TREE STRUCTURE, SPECIES COMPOSITION, AND CARBON STORAGE IN TROPICAL SILVOPASTORAL SYSTEMS †

ESTRUCTURA ARBÓREA, COMPOSICIÓN DE ESPECIES Y ALMACENAMIENTO DE CARBONO EN SISTEMAS SILVOPASTORALES TROPICALES

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SUMMARY

Background: Silvopastoral systems, agroforestry with grazing livestock, have a high capacity for carbon sequestration in tree biomass and enhance biological diversity in grasslands, contributing to counteract the negative effects of deforestation led by the expansion of open pasturelands. **Objective:** To assess tree structure, species diversity, and carbon storage in biomass components in three different silvopastoral systems (SPS): 1) scattered trees in pasture (STP), 2) live fences (LF), 3) forest plantations (FP), and compare them with pasture monoculture (PM). **Methodology:** Carbon stock in biomass, relative importance value of tree species, Shannon´s biodiversity, Pileou´s evenness, and Sorenson´s similarity indices were calculated in forty sampling plots, ten for each system in Tabasco, Mexico. **Results:** Biomass stock varied significantly ($P<0.05$) between SPS and PM. FP had the highest carbon stock in the biomass pool with an average of 73.5 $MgCha^{-1}$, followed by STP (45.8), LF (20.8), and PM (9.1). STP system tended to be more diverse with a relatively even distribution of tree species, while tree density per hectare was greater in FP. Species composition and their relative value indices varied between SPS but there was a medium level of similarity between them. Furthermore, we determined an optimum basal area of 14.5 m^2ha^{-1} to harmonize the trade-offs between carbon sequestration in woody biomass and forage production in grass (herbaceous) biomass in these SPS. **Implications:** These results

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are useful to farmers and policymakers in developing and incentivizing climate-smart livestock production systems in line with the Sustainable Development Goals (SDGs). **Conclusion:** SPS are biodiverse and accumulate more carbon in biomass than pasture monoculture. The STP was the most biodiverse, followed by LF and FP, while carbon storage was higher in FP followed by STP and LF. An optimal tree cover with 14.5 m^2ha^{-1} basal area can balance the trade-off between carbon sequestration and forage productivity in SPS.
Key words: Livestock agroforestry; carbon sequestration; tree biomass; grassland management; tree diversity.

RESUMEN

Antecedentes: Los sistemas silvopastoriles, un sistema de agroforestería pecuaria, tienen una gran capacidad de secuestro de carbono en la biomasa arbórea y mejoran la diversidad biológica de los pastizales, contribuyendo a contrarrestar los efectos negativos de la deforestación provocada por la expansión de potreros abiertos. **Objetivo:** Evaluar la estructura arborea, la diversidad de especies y el almacenamiento de carbono en los componentes de biomasa en tres diferentes sistemas silvopastoriles (SSP): 1) árboles dispersos en potrero (ADP), 2) cercas vivas (CV), 3) plantaciones forestales (PF), y compararlos con el monocultivo de pasto (MP). **Metodología:** Se calcularon el almacenamiento de carbono en biomasa, el valor de importancia relativa de las especies arbóreas, la biodiversidad de Shannon, la uniformidad de Pileou y los índices de similitud de Sorenson en cuarenta parcelas de muestreo, diez por cada sistema en Tabasco, México. **Resultados:** El stock de carbono en biomasa varió significativamente ($P<0.05$) entre SSP y MP. PF tuvo el mayor almacén de carbono en la reserva de biomasa con un promedio de 73.5 Mg Cha^{-1}, seguido por ADP (45.8), CV (20.8), y MP (9.1). El sistema ADP tendió a ser más diverso, con una distribución relativamente uniforme de las especies arbóreas, mientras que la densidad de árboles por hectárea fue mayor en PF. La composición de especies y sus índices de valor relativo variaron entre los SSP, pero hubo un nivel medio de similitud entre sistemas. Además, determinamos un área basal óptima de 14.5 m^2 ha^{-1} para armonizar las compensaciones entre el secuestro de carbono en la biomasa leñosa y la producción de forraje en la biomasa herbácea en estos SSP. **Implicaciones:** Estos resultados son útiles para los productores e instituciones políticas en la toma de decisiones sobre la gestión de potreros para el desarrollo de sistemas de producción ganadera climáticamente inteligentes en línea con los Objetivos de Desarrollo Sostenible. **Conclusiones:** Los SSP son biodiversos y acumulan más carbono en biomasa que el monocultivo de pastos. El ADP fue el más biodiverso, seguido de CV y PF, mientras que el almacenamiento de carbono fue mayor en PF seguido de ADP y CV. Una cobertura arbórea óptima de 14.5 m^2ha^{-1} de área basal puede balancear la compensación entre el secuestro de carbono y la productividad forrajera en los SSP.
Palabras clave: Agroforestería pecuaria; secuestro de carbono; biomasa arbórea; manejo de pastizales; diversidad arbórea.

INTRODUCTION

Due to the increase in global animal protein demand, many regions of the world are facing strong pressure of land conversion from native forests to pasturelands (Marques *et al.*, 2019; Pendrill *et al.*, 2022). Such land use change from forests to open pasturelands implies removing a huge amount of carbon stored in woody biomass. Since 1950, south-southeastern Mexico has undergone a strong land use change due to the expansion of cattle ranching (Villanueva-López *et al.*, 2019). For example, in the state of Tabasco, the accelerated land use change has caused the loss of about 90% of the native forests between 1960 and 2010 (Tudela, 1989; Vargas-Simón, 2019). This loss of humid tropical forests has led to significant levels of ecosystem degradation and biodiversity decline (Pinkus-Rendón and Contreras-Sánchez, 2012). Most of the current pasturelands in this region and in many parts of the globe are grass monoculture without trees (Villanueva-López *et al.*, 2015). This has completely altered the vegetation structure, plant species composition, micro-climate, and the size of the biomass carbon pool (Gallardo-Cruz *et al.*, 2021; Aryal *et al.*, 2024). The loss of forest cover also led to the fragmentation of the landscape, breaking habitat connectivity for wildlife (Qu *et al.*, 2024). Some studies also pointed out that land use change from forests to pasture monoculture caused a significant depletion of soil nutrient reserve and deteriorated the overall soil health conditions (Aryal *et al.*, 2018; Merino *et al.*, 2023). The changes in vegetation structure and species composition from highly diverse forested ecosystems to pasture monoculture also alter the community of soil organisms and their activity, leading to the degradation of soil biological properties (de Souza *et al.*, 2023; Qu *et al.*, 2024). Furthermore, carbon sequestration and storage rates are smaller in open pasturelands due to the absence of woody biomass, which, if combined with the poor forage quality of the grasses, lowers the potential to offset the emissions of greenhouse gases (GHG) from livestock farms (Casanova-Lugo *et al.*, 2022).

