table 1). The wood density was assumed to be 0.6 g cm^3 according to Pardo-Rozo et al. (2021). Four pruned trunks of *E. poeppigiana* including leaves in the FB were randomly and destructively sampled to obtain the above-ground dry biomass. The C content was 48% of dry matter biomass (Penman et al. 2003). Structural indicators of the vegetation in each SPS were obtained, such as total height, basal area, average diameter at chest height DBH and the carbon C distribution in LAB in different diameter classes. The C in Soil Organic Matter, SOC, was obtained using the wet combustion Walkley & Black method as recommended by the FAO and

described by Vargas (2009). Four composite samples in circular plots and six composite samples in rectangular plots were used for physical–chemical analysis that were conducted at the Agrosavia soil laboratory (Tibaitá, Colombia).

The ACAR was estimated in three scenarios. The total ACAR, combining all assessed carbon stocks (above and below ground), the ACAR only for living above-ground biomass, and the ACAR for soil (0–10 cm depth). For this purpose, the carbon found in each evaluated component was divided by the plot age (years) as declared by the farmer. To facilitate the carbon balance, the ACAR of each

Table 3 Emission factors used for swine, bovines, and other sources of GHG on farm

Pollutant	Units	Factor	Reference
Swine			
CH_4 enteric fermentation	kg CH_4 head y^{-1}	1.5	Nieves and Olarte (2009)
CH_4 manure management	kg CH_4 head y^{-1}	1.3	Nieves and Olarte (2009)
Commercial concentrate	Kg CO_{2eq} Kg input	0.7	Ecoinvent 3 (2013a, b)
Bovines and other sources			
Electricity	kg CO_2 eq KWh input	0.203	UPME (2021)
Urea	kg CO_2 y^{-1}	0.2	de Klein et al. (2006)
Fuel	kg CO_2 eq /lt	2.35	Carrasco (2015)
Lime	kg CO_2 y^{-1}	0.12	Ecoinvent 3 (2013a, b)
Organic fertilizer	N_2O/kg N_2	0.016	de Klein et al. (2006)
	kg CH_4/kg	0.004	de Klein et al. (2006)
Mineral Salt	kgCO_2 eq kg^{-1} input	0155	Ecoinvent 3 (2013a, b)

scenario, expressed in $MgCha^{-1}$, was converted to $MgCO_2eha^{-1}$ using the molar proportion of C to CO_2 equivalent of 3.67 suggested by Krug et al. (2006). To obtain the CO_2e captured on the farm, the ACAR of each system was multiplied by its area. Differences in C stocks between the SPS and PT were then tested with ANOVA and LSD Fisher tests with a 95% confidence interval. Differences in C stocks between the SPS and PT were then tested with ANOVA and LSD Fisher tests with a 95% confidence interval.

Inventory of GHG emissions

To account for the net GHG emissions of the farm, a life cycle assessment (LCA) analysis was conducted, following the guidelines for evaluating GHG emissions of goods and services (BSI and Carbon Trust 2011) and previous reference studies applied to cow-calf systems in Colombia (González-Quintero et al. 2022). The LCA covered the entire life cycle, "from cradle to farm gate", and accounted for emissions from both on-farm and upstream sources. On-farm resources included the total emissions generated by the bovine system (enteric and manure CH_4, direct and indirect N_2O from urine) and the pig system (enteric and manure CH_4), as well as emissions from pasture management, including direct emissions (N_2O and CH_4) from pig composting and indirect emissions (CO_2) from the use of urea and lime. Off-farm resources encompassed CO_2 emissions from the use of concentrate, mineral salt, electricity, and fuel used up to the farm site. GHG emissions were expressed in CO_2e units, using specific emission factors based

on the herd composition, as detailed in Table 2. The inventory considered five years of records (2017–2021). The global warming potential (GWP) of CH_4 was 28 times higher than that of CO_2 and for N_2O, 265 times higher than that of CO_2 as suggested Stocker et al. (2014) (Table 3).

CFP

Functional reporting units were $MgCO_2e$ $ha^{-1}y^{-1}$ (surface) and LW $MgCO_2e$ $ha^{-1}y^{-1}$ LW $ha^{-1}y^{-1}$ and LWG $MgCO_2e$ LWG (product) according to life cycle analysis in beef cattle production systems (Cusack et al. 2021). The LW was quantified in animal units (AU). This is equivalent to one 500 kg cow over 3 years. One AU is equivalent to, 3.3 male or female calves below 1 year of age, 1.7 female or male calves aged 1 to 2 years, 1.3 heifers aged 2 to 3 years, 1.3 bulls aged 1 to 2 years, or 0.8 adult bulls, as suggested by González-Quintero et al. (2022) in studies on CFP in cattle production systems in Colombia.

C balance and GHG emission neutralization potential

The C balance was obtained annually in four scenarios as the difference between ACAR in $MgCO_2eha^{-1}y^{-1}$ of living above and below-ground biomass, ACAR of soil and total ACAR (identified in each SPS and totalized according to the each SPS surface present in the farm), and the CFP per area. The CFP per area in $MgCO_2eha^{-1}y^{-1}$ of year five that includes total emissions of bovine and swine sub-systems was token as a reference to obtain the numbers

Table 4 Age, structural characteristics in above-ground biomass of SPS and below-ground physicochemical properties (0–10 cm deep) in the SPS and pasture in the *Villa Lucero* farm in the Amazon of Colombia

Variable	LF Live fence	FW Fallow	ST Scattered Trees	FB Fodder bank	PT Pasture	Units
System age	15 ± 0	14.3 ± 5.4	12 ± 0.3	12 ± 0	12 ± 0	y^{-1}
LAB characteristics						
Average total height	$8.1a \pm 1.5$	$6.3ab \pm 0.3$	$4.8b \pm 0.3$	$2.4c \pm 0.2$		m
Basal area	$13.6ab \pm 3.3$	$11.3ab \pm 3.6$	$7.4b \pm 1.9$	$16.8a \pm 0.5$		m^2/ha
Average DBH	15.7 ± 5.7	11.4 ± 3.7	8.3 ± 0.8	12.7 ± 1.2		cm
Density of individuals	750 ± 267	1396 ± 636	1257 ± 167	1544 ± 300		ind/ha
Distribution of C in LAB in different diameter classes (cm)						
DBH $1 < 10$	2 ± 1	8 ± 5	9 ± 7	30 ± 10		%
DBH $10 < 20$	13 ± 4	28 ± 10	42 ± 7	42 ± 11		%
DBH $20 < 40$	64 ± 15	39 ± 14	48 ± 1	28 ± 17		%
DBH $40 < 60$	8 ± 8	25 ± 25	0 ± 0	0 ± 0		%
DBH $60 < 80$	12 ± 12	0	0	0 ± 0		%
Distribution of density in different diameter classes (cm)						
DBH $1 < 10$	46 ± 24	0 ± 0	77 ± 3	59 ± 8		%
DBH $10 < 20$	24 ± 8	49 ± 11	19 ± 2	33 ± 4		%
DBH $20 < 40$	25 ± 11	39 ± 7	4 ± 1	8 ± 4		%
DBH $40 < 60$	3 ± 3	7 ± 1	0 ± 0	0 ± 0		%
DBH $60 < 80$	3 ± 3	5 ± 5	0 ± 0	0 ± 0		%
BLGcharacteristics (0–10 cm deep)						
Soil organic C	$2.5^b \pm 0.21$	$2.2^b \pm 0.03$	$2.7^{ab} \pm 0.24$	$2.3^b \pm 0.19$	$3.2^a \pm 0.06$	g/100 g
Bulk density	$1.1^b \pm 0.04$	$1.1b^c \pm 0.02$	$1.3^a \pm 0.01$	$1.2^{ab} \pm 0.05$	$1.0^c \pm 0.03$	g /cm3
Sand	54 ± 8.8	43.7 ± 12.4	48 ± 1.3	52.9 ± 3	39.6 ± 9.3	g/100 g
Clay	24.02 ± 8.59	38.54 ± 14	32.87 ± 0.7	29.36 ± 2.46	42.03 ± 6.07	g/100 g
Organic Matter	$4.3^b \pm 0.37$	$6.2^b \pm 1.27$	$4.6^b \pm 0.41$	$4.0^b \pm 0.33$	$10.8^a \pm 0.2$	g/100 g
Soil pH	$4.4^b \pm 0.2$	$4.7^{ab} \pm 0.07$	$5.1^a \pm 0.15$	$4.6^b \pm 0.09$	$5.0^a \pm 0.04$	pH units
Total nitrogen (N)	0.3 ± 0.03	$0.3 \pm E\text{-}03$	0.3 ± 0.03	0.3 ± 0.04	0.3 ± 0.02	g/100 g
Available potassium (K)	$0.2^{ab} \pm 0.02$	$0.2^{ab} \pm 0.06$	$0.3^a \pm 0.09$	$0.1^b \pm E\text{-}03$	$0.2^{ab} \pm 0.01$	cmol(+)/kg
Phosphorus (P) Available	3.6 ± 0.72	2.5 ± 0.26	2.1 ± 0.1	3 ± 0.62	2.3 ± 0.15	mg/kg

[a,b,c] Rows with different superscript indicate significant differences (p < 0.05)

LAB living above-ground biomass, *DBH* average diameter at breast height, *BLG* below-ground

of trees and the surface required to mitigate de CFP. We assume that the potential of ACAR in the above-ground biomass is associated to the structural vegetation characteristics (trees/ha, the distribution of trees in different diameter classes, the basal area and the total height) identified in this study.