This scenario has prompted the development of alternatives to counteract deforestation and mitigate climate change in the livestock sector (Contreras-Santos *et al.*, 2023). Silvopastoral systems (SPS) are considered one of the alternatives to address the problems related to land use change for pastureland establishment (López-Santiago *et al.*, 2019). SPS are livestock agroforestry systems with trees or shrubs on grasslands, where environmental and animal production benefits are optimized through the enhancement of biodiversity and ecosystem services (Mackay-Smith *et al.*, 2023; Fernández *et al.*, 2024). Carbon sequestration is one of the ecosystem services that can be improved through silvopasture due to the accrual and accumulation of carbon in woody biomass and its translocation into the deeper soil horizons (Villanueva-López *et al.*, 2015). These systems can contribute large amounts of organic matter, through the accumulation of leaf litter and fine roots, improving the physical, chemical, and biological conditions of the soil (Sotelo Cabrera *et al.*, 2017; Dollinger and Jose, 2018; Contreras-Santos *et al.*, 2023; Vásquez *et al.*, 2021). Atmospheric carbon sequestration and forage quality improvement through silvopasture are vital to offset enteric methane and other sources of GHG emissions at the farm level (Valenzuela-Que *et al.*, 2022). In addition to GHG mitigation through carbon sequestration, silvopastoral systems (SPS) contribute to climate change adaptation of plants and animals by regulating micro-climate within the livestock ranches due to tree canopy cover and vertical stratification (Schinato *et al.*, 2023).

In this regard, several studies indicate that managing pastures without shade causes animals to suffer heat stress, while pastures with tree cover as in SPS improve animal welfare by reducing heat stress. In addition, cattle spend more time ruminating and resting under tree shades in SPS, positively influencing productive and reproductive indicators (Skonieski *et al.*, 2021). Other studies indicate that pastures growing under tree cover can favor forage growth and produce a large amount of edible biomass, even with better fiber and protein content than grass growing in full sun (Castillo *et al.*, 2020; Casanova-Lugo *et al.*, 2022). Furthermore, the shade of woody plants in SPS helps to maintain higher soil and environmental moisture, which reduces water loss from the system by evapotranspiration as a result of the lower temperature in the herbaceous layer and keeps the grass green for a longer time than in open pasturelands (Castillo *et al.*, 2020). Trees in SPS also have commercial or environmental uses such as timber, fiber, and biofuels, among others (Villanueva-Partida *et al.*, 2016; Fernandes *et al*., 2018). SPS such as live fences (hedgerows) contribute to connecting habitats for the mobility of wild fauna within the fragmented landscapes, while the diversity of tree species scattered on pasturelands provide food and shelter for fauna, both contributing to the conservation of biodiversity (Kremen and Merenlender, 2018; Villanueva-López *et al.*, 2019; Lara-Pérez *et al.*, 2023).

Therefore, assessing vegetation structure, plant species diversity, and C storage in biomass among different SPS has become increasingly important. However, there are huge variations in the amount of carbon storage, related to the design, vegetation structure, and tree species composition of the SPS (Schinato *et al.*, 2023; Esquivel *et al.*, 2023). Different types of SPS are found in southeastern Mexico, the most common include scattered trees on pastureland (STP), live fences around pasture (LF), and forest plantations with occasional grazing (FP). Carbon storage in plant biomass in these SPS varies because of the differences in plant community composition, vegetation structural attributes, and tree density per hectare. The diversity of plant species composition, biomass storage, vegetation structure, and the ideal tree cover for optimizing carbon sequestration and forage biomass production in different SPS have not been studied widely. Therefore, this study aimed to quantify carbon storage, species diversity, and tree structure in three silvopastoral systems and compare them with pasture monoculture. We also determined the optimal tree cover to harmonize the trade-off between forage production and carbon sequestration in these tropical silvopastoral systems of the region. We hypothesize that SPS with higher woody cover stores more carbon in biomass, but ideal tree cover should optimize the trade-offs between grass biomass and woody species biomass.

MATERIALS AND METHODS

Area of the study, livestock systems, and sample plots

This study was carried out in localities of the Canyon de Usumacinta flora and fauna protection area in Tenosique, Tabasco, Mexico (Figure 1). According to the Köppen classification, the region's climate is Af: warm humid with abundant rainfall in summer and rainfall throughout the year with an average of 1500 to 2500 mm per year.

Study plots are found within an altitude between 50 - 150 m above sea level with an average temperature of 28 °C (Pease *et al.*, 2023; INEGI, 2010). The prevailing soils in the grazing plots are vertisols, gleysols, phaeozems, and cambisols (Geissen *et al.*, 2009). The sampling sites are distributed in the ejidos of San Marcos, Redención del Campesino, Bejucal, Francisco Villa, Ignacio Allende, Repasto, and Miguel Hidalgo, where they mainly practice large-scale cattle ranching and rain-fed agriculture.

For the selection of the silvopastoral systems, ejido authorities from the localities located in the Usumacinta River Basin were visited to inform them of our presence in the area, then a cooperating producer was contacted to carry out a transect throughout the basin to identify sites and each landowner was visited to request permission to enter the plots. Four livestock systems were selected for the study (Figure 2): a) Grazing under forest plantations (FP), b) scattered trees in pastures (STP), c) live fences around pastures (LF), and d) pasture monoculture (PM). FP consists of the plantation of commercial woody tree species at high density with understory vegetation occasionally grazed with cattle, with around 20 to 25 years of establishment. Different species of trees are found dispersed without any specific order within paddocks in STP, with around 21 to 30 years of establishment. Trees are planted on the perimeter of the pastureland as fences to delimit the land in LF. PM systems are open grasslands without trees. *Urochloa decumbens* and *Cynodon plectostachyus* are the most common grass species in these silvopastoral and open pasture systems with about 25 to 35 years of establishment. These grasses are introduced and cultivated grasses found to be established by farmers.