Results

Above and below-ground characteristics of SPS and pasture

The SPS between 12 and 15 years after implementation presented structural differences in the LAB, particularly those concerning basal area and total height. The FB presented the highest basal area (16.8 ± 0.5 m^2 ha) and lowest height (2.4 ± 0.2 m) while the LF (8.1 ± 1.5 m) and FW (6.3 ± 0.3 m) presented the highest total height and the highest proportion of individuals and C in the LAB in the trees with

Table 5 Area of each system assessed in the farm. Above, below ground, and total carbon stocks

Components assessed	LF Live fences	FW Fallows	ST Scattered trees	FB Fodder bank	PT Pastures	Units	Total on farm	Units
Area	0.7	1.3	1.4	0.3	2.9	ha⁻¹	6.6	ha
AGC								
LAB	$63.8^a \pm 17.2$	$48.1^{ab} \pm 20.8$	$25.7^b \pm 6.1$	$15.6^b \pm 2.9$	$1.2^c \pm 0.1$	Mg C ha⁻¹	151.4	Mg C
Leaf litter	$1.7^b \pm 0.4$	$4.1^a \pm 0.8$	$0.8^b \pm 0.5$	$1.9^b \pm 0.6$	$0.0^c \pm 0$	Mg C ha⁻¹	8.2	Mg C
BGC							0.8	
SOC 0–10 cm deep	26.6 ± 3.2	27.1 ± 1.9	33.3 ± 2.9	29 ± 2.4	32.8 ± 0.9	Mg C ha⁻¹	204.3	Mg C
Coarse–fine roots	$13.2^a \pm 3.5$	$10.2^a \pm 4$	$5.8^{ab} \pm 1.4$	$3.6^{ab} \pm 0.8$	$0.4^c \pm 0$	Mg C ha⁻¹	32.8	Mg C
TCS	$105.3^a \pm 17.4$	$89.5^{ab} \pm 26.3$	$65.7^{ab} \pm 10.5$	$50.1^{bc} \pm 1.9$	$34.3^c \pm 0.9$	Mg C ha⁻¹	396.8	Mg C
ACAR								
Total	7 ± 1.2	9 ± 4.6	5.5 ± 0.8	4.2 ± 0.2	2.9 ± 0.1	Mg C ha⁻¹ y⁻¹	33.8	Mg C
LAB	$4.3^a \pm 1.2$	$5.0^a \pm 3.1$	$2.1^a \pm 0.5$	$1.3^{ab} \pm 0.2$	$0.1^b \pm 0$	Mg C ha⁻¹ y⁻¹	13.2	Mg C
LBB	$0.9^a \pm 0.2$	$1.0^a \pm 0.6$	$0.5^{ab} \pm 0.1$	$0.3^{ab} \pm 0.1$	$0.03^b \pm 0$	Mg C ha⁻¹ y⁻¹	2.8	Mg C
SOC 0–10 cm deep	1.8 ± 0.2	2.5 ± 0.8	2.8 ± 0.2	2.4 ± 0.2	2.7 ± 0.1	Mg C ha⁻¹ y⁻¹	17	Mg C

[a,b,c] Rows with different superscripts indicate significant differences ($p < 0.05$)

Annual C accumulation rate in total, living above-ground biomass LAB, living below-ground biomass LBB and soil in the four SPS and pasture in the *Villa Lucero* farm in the Amazon of Colombia

AGC above-ground carbon, *BGC* below-ground carbon, *SOC* soil organic C, *TCS* total carbon stocks. *ACAR* Annual C accumulation rate. Data shown as means ± SE

DBH classes above 20 cm. Concerning the below ground BLG characteristics, the % SOC was higher in the PT (3.2 ± 0.06 g/100 g); when compared to LF (2.5 ± 0.21 g/100 g), FB (2.3 ± 0.19 g/100 g) and FW (2.2 ± 0.03 g/100 g), the ST (2.7 ± 0.24 g/100 g) did not show differences between the systems. The LAB and LBB characteristics in different SPS alternatives and pasture are detailed in Table 4.

C stocks and ACAR

Forty-two percent of the farm (3.7 ha⁻¹) has SPS cover, mainly in ST (1.4 ha⁻¹) and FW (1.3 ha⁻¹). The C in LAB was the largest stock in LF (63.8 ± 17.2 MgCh⁻¹) and FW (48.1 ± 20.8 MgCh⁻¹). The C stock in leaf litter ranged between 1 and 5% of total C in the SPS and was higher in FW (4.1 ± 0.8 MgCh⁻¹). No differences were evident in SOC stocks at 0–10 cm depth. The lowest C stocks in roots were in PT (0.4 ± 0.0 MgCh⁻¹) and FB (3.6 ± 0.8 MgCh⁻¹); this component ranged between 7 and 13% of total C in the SPS and represented 1.2% of total C in PT. The

total and soil ACAR did not differ, whilst the ACAR in LAB in the LF (4.3 ± 1.2 MgCh⁻¹), FW (5.0 ± 3.1 MgCh⁻¹) and ST (2.1 ± 0.5 MgCh⁻¹) were higher when compared to PT (0.1 ± 0 MgCh⁻¹). The FB (1.3 ± 0.2 MgCh⁻¹) had an intermediate ACAR. The total C stocks ranged from 34.4 MgC ha⁻¹ in PT to 105.3 MgC ha⁻¹ in LF. The total ACAR of farm was 33.8 Mg C or 5.0MgC ha⁻¹y⁻¹ including all assessed systems (6.7 ha). The ACAR in farm through LAB was 13.2 Mg C or 2.0 MgC ha⁻¹y⁻¹O_2 and 17.0 Mg C or 2.5 MgC ha⁻¹y⁻¹ through the soil. The carbon stocks and ACAR are detailed in Table 5.

Farm emissions, CFP and C balance

The emissions increased 96% when compared to the first year (27.2 MgCO$_2$e year 1 VS 47.1 MgCO$_2$e year 5) and following the increase in stocking rate AU and the introduction of the swine subsystem in the last year. The CFP per area (3.1 MgCO$_2$e ha y¹ year 1 VS 5.3 MgCO$_2$e ha y¹) and bovine product (19.5 MgCO$_2$eLWG year 1 VS 33.7 MgCO$_2$eLWG year

Table 6 Annual C balance based on the difference between the ACAR in LAB and total emissions in *Villa Lucero* farm in the Amazon of Colombia

Sources	Emissions ($MgCO_2e$)							
	2017	2018	2019	2020	2021	Total	Total ha^{-1}	%
Bovine								
Enteric CH$_4$	24.9	23.3	26.4	31.9	37.3	143.8	16.2	87
Manure CH$_4$	0.2	0.2	0.2	0.3	0.3	1.3	0.1	1
Direct N$_2$O	1.1	1	1.6	1.9	2.2	7.7	0.9	5
Indirect N$_2$O	0.5	0.5	0.7	0.8	1	3.4	0.4	2
Electricity	0.4	0.4	0.4	0.4	0.4	2	0.2	1
Fuel	0.1	0.1	0.1	0.1	0.1	0.3	0	0
Urea	0	0	0	0.01	0.01	0	0	0
Lime	0	0	0	0	0.5	0.5	0.1	0
Mineral salt	0.1	0.1	0.1	0.1	0.1	0.4	0	0
Organic fertilizer	0	0	0	0	5.2	5.2	0.6	3
Total emissions	27.2	25.4	29.5	35.5	47.1	164.6	18.5	100
Total AU	9	8	14	16	18	64		
AU/ha	1	1	2	2	2			
Total LW Mg	4.4	4.1	6.8	7.9	8.8	32		
LW Mg ha y^{-1}	0.5	0.5	0.8	0.9	1			
CFP per area $MgCO_2e$ ha y^{-1}	3.1	2.9	3.3	4	5.3	18.5	3.7	
CFP per product $MgCO_2e$ MgLW ha^{-1}y^{-1}	6.2	6.2	4.3	4.5	5.3		5.3	
CFP per product $MgCO_2e$ LWG	19.5	18.2	21.1	25.4	33.7		23.6	
Swine								
Enteric Methane					2.5	2.5		41
Manure Methane					2.2	2.2		36
Commercial concentrate					1.4	1.4		23
Total emissions					6.1	6.1		100
Total LW Mg					5.4			
CFP $MgCO_2e$ MgLW					1.1			
Total farm emissions $MgCO_2e$ y^{-1}	27.2	25.4	29.5	35.5	53.2	170.8		
CFP surface $MgCO_2e$ ha y^{-1}	3.1	2.9	3.3	4	6	19.2		
Total removals by the ACAR in LAB $MgCO_2e$ ha y^{-1}	7.2	7.2	7.2	7.2	7.2	36		
Balance total year (Total removals–total emissions) $MgCO_2e$ ha y^{-1}	4.1	4.3	3.9	3.32	1.3	16.7		