Trees, grass, and litter sampling

Forty plots, ten for each grazing system, with different dimensions but all with an area of 1000 m^2 each were delimitated to sample biodiversity, tree species composition, vegetation structure, and carbon storage in biomass. The sample plots were rectangular with a dimension of 20 X 50 m^2 in the FP systems, circular with a radius of 17.80 m in STP and PM, and 100 m linear in LF. In each plot, an inventory of all the trees of ≥7 cm diameter at breast height (DBH) was carried out, identifying the taxonomic and common names. DBH was measured with a diametric tape at a height of 1.3 m, and the total height (H) with a Criterion RD 1000 laser gun (Laser technology). Each tree's basal area was calculated using DBH and summed to estimate the plot level values. Tree density was calculated by extrapolating the number of trees inventoried at each plot (1000 m^2) to one hectare (10,000 m^2) area for STP and FP. For the purpose of comparison between systems, 100 m linear sampling in LF was converted to per hectare based on the assumption that the periphery of a one-hectare paddock is 400 m linear distance that is shared with the surrounding paddocks. In that way, a one-hectare paddock corresponds to a 200 m linear distance. Therefore, both C storage and tree density data in LF were extrapolated to a 200 m linear distance corresponding to a hectare paddock. Grass biomass and leaf litter on the ground surface were sampled by harvesting and collecting the biomass or litter within four 0.25 m^2 square frames distributed randomly within each plot. Samples were oven-dried, weighed, and extrapolated to one-hectare area.

Tree biomass, species composition, and diversity indices

The aboveground biomass of the trees was calculated using the allometric equation (eq. 1) developed for tropical tree species (Chave *et al.*, 2014).

$$AGB = 0.0673*(\rho*D^2*H)^{0.976} \text{ ------------------- eq. 1}$$

where AGB is aboveground biomass (kg weight), ρ is wood density (g cm^{-3}), D is diameter at breast height and H is total tree height (m). Wood density data was collected from different sources including the world wood density database (Zanne *et al.*, 2009; Aryal *et al.*, 2022a; Chan-Coba *et al.*, 2022). The biomass values of individual trees within a plot were summed and converted to Mg ha^{-1}. A carbon fraction 0.47 was used to convert biomass values to C stock (Martin *et al.*, 2018).

The trees' root biomass was calculated using an AGB-based allometric equation (eq. 2) (Cairns *et al.*, 1997).

$$RB = \exp(-1.085+0.926*\mathrm{Ln}\ (AGB) \text{ ----------- eq. 2}$$

Where RB is the root biomass of the tree (kg dry weight) and AGB is the aboveground biomass (kg dry weight).

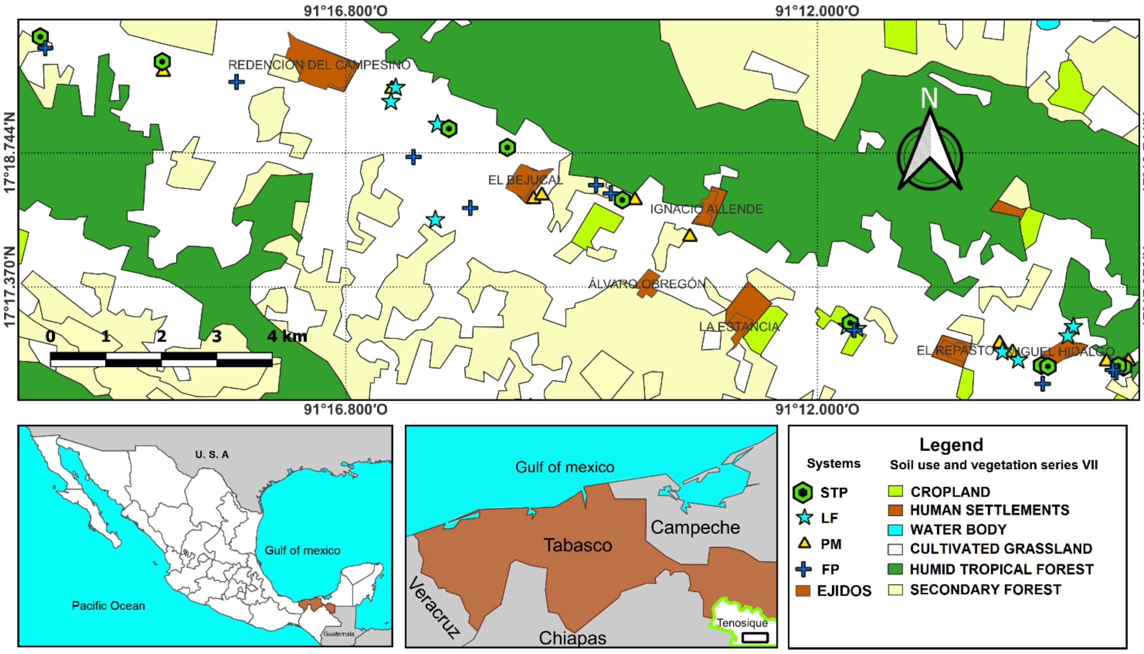

Figure 1. Study site and location of sample plots in Tenosique, Tabasco, Mexico. STP = scattered trees on pastureland, LF = live fences, FP = forest plantations, PM = pasture monoculture. (Source: own elaboration).