Estimated emissions in $MgCO_2e$ of bovines and swine on farm over five years. Annual CFP per surface and per product

AU Animal units, *LW* live weight, *LWG* live weight gain, *CFP* Carbon footprint, *ACAR* annual carbon rate accumulation rate (transforated from C to CO_2e through the 3.7 factor), *LAB* Living Above-ground biomass

5) increased 73% in the same proportion. The CFP per product of $MgCO_2e$ MgLW decreased by 13% between 2017 (6.2 $MgCO_2e$ MgLW year 1) and 2021 (5.3 $MgCO_2e$ MgLW year 5). The carbon balance, considering the difference between the ACAR in the LAB (7.2 $MgCO_2eha^{-1}y^{-1}$) on farm (22% in LF, 50% in FW, 4% in FB, 2% in PT and 23% in the ST) and the CFP per area was positive all years. The surpluses of $MgCO_2e$ decreased with the increase of CFP per area (Table 6).

Table 7 Annual Carbon Accumulation Rate ACAR in SPS and PT in different evaluated components at *Villa Lucero* farm in the Colombian Amazon, values are totaled based on the area of each system

Components	LF Live Fence	FW Fallow	ST Scattered Trees	FB Foder Banck	PT Pasture	Total	Unit
Total	18.1	42.6	28.1	4.6	30.5	124.0	$MgCO_2e\ y^{-1}$
Living Above-ground biomass	10.9	24.0	11.1	1.4	1.1	48.5	$MgCO_2e\ y^{-1}$
Living Below-ground biomass	2.3	5.0	2.5	0.3	0.3	10.4	$MgCO_2e\ y^{-1}$
SOC 0–10 cm deep	4.5	11.9	14.3	2.7	29.0	62.3	$MgCO_2e\ y^{-1}$

Table 8 Area required to mitigate the maximum greenhouse gas emissions in year 5 through different components of SPS at *Villa Lucero* farm in the Colombian Amazon

Components	LF Live Fence	FW Fallow	ST Scattered Trees	FB Foder Banck	PT Pasture	Unit
Total	2.1	1.6	2.6	3.5	5.1	ha
Living Above-ground biomass	3.4	2.9	6.7	11.1	133.0	ha
Living Below-ground biomass	16.6	14.6	29.6	48.4	532.0	ha
SOC 0–10 cm deep	8.2	5.8	5.2	6.0	5.3	ha

Scenarios for neutralizing GHG emissions through assimilation of CO_2e with SPS

Based on the GHG removal capacity through the ACAR of SPS in their different evaluated components (total, above and belowground live biomass, and soil) and the area occupied by each SPS in the farm (Table 5), the farm achieves a total ACAR of 124.0 $MgCO_2\ y^{-1}$ (34% FW, 25% PT, 23% ST, 15% LF, and 4% FB). In total, 57.3 $MgCO_2\ y^{-1}$ (46%) is captured by the above and belowground live biomass, and 62.3 $MgCO_2\ e\ y^{-1}$ (50%) is captured by the soil (Table 7). Considering the maximum emission in year 5 (53.2 $MgCO_2\ e\ y^{-1}$, as described in Table 6), the area required to achieve a net zero balance (removals – emission = zero) was determined (Table 7). Thus, this emission can be neutralized with 2.1 hectares of LF, 1.6 hectares of FW, 2.6 hectares of ST, 3.5 hectares of FB, and 5.1 hectares of PT, considering the ACAR with all components. However, if only the ACAR of aboveground biomass is considered, a range of 2.9 hectares of FW to 11.1 hectares of FB is required for total mitigation. In the scenario of considering only the aboveground biomass of pasture, the required area is 133 hectares (Table 8). Considering the area required based on the ACAR in the aboveground live biomass (Table 8) and the density of individuals per hectare in each system (Table 4), 2558 trees are required in LF, 4036 in FW, 8465 in ST, and 17,113 in FB.

The carbon balance (removals–emissions) per year, considering mitigation scenarios through total ACAR, in above and belowground biomass, and soil, are described in Fig. 3. The balance indicates that if the total ACAR is considered, mitigation occurs every year. However, if only the soil is considered, in year 5, the balance is negative. The balance is also positive every year if the above ground biomass ACAR is considered, but negative if only the belowground biomass or roots ACAR is considered.

Discussion

Variability in ACAR of CO_2e in LAB

This study found a potential ACAR in the LAB between 4.8 and 15.6 $MgCO_2eha^{-1}y^{-1}$ in the different SPS assessed. In the context of agroforestry systems, the ACAR in LAB may range from 1.06 to 55.82 $MgCO_2eha^{-1}y^{-1}$ (Nair et al. 2009). In this study, the LF (15.6 $MgCO_2eha^{-1}y^1$) presented the highest assimilation potential. Linear plantations can assimilate up to 33.00 $MgCO_2e\ ha^{-1}y^1$ (Feliciano

Fig. 3 Carbon balance (Emissions–Removals or ACAR) per year at *Villa Lucero* farm in the Colombian Amazon, considering 4 scenarios: total ACAR, soil ACAR, aboveground biomass ACAR, and belowground biomass ACAR
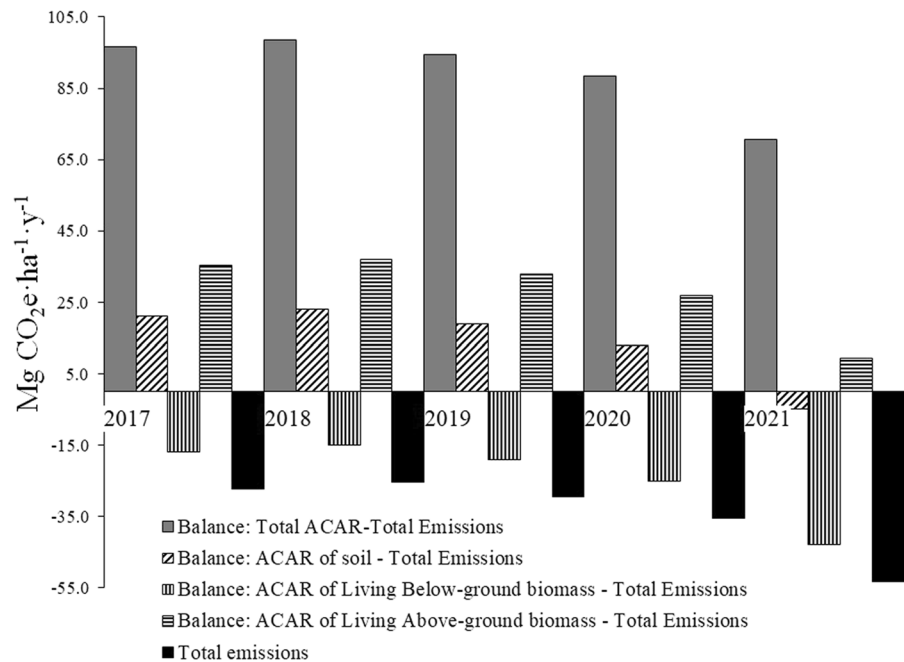
et al. 2018). In the case of Colombia, the general reference average is 5.4 $MgCO_2e$ $ha^{-1}y^1$ (CIPAV et al. 2021) that varies according to the region. FW natural regeneration systems also stand out in their ACAR. The results of this study (18.4 $MgCO_2e$ $ha^{-1}y^1$) are similar to those reported for secondary forests in the Colombian Amazon with 19.4 $MgCO_2e$ $ha^{-1}y^1$ (CIPAV 2021). It is also similar to those reported in 12-year improved FW with 20.40 $MgCO_2e$ $ha^{-1}y^1$ (Feliciano et al. 2018) but is higher than those reported for instance in agricultural landscapes in the Brazilian Amazon in 12-year FW that ranged between 9.2 and 8.4 $MgCO_2e$ $ha^{-1}y^1$ in secondary farm forests and pasture regeneration forests respectively (Fearnside and Guimarães 1996). The reference ACAR in mixed FB for Colombia presents an average of 4.5 $MgCO_2e$ $ha^{-1}y^1$ (CIPAV et al. 2021) similar to the results of this study (4.8 $MgCO_2eha^{-1}y^1$). In intensive SPS with ST in reference pasture for Colombia, they have an assimilation potential of 14.80 $MgCO_2e$ $ha^{-1}y^1$ (CIPAV 2021), higher than the results of this research (7.9 $MgCO_2eha^{-1}y^1$). The assimilation in improved pastures for Colombia is 0.3 $MgCO_2e$ $ha^{-1}y^1$ (CIPAV 2021), similar to the present study (0.4 $MgCO_2eha^{-1}y^1$) and up to 1.50 to 3.00

$MgCO_2eha^{-1}y^1$ in degraded pastures in Brazil (Fearnside and Guimarães 1996).