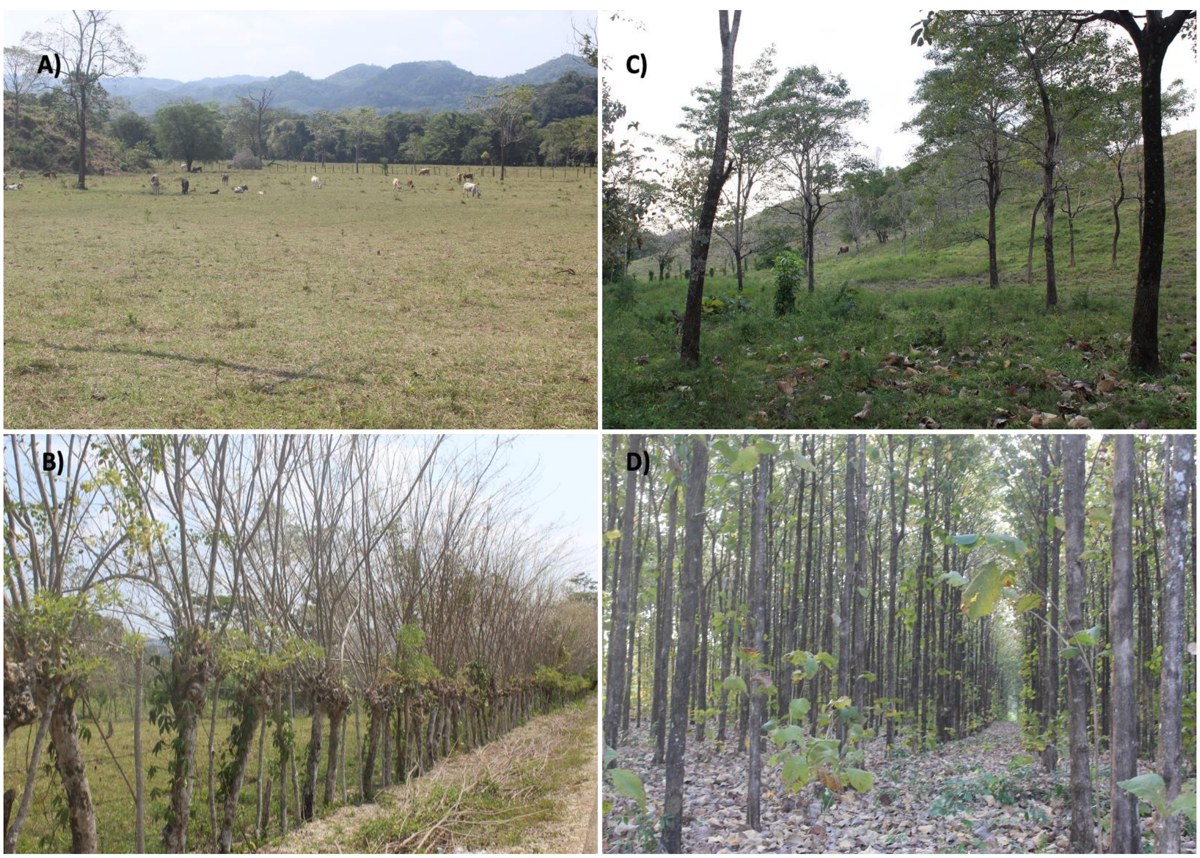

Figure 2. Representation of the four livestock systems studied. A) pasture monoculture (PM), B) live fence (LF), C) scattered trees in pastureland (STP), and D) forest plantation (FP). (Photographs of Aryal D. R.).

To compute the relative importance value index, we used basal area (dominance), the number of individuals of each species (abundance), and the number of records or plots where the particular species were inventoried (frequency). The relative dominance was calculated as the ratio between the basal area of the particular species to the total basal area of all species. The relative abundance was the ratio between the number of individuals of a particular species and the total number of individuals of all the species in a particular system. The relative frequency was the proportion between the number of plots of a particular species to the total number of plots for each system. We then summed the relative dominance, relative abundance, and relative frequency to determine the relative importance value index (Mueller-Dombois and Ellemberg, 1974; Díaz-Gallegos *et al.*, 2002). We calculated Shannon's diversity index (H) (eq. 3) (Shannon, 1949), Pielou's evenness index (J) (eq. 4) (Pielou, 1966), and Sorenson's similarity coefficient (eq. 5) (Sorensen, 1948). The species richness calculation was based on the number of trees recorded within the study area of 1000 m^2.

Diversity index of Shannon (H)= $-\sum pi*Ln(pi)$ eq. 3

Evenness index of Pileou (J) =H*Ln(S) ------- eq. 4

Similarity coefficient of Sorenson (CC) = 2C/(S1 + S2) -- eq. 5

Where pi is the proportion (n/N) of individuals of a particular tree species (n) divided by the total number of individuals of all species found (N), Ln(pi) is the natural logarithm of Pi, S is the total number of tree species in the plot respectively, C = number of species sharing two systems, S1 = number of species in one system, and S2 = number of species in another system. A higher H index means that the SPS is more diverse in terms of tree species. The evenness index (J) is low when only a few species are more abundant than others (Monarrez-Gonzalez *et al.*, 2020). CC is 0 when species composition is completely dissimilar and 1 when there is a complete overlap (sharing) of species between two communities.

Data analysis

To know whether the data distribution complied with the normality, Kolmogorov-Smirnov tests were applied. The normal data were subjected to one-way analysis of variance (ANOVA) to test the effect of silvopastoral systems on C stocks in tree biomass, grass biomass, and litter pools as well as the species diversity indices. Where significant, a Tukey HSD test at a 95 % significance level was used to determine the significant differences between system means. Where relevant, we calculated the respective 95% confidence intervals of each mean. Linear regression analysis was performed to test the relationship between tree biomass, basal area, and grass biomass stocks. For these linear models, tree biomass and grass biomass were taken as response variables, while basal area was considered as an explanatory variable. The respective R^2 values were considered to assess the goodness of fit between the observed data and the regression models. Data analyses were performed with Statistica software version 10.0 for Windows (StatSoft, Inc. 2010).

RESULTS

Woody species composition and diversity

A total of 1130 individuals of 21 different species were recorded across all the silvopastoral systems. On average, they represent 283 individuals per ha, with DBH ≥1 cm). The relative importance value index showed that *Cedrela* odorata and *Tabebuia rosea* were the most dominant species in the STP system (Figure 3A), *Gliricidia sepium* in the LF (Figure 3B), and *Tectona grandis* in PF (Figure 3C). The average number of species ranged from 11 to 15 in each system.

The Shannon's biodiversity index ranged from 0.29 to 0.56; higher values indicate a higher diversity. The highest values were found in STP compared to the other silvopastoral systems (Table 1). The Pileou's Evenness index ranged from 0.41 - 0.74, where the higher values indicated a more even distribution among tree species within the system. STP had a higher evenness value compared to LF and FP. Sorenson´s similarity coefficient values ranged from 0.59 to 0.62, the higher values indicate that the greater number of species are shared between two systems (Table 1).

The tree basal area differed significantly between silvopastoral systems ($F = 250.6$; $P<0.01$), which ranged between 4.2 and 17.0 m^2 ha^{-1} (Figure 4). The highest basal area was found in the FP followed by STP and LF (Figure 4). The tree density per hectare was significantly higher in FP (689 trees ha^{-1}) compared to STP (116 trees ha^{-1}) and LF (130 trees ha^{-1} or per 200 m linear distance). A higher basal area but a smaller tree density in STP indicates that trees in this system were bigger on average than in the other two systems (Figure 4).