Such heterogeneity and contrasting results may be explained by the vegetation structure. Indeed, in the LF and FW with higher assimilation capacity, trees above 20 cm DBH accounted for less than 36% of individuals in LF and less than 7% of FW, but contributed 84 and 64% of the C stored in LAB. The abundance of trees below 10 cm DBH accounted for 59% in all SPS. However, they contribute less than 30% of the C in LAB. In ST and FB, trees below 20 cm DBH predominated, and in the case of FB, the density of individuals with DBH between 20 and 40 cm represented 8%. However, they contributed less than 28% of the total biomass, mainly due to the high density of pruned *E. poeppgiana*. The influence of tree density in diameter classes > 20 cm DBH and LAB assimilation potential in agroforestry systems has also been reported in studies such as those by Roncal et al. (2008) or Gómez Cardozo et al. (2018).

Considering that the SPS of the farm does not have a forest harvesting plan, new studies on safe storage in the timber industry and the staggering of new forest production cycles within the farm are necessary to guarantee the neutralization of emissions on

a permanent basis as suggested in experiments on C neutral meat brands (Alves et al. 2017).

Below-ground C

The ST maintained a SOC percentage similar to that of PT without trees. In this system, the SOC % had a slight reduction compared to the PT, which denotes the effect of the interaction of the LAB on SOC %, possibly due to increased competition for light under the canopy and the contribution of leaf litter with different compositional qualities (lignin and polyphenols) that affect the contributions of C in the soil. The PT presented the lowest bulk density, consequently, the lowest volume of C reserves, despite having a predominant clay ratio, which directly influences the incorporation of recent organic matter, mainly from fine roots of grasses that are rapidly renewed and incorporated into the smallest soil particles (less than 0–2 μm) (Nair et al. 2009; Desjardins et al. 2004). Although PT have a higher SOC % they lack the potential to store C in coarse roots which is a component that adds C to bovine agroecosystems and makes them more efficient in terms of gross primary productivity. This research showed that both carbon stock and ACAR in coarse roots in SPP are higher than in open pasture, and they can mitigate approximately 7% of the total farm emissions.

While physical factors such as bulk density and chemical factors such as soil organic matter content influence SOC %, proper pasture management practices play an important role. Pasture rotation practices (45 days recovery and 3 days of occupancy) with stocking rate of 2.0 AU applied on the farm indicate that biomass recovery after harvesting also positively influences the maintenance of soil organic matter content.

On farm GHG emissions

In the bovine subsystem, the highest proportion of GHG emissions corresponds to enteric CH_4 (87%), followed by direct N_2O from urine (5%), and the use of on-farm pig composting (3%). These emissions account for 95% of the total bovine emissions, with only 2% attributed to off-farm resources. These results are similar to reports on cow-calf systems in northern, eastern and central Colombia, with a proportion of 90% for enteric CH_4, 5% for N_2O from excreta, and

2% from supplementation (González-Quintero et al. 2022). Regarding the swine subsystem, this contributes in 4% to the total farm emissions, 76% of the emissions are attributed to CH_4 (41% enteric and 35% manure). In addition to representing a small proportion of total farm emissions, this sub-system also contributes to soil organic enrichment through the application of manure compost, making this sub-system integration advantageous for maintaining adequate organic matter conditions in pastures. In general, at the farm level, 88% of the emissions are attributed to enteric methane and manure. Therefore, it is necessary to improve the productive efficiency and monitoring the proportion of SPS needed to ensure the mitigation of GHG emissions.

CFP per unit of land area and product

The CFP per unit area increases according to the cattle stocking rate and decreases per unit of product due to obtaining higher LW in the same area (Cusack et al. 2021). In this study, with the increase in total LWy^{-1} due to the increase from 1 to 2AU on the farm, the CFP per unit of product was reduced by 13%, evidencing the impact of productive intensification. The CFP per unit of product in grazing livestock systems in Colombia ranges between 11.0 and 16.3 $MgCO_2eha^{-1}y^{-1}$ LWG depending on the region and the degree of technological development of the farm (González-Quintero et al. 2022), in contrast, this indicator in our study ranges between 18. 1 and 33.6 $MgCO_2eha^{-1}y^{-1}$. Such variation is explained by the specific characteristic of the cows of the *Hartón del Valle* breed with 154 kg LWG, contrasting with indicators of meat production systems in northern Colombia with indicators of up to 306.5 kg LWG. Further research is nevertheless required to evaluate the performance of F1 fattening and its impact on CFP.