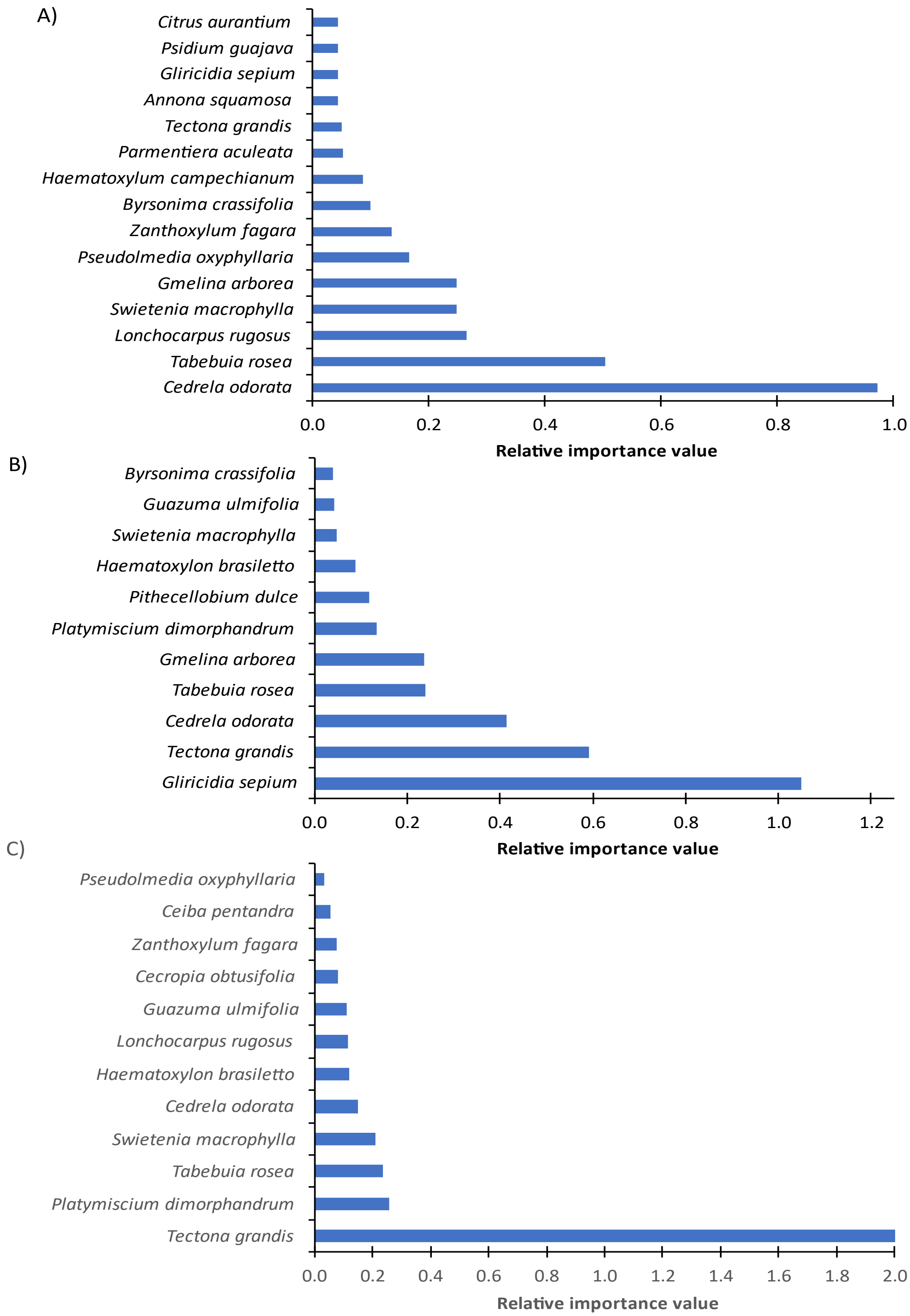

Figure 3. Floristic composition (presented as the relative importance value index) of the different silvopastoral systems: A) scattered trees in pasture, B) live fence, and C) forest plantation.

Table 1. Shannon´s diversity index, Pileou´s evenness index, and Sorenson´s similarity coefficient between silvopastoral systems for tree species. FP = forest plantation, STP = scattered trees in pasture, LF = live fence silvopasture, CI = confidence interval, S1, and S2 indicate the number of species in livestock systems 1 and 2.

Ecological indices		FP	STP	LF
Shannon´s diversity index				
	Mean	0.286	0.555	0.429
	Std. error	0.115	0.177	0.113
	-95% CI	0.025	0.155	0.175
	95.% CI	0.547	0.954	0.684
Pileou´s evenness index				
	Mean	0.407	0.735	0.473
	Std. error	0.216	0.290	0.147
	-95% CI	-0.082	0.078	0.141
	95% CI	0.896	1.391	0.806
Sorenson´s similarity coefficient				
	Common	S1	S2	Sorenson´s coefficient
FP-STP	8	12	15	0.59
FP-LF	7	12	11	0.61
LF-STP	8	11	15	0.62

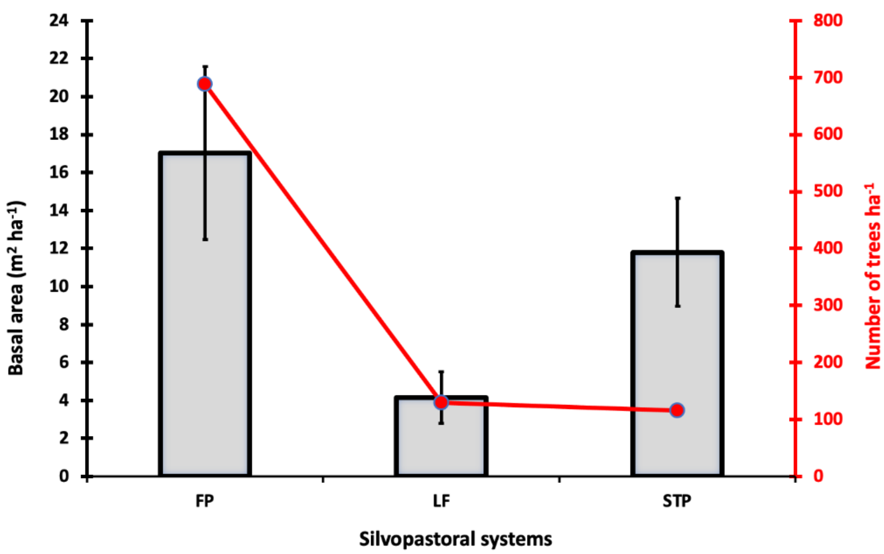

Figure 4. Basal area (m^2 ha^{-1}) and tree density (number of individuals ha^{-1}) among silvopastoral systems. FP: forest plantations, STP: scattered trees in paddocks, LF: live fences. The number of trees and basal area in LF were converted from 100 m linear sampling to per hectare assuming the 200 m linear distance that corresponds to one-hectare paddock. Error bars represent the respective 95% confidence intervals.

Biomass carbon storage

Carbon storage in silvopastoral systems in aboveground biomass presented statistically significant differences (F = 9.22, P = 0.00) between the three silvopastoral systems (Table 2). This was higher in forest plantations with 54.58 Mg C ha^{-1} (Table 2). It was lower in LF which stored 10.71 Mg C ha^{-1}. Root biomass stock also followed the FP>STP>LF trend. The number of trees present and their size influenced aboveground biomass carbon storage (Figure 3). Grass biomass presented statistically significant differences (F = 6.22, P = 0.001) between silvopastoral systems. Pasture monoculture showed higher grass biomass (9.07 Mg C ha^{-1}), followed by LF, STP, and FP (Table 2). Litter mass also presented significant differences among systems (F = 5.71, P = 0.002), but PF had the highest litter stock, followed by STP and LF. Litter stock was null in PM (Table 2). The total carbon stored in biomass showed statistically significant differences ($F=16.32$, $P < 0.01$) between silvopastoral and pasture monoculture systems, being higher in forest plantations where they stored 73.47 Mg C ha^{-1} (Table 2). It was lower in pasture monoculture pasture where they stored only 9.07 Mg C ha^{-1}, STP and LF silvopasture stored 4.1- and 1.3-times higher carbon stock in biomass component than pasture monoculture.

Optimal tree cover for C sequestration and grass biomass for animal forage

Across all silvopastoral systems, there was an inverse relationship between tree biomass and grass biomass stocks when regressed with basal area (Figure 5). Tree biomass increased with the increase in basal area as expected but grass biomass decreased with increasing basal area. The point of intersection between tree biomass and grass biomass regression lines determined about 14.5 m^2 ha^{-1}, with the tree biomass stock of 40 Mg C ha^{-1} and grass biomass stock of 5 Mg C ha^{-1}. This basal area could be considered an ideal amount of tree cover to optimize carbon sequestration and forage availability in these silvopastoral systems (Figure 5).

DISCUSSION

Differences in species composition and diversity among silvopastoral systems

Compared to pasture monoculture, silvopastoral systems enhanced plant species diversity with small differences between scattered trees on paddocks and live fences but greater than in forest plantations. The diversity of tree species tended to be higher in STP than in LF or FP, but we found a high variation between sampling plots of the same systems. The higher richness and more even distribution among species in scattered tree silvopasture were due to the presence of multiple species with distinct tree architecture, which is not common in live fences and forest plantations. The composition of the species differed among SPS because farmers generally choose different species for different systems as per their criteria such as resprouting capacity after pruning, tree architecture, primary or secondary growth type,

Table 2. The amount of carbon in above-ground and below-ground biomass (Mg C ha^{-1}), grass biomass, ground litter, and total stock among three silvopastoral systems. FP = forest plantations, STP = scattered trees in pasture, LF = live fences. Lowercase letters in superscript indicate significant differences (P<0.05) between systems, CI: confidence interval, N: sample size. Tree biomass in LF was converted from 100 m linear sampling to per hectare considering the 200 m linear distance that corresponds to a one-hectare paddock.

System	Carbon stock (Mg C ha^{-1})	Std. error	-95% CI	+95% CI	N
Tree aboveground biomass					
FP	54.58^{b}	11.37	28.84	80.33	10
STP	33.25^{ab}	4.79	22.39	44.11	10
LF	10.71^{a}	2.00	6.18	15.24	10
Tree root biomass					
FP	9.61^{b}	1.84	5.43	13.78	10
STP	5.25^{a}	0.70	3.66	6.84	10
LF	1.79^{a}	0.30	1.10	2.47	10
Grass biomass					
FP	4.13^{a}	1.05	1.75	6.51	10
STP	4.87^{a}	0.46	3.82	5.92	10
LF	6.05^{ab}	1.01	3.75	8.36	10
PM	9.07^{b}	0.82	7.20	10.94	10
Litter mass on the ground surface					
FP	5.13^{b}	1.49	1.74	8.52	10
STP	2.44^{a}	0.78	0.67	4.21	10
LF	2.27^{a}	0.48	1.18	3.37	10
PM	0.00^{c}	0	0	0	10
Total biomass stock					
PF	73.47^{b}	12.71	44.72	102.23	10
STP	45.83^{c}	5.65	33.04	58.61	10
LF	20.84^{ac}	2.42	15.36	26.32	10
PM	9.07^{a}	0.83	7.21	10.94	10

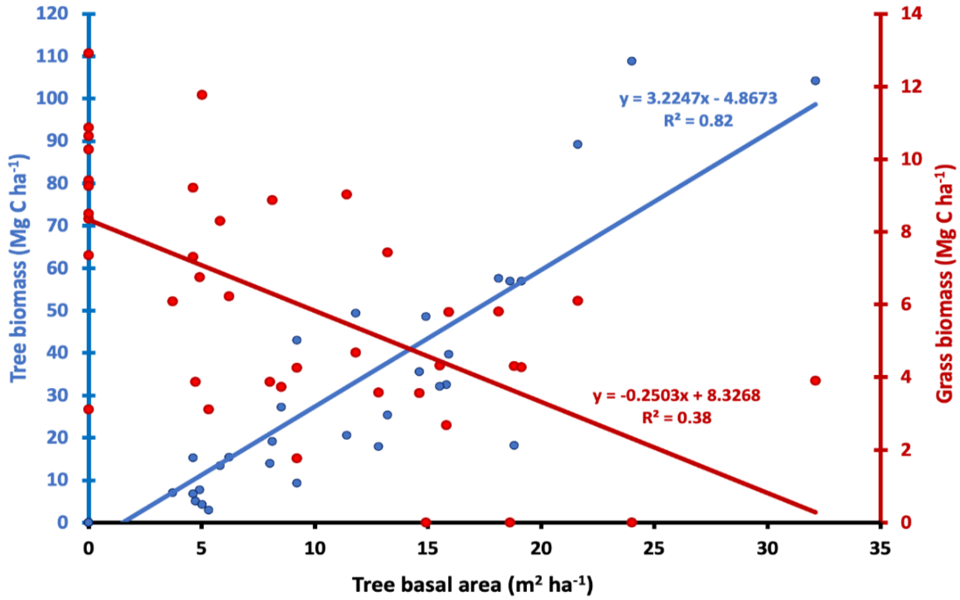

Figure 5. Relationship between tree biomass and grass biomass stocks (Mg C ha^{-1}) with basal area (m^2 ha^{-1}).