The CFP per area varies depending on the level of technology adopted. The CFP of 3.5 to 5.3 $MgCO_2e\ ha^{-1}y^1$ with stocking rates between 1 and 2 AU found in this study is similar to the results of Oliveira et al. (2020). In such works, the CFP in pasture-based beef cattle systems with Nellore cows ranged from 3.0 $MgCO_2e\ ha^{-1}y^1$ in degraded pasture systems with 1.4 AU to to 9.1 $MgCO_2e\ ha^{-1}y^1$ in systems with high stocking rate 4.2 AU ha and with intensively managed rainfed pastures of *Panicum maximum* Jacques (cv. *Tanzânia*). Figueiredo

et al. ([2017]), evidenced that for beef cattle systems in Brazil, the CFP was 0.8 $MgCO_2e\ ha^{-1}y^1$ in systems in degraded pastures with (0.5 head ha), 8.4 in improved pastures (4 head ha) and 6.4 in agrosilvopastoral agricultural-livestock-forestry integration systems (3.4 head ha). This research suggests that the increase in stoking rate and the adoption of practices such as artificial insemination, rotational grazing in cow-calf cattle contribute to decrease the CFP, and this can be neutralized with the adoption of SPS at the farm level.

Considering the productivity and CFP indicators presented in both the bovine and swine systems at *Villa Lucero* farm, it is possible to establish that implementing simultaneous actions, focusing on both productive efficiency and the adoption of SPS, is highly promising for reducing the carbon footprint per product and mitigating emissions per area at the farm scale. As evidenced, the farm, with an area of 8.8 hectares and a direct occupancy of 42% in SPS (16% ST, 15% FW, 8% LF, and 3% FB) achieved the mitigation of 91% of the total emissions, through the living aboveground biomass LAB in the fifth year (maximum emissions). When considering the capture in the above and below-ground living biomass, the carbon capture exceeds emissions by 110%. Furthermore, the superiority of SPS over open pasture is evident, as LF, FW, and ST consistently outperform PT in greenhouse gas absorption.

Therefore, for livestock farms with less than 10 hectares and a diversified adoption of SPS along with appropriate productive intensification, it is possible to achieve 100% mitigation of GHG emissions based on the carbon capture of the live biomass (above and below-ground biomass) from SPS. If we consider the CO_2e absorption potential through the ACAR of both, above and below-ground biomass in LF (18.8 $MgCO_2e\ ha\ y-1$), FW (22.3 $MgCO_2e\ ha\ y^{-1}$), ST (9.7 $MgCO_2e\ ha\ y^{-1}$), and FB (5.9 $MgCO_2e\ ha\ y^{-1}$), any of the following areas would be required to mitigate a carbon footprint per area of 55.3 $MgCO_2e\ ha\ y^{-1}$ found in year 5: 2.8 ha in LF, 2.4 ha in FW, 5.5 ha in ST, or 9.0 ha in FB. In the context of Colombia, 57,090 farms (14% of beef cattle farms) have between 5 and 10 hectares (UPRA [2020]), which means that SPS can be scaled up for greenhouse gas mitigation purposes and the utilization of other environmental services, taking into account the agroecological conditions of each region.

Conclusions

The CFP per surface of 6.0 $MgCO_2e\ ha^{-1}y^1$ in integrated farms and cattle CFP per product of 5.3 $MgCO_2eLWy^{-1}$ can neutralize the emissions through CO_2e capture in the above-ground biomass with less than 1 ha in the LF, FW and ST and with 1.3 ha of FB. If ACAR via LAB is considered in PT, it requires an area expansion, making it an unfeasible alternative. Total ACAR in PT based on rotation practices and low external inputs can neutralize the emissions. SPS, as demonstrated by the case study herein presented and that can be a representative example for the Colombian Amazon, have therefore a high potential for neutralizing GHG emissions in cow-calf livestock systems and are much more interesting than the scenario of pasture without trees when considering the LAB. The results presented in this study may furthermore be extrapolated to other tropical regions, namely in Colombia and elsewhere in South America.

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Declarations

Conflict of interest Authors declares no conflict of interest.

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