wood quality, propagation method, forage potential, and the adaptability to the particular land use (Kumar *et al.*, 2022; Steinfeld *et al.*, 2024). Forest plantations were mainly established with one or a few woody commercial species such as *T. grandis*, *Platimiscium dimorphandrum*, or others. Live fences were dominated by *G. sepium* trees for their quality of resprouting after pruning and the ease of propagation by branch cutting. Species with light seeds for dispersal to wider areas such as *T. rosea* and *C. odorata* are found common in scattered tree silvopasture. Compared to pasture monoculture, these SPS improve many regulating services in grazing lands by providing shade to the animals that improve the animal health and wellbeing, capturing atmospheric carbon dioxide, and improving soil health through organic matter input, in addition to supplying commercial wood and poles for fencing (De la Cruz-López *et al.*, 2023; Alcudia-Aguilar *et al.*, 2024). Higher tree density and diversity increase carbon stocks and regulate micro-climate in silvopastoral systems, thus improving animal welfare (Castillo *et al.*, 2020). Tree species diversity in these livestock agroforestry systems provides feed and habitat for diverse fauna groups, contributing to protecting wildlife (Villanueva-López *et al.*, 2019; Lara-Pérez *et al.*, 2023). Though not focused in this study, tree species diversity in these SPS contributes to connecting habitats and linking biological corridors among nearby natural reserves such as Cañon de Usumacinta flora and fauna protection area.

Despite these benefits, there is a tendency to decrease the abundance of individuals and species diversity because the landscape composition is increasingly dominated by a few species due to animal selectivity, availability of economic resources, and producers' decisions on managing their paddocks. This is because farmers choose species based on the uses and customs of forest resource utilization, the maintenance and replacement of native forest trees in their pastures with those species that represent a benefit in terms of their uses, such as the production of timber, poles, firewood, and particularly shade, fruits and higher nutritional quality fodder for their animals; planted species (often including exotic species) that contribute to improving their livelihoods and generating income (Villanueva-Partida *et al.*, 2016; Villanueva-López *et al.*, 2019). The adoption of agroforestry practices with a higher richness of tree species is therefore fundamental to reconvert the deforested landscapes into biodiverse silvopastoral systems as a strategy for the sustainability of livestock farming in the region in the medium to longer term and reduce the pressure on native tropical forests in the region (Kremen and Merenlender, 2018; Aryal *et al.*, 2022b; Cach-Pérez *et al.*, 2022).

Importance of the tree species

The twenty-one tree species identified in this study belong to 12 families, and most of them were found to have multiple uses (Ramirez-Marcial *et al.*, 2012). As per the information obtained from the ranchers´ interviews, nine local uses of the tree species were identified in addition to carbon sequestration (Table 3). The main category of use was timber sale, followed by use as fuel (firewood) paired with timber for poles, shade, and forage for livestock This was followed by the use of boards for the construction or arrangement of houses, followed by wood to design furniture, source of seeds to reproduce plants in nurseries, and fruits for family consumption. Of the total number of species reported, seven are introduced species such as *Gmelina arborea, Mangifera indica, Citrus sinensis, Theobroma cacao, Annona muricata*, and *Psidium guajava*, which are well accepted by farmers to produce them and obtain benefits such as fruit consumption. Plant propagation is mostly by seed with species native to the region but the cutting method is used to propagate *G. sepium* for live fences. Three of the species found in these SPS such as *T. grandis, C. odorata*, and *Swietenia macrophylla* are found in the IUCN red list to be in danger or vulnerable to extinction. Environmentally, they are highly important because of the use given by the producers as they are the species known by locals as food or habitat for birds and other species of fauna that inhabit the region (Soto-Pinto *et al.*, 2010). The services of habitat and biological corridors provided by these tree species in the livestock-dominated and fragmented landscapes in the region are extremely important because the study site is submerged within the natural protected area “Cañon del Usumacinta flora and fauna protection area”. Socially, the native and introduced species are given multiple uses and known by the producers for their specific values, for example, *T. grandis, G. arborea, C. odorata* and *S. macrophylla* are good quality wood for various purposes.

Carbon contribution of the silvopastoral systems compared to grass monoculture

Biomass contribution of SPS has been reported in other studies but the amount varies with species composition, age, tree density, and the typology of the system (López-Hernández *et al.*, 2023; Schinato *et al.*, 2023). The differences in biomass stocks among SPS in this study are principally explained by the differences in the arrangement of trees, their density per hectare, and species composition. The amounts of carbon stored in tree biomass are found within the reported range (Table 4).

Table 3. Most important tree species sampled in silvopastoral systems and their main uses within the Usumacinta River Basin in six ejidos (Redención del Campesino, Bejucal, Ignacio Allende, Francisco Villa, Repasto, and Miguel Hidalgo) of Tenosique, Tabasco, Mexico.

Local name	Scientific name	Uses	IUCN species extinction status
Teca	*Tectona grandis*	1, 4, 6, 7, 8	Endangered
Cedro	*Cedrela odorata*	1, 4, 6, 7, 8	Vulnerable
Hormiguillo	*Platymiscium dimorphandrum*	1, 2, 3, 4	Least concern
Macuili	*Tabebuia rosea*	1, 4, 6, 7	Least concern
Caoba	*Swietenia macrophylla*	3, 4, 7, 8	Endangered
Mata buey/xalteco	*Lonchocarpus rugosus*	3, 4, 8	Least concern
Melina	*Gmelina arborea*	1, 4, 7	Least concern
Nance	*Byrsonima crassifolia*	2, 3, 9	Least concern
Caulote	*Guazuma ulmifolia*	2, 4, 5	Least concern
Cocohite	*Gliricidia sepium*	3, 4, 5	Least concern
Palo Brasil	*Haematoxylon brasiletto*	2, 3	Unknown
Tinto	*Haematoxylum campechianum*	2, 3	Least concern
Guamúchil	*Pithecellobium dulce*	2, 5	Least concern
Chío/tomatillo	*Pseudolmedia oxyphyllaria*	3, 4	Unknown
Naranja agria	*Citrus aurantium*	2, 9	Unknown
Anona	*Annona squamosa*	9	Least concern
Guayaba	*Psidium guajava*	9	Least concern
Lomo de lagarto	*Zanthoxylum fagara*	4	Least concern
Guarumbo	*Cecropia obtusifolia*	4	Least concern
Ceiba	*Ceiba pentandra*	4	Least concern
Cuajilote	*Parmentiera aculeata*	4	Least concern

The species were classified into nine main uses: 1) Commercialized timber, 2) Firewood, 3) Posts, 4) Shade, 5) Forage, 6) Planks for construction or repair of houses, 7) Manufacture of furniture, 8) Collection of seeds to produce nursery plants, 9) Edible fruits (information obtained from ranchers).

Table 4. Comparison of carbon in systems silvopasture and pasture monoculture reported by different studies.

Silvopastoral systems	Climate and study region	C storage (Mg ha^{-1})		References
		Pasture monoculture	Silvopasture	
Scattered trees silvopasture and Live fence	Humid tropics, Center, Tabasco, Mexico	n/d	25.5 – 30.6	De la Cruz-López *et al.*, 2023
Alley silvopasture of *Leucaena leucocephala* vs pasture monoculture	Sub-humid tropics, Chiapas, Mexico	6.9	15.5	López-Hernández *et al.*, 2023
Scattered trees silvopasture vs. pasture monoculture	Humid tropics, Tacotalpa, Tabasco, Mexico	16.3	69.5	Valenzuela-Que *et al.*, 2022
Silvopastoral system vs pasture monoculture	Sub-humid tropics, Campeche, Jalisco, Chiapas, Mexico	3.1	40.2	Aryal *et al.*, 2022b
Silvopastoral systems vs pasture monoculture	Sub-humid tropics, Chiapas, Mexico	6.2	44.5	Morales-Ruiz *et al.*, 2021
Pasture monoculture	Humid tropics, Center, Tabasco, Mexico	14	n/d	Ramos-Hernández and Martínez-Sánchez, 2020
Silvopastoral system vs pasture monoculture	Humid tropics, Turipana, Monteria, Colombia.	38.3	65.1	Contreras-Santos *et al.*, 2023
Scattered trees silvopasture vs. pasture monoculture	Sub-humid tropics, Chiapas, Mexico	12.9	34	Aryal *et al.*, 2019
Live fences vs pasture monoculture	Humid tropics, Tacotalpa, Tabasco, Mexico	15.3	22.4	Villanueva-López *et al.*, 2015
Silvopastoral system vs pasture monoculture	Humid tropics, Huatusco, Veracruz, México.	49.9	63	Torres-Rivera *et al.*, 2011
Live fence silvopasture vs. pasture monoculture	Tenosique, Tabasco, Mexico	9.1	20.8	This study
Scattered trees silvopasture vs. pasture monoculture	Tenosique, Tabasco, Mexico	9.1	45.8	This study
Forest plantation vs. pasture monoculture	Tenosique, Tabasco, Mexico	9.1	73.5	This study

Woody species biomass stocks ranged between 2.2 to 43.9 Mg C ha^{-1} in southeastern Mexico, depending upon the type of silvopastoral system and the geographic regions (Aryal *et al.*, 2022b). In a Colombian silvopastoral system, (Hernández-Núñez *et al.*, 2021) reported 24.5 Mg C ha^{-1}, where the highest amount of carbon was stored by the tree species Fabaceae, Lauraceae, and Primulaceae families. Carbon sequestration through silvopasture has a significant contribution in offsetting the total greenhouse gas emissions from the livestock sector (Brook *et al.*, 2022; Mavisoy *et al.*, 2024). In the xeric forest biome of Argentina, Utello (2024) simulated that silvopastoral systems with tree basal area of 17.5 m^2 ha^{-1} and a biomass of stock of 38.9 Mg C ha^{-1} capture 0.67 Mg C ha^{-1} year^{-1}, which potentially offset total GHG emissions from livestock. Valenzuela-Que *et al.* (2022) found that STP with a high density of diverse tree species such as *Cordia alliodora, C. odorata, Ceiba pentandra, C. sinensis, Persea americana*, *M. indica*, *Bursera simaruba*, *Vatairea lundellii, Garcinia intermedia and Diphysa robinioides* stored 59% more C than in PM in Tacotalpa, Tabasco. López-Santiago (2019) in this same region found that STP associated with *Brachiaria brizantha* grass stored a total of 13 Mg C ha^{-1} in biomass. Another study reported that a medium to high tree density silvopasture stored 65 – 73 Mg C ha^{-1} compared to 40 Mg C ha^{-1} in open pasture and 65 Mg C ha^{-1} in natural woodland in Argentinian Chaco region, where the medium tree density silvopasture showed a better trade-off with beef production (Fernández *et al.*, 2024). Increasing tree biomass in SPS has also been linked to the improvement of physicochemical properties, fertility, and overall soil health, especially in restoring degraded lands, which should be further studied in these systems (Vásquez *et al.*, 2021).

CONCLUSIONS

Carbon storage in living biomass varied between silvopastoral systems and pasture monoculture and was found in the order of forest plantation > scattered trees in pasture > live fences > pasture monoculture. Vegetation structural attributes such as tree density per hectare and basal area explained the differences in carbon storage among silvopastoral systems. Tree species composition differed between silvopastoral systems but they share some of the species with each other, evidenced by Sorenson´s similarity coefficient. Scattered trees in pasture systems had a more even distribution of tree species while live fences and forest plantations were dominated by a few species as demonstrated by Pileou´s evenness index. STP was more biodiverse, followed by LF and FP. The determined basal area (14.5 m^2 ha^{-1}) could be considered an ideal amount of tree cover to optimize carbon sequestration and forage availability in these silvopastoral systems. Research on the role of vegetation attributes to soil organic carbon storage is required to assess the importance of trees to the whole carbon pool among these silvopastoral systems. The contribution of the silvopastoral systems to offset the net greenhouse gas emissions from livestock farms is the subject of further study in the region.

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