



## Silvopastoral systems reduce soil CO<sub>2</sub> emissions, enhance carbon stocks, and regulate the micro-environment in tropical grazing lands



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### ARTICLE INFO

#### Keywords:

Carbon sequestration  
Livestock agroforestry  
Soil respiration  
Soil organic carbon  
Microclimate  
Tropical grasslands

### ABSTRACT

Soil carbon dioxide (CO<sub>2</sub>) flux is a fundamental component of the global carbon cycle and can be regulated by land use and management practices. Silvopastoral systems, livestock agroforestry that includes trees in grazing lands, can increase carbon storage and reduce soil CO<sub>2</sub> fluxes, yet their relationship with micro-climate, soil properties, and vegetation attributes has not been studied well. The objective of this research was to evaluate carbon storage and soil CO<sub>2</sub> fluxes and decipher the linkage between micro-climatic variables, soil properties, and vegetation characteristics in three silvopastoral systems: 1) dispersed trees in pasturelands, 2) grazing under forest plantations, and 3) live fences around pastureland, and 4) full-sun pastureland. Soil CO<sub>2</sub> fluxes were measured *in situ* using an EGM-5 gas analyzer connected with a soil respiration chamber (PP Systems, USA) over twelve months. Structural equation modeling was used to untangle the relative contribution of vegetation characteristics, soil properties, and micro-climatic variables on soil CO<sub>2</sub> fluxes. Soil CO<sub>2</sub> flux varied significantly between silvopastoral systems and full-sun pasturelands ( $p < 0.01$ ), ranging from 0.59 to 0.87 g m<sup>-2</sup> hr<sup>-1</sup>, with the full-sun pastureland having the highest flux, followed by live fences around pastureland, dispersed trees in pasturelands, and grazing under forest plantations. Silvopastoral systems reduced 12 – 32 % of soil CO<sub>2</sub> fluxes compared to the full-sun pasture. Soil organic carbon stocks to 100 cm depth were 12 % and 29 % higher in grazing under forest plantations (187 Mg C ha<sup>-1</sup>) and dispersed tree silvopastoral systems (215 Mg C ha<sup>-1</sup>), respectively, than in full-sun pasturelands (167 Mg C ha<sup>-1</sup>). Soil temperature, air temperature, and relative humidity also differed significantly between pastoral systems, with the full-sun pasture (grass monoculture) having the highest temperature and the lowest relative humidity. In a structural equation model, soil CO<sub>2</sub> flux showed a negative path coefficient (-0.82,  $p = 0.03$ ) with vegetation attributes that include the number of trees per hectare and biomass stocks, which covaried significantly with the micro-climatic variables. The soil properties construct was not a strong predictor of CO<sub>2</sub> flux but covaried positively with vegetation, including plant biomass and litter stocks. While further studies on soil microbial activities may help better understand the patterns of soil CO<sub>2</sub> fluxes among these livestock agroforestry systems, this study shows that the presence of trees modifies micro-environmental conditions in grazing lands, thereby reducing soil CO<sub>2</sub> emissions and enhancing carbon sequestration. The results have important implications in designing climate-smart and environment-friendly livestock production systems.

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## 1. Introduction

Land use and management have a crucial role in the global carbon cycle, including CO<sub>2</sub> flux from soil respiration (Friedlingstein et al., 2023; Hong et al., 2021; Yue et al., 2020). While soil respiration (Rs) is a natural process and an essential component of the global carbon (C) cycle, it is the largest source of carbon dioxide (CO<sub>2</sub>) flux from the land to the atmosphere (IPCC, 2023; Raich and Schlesinger, 1992; Schlesinger and Andrews, 2000). Soil CO<sub>2</sub> flux represents the sum of the autotrophic (from plant roots) and heterotrophic (from microbial activities) respiration as well as abiotic fluxes (Schindlbacher et al., 2009). The CO<sub>2</sub> flux from Rs annually returns more than 50 % of C fixed through photosynthesis to the atmosphere, and the rate is accelerated with time due to global warming (Bond-Lamberty et al., 2018; Nissan et al., 2023; Nottingham et al., 2020). The soil CO<sub>2</sub> flux rate is highly sensitive to the changes in vegetation cover, soil use, and cultivation practices, thus, even a small change in this rate can have a huge impact on atmospheric CO<sub>2</sub> concentration (Crippa et al., 2021; Hu et al., 2018). The increase in soil CO<sub>2</sub> flux rate substantially depletes the soil organic matter stock, reduces soil fertility, and degrades the overall soil health condition (Abdalla et al., 2022; Lehmann et al., 2020). To limit global warming below 2°C as envisioned in the Paris Agreement, it is crucial to identify or develop land use and management strategies that sequester more C, mitigate CO<sub>2</sub> emissions, adapt to climate change, and increase food production sustainably (Mbow et al., 2014; Quandt et al., 2023; Rogelj et al., 2016).

Globally, land use change has transformed more than 2 million km<sup>2</sup> of native vegetation into grazing lands, and more than half of them are severely degraded or in the process of degradation (Houghton and Nassikas, 2017; Song et al., 2018; Veldkamp et al., 2020). In Mexico alone, about 76 thousand km<sup>2</sup> of native forests were converted into grazing lands, mostly to full-sun pasture monocultures in the last 60–70 years (Bonilla-Moheno and Aide, 2020; INEGI, 2018; Mendoza-Ponce et al., 2018). The state of Tabasco in southeastern Mexico has lost more than 90 % of the native forest cover during the last 6–7 decades (Silván-Hernández et al., 2017; Villanueva-López et al., 2019). Such change of native forests into full-sun pasturelands causes significant depletion of soil organic carbon (SOC) by accelerating the soil CO<sub>2</sub> fluxes in addition to the loss of C stored in tree biomass (Aryal et al., 2018; Beillouin et al., 2023; Merino et al., 2023). The loss of forested vegetation also increases the land surface temperature and reduces soil moisture due to the removal of canopy cover and the lack of vertical stratification (de Oliveira Silva et al., 2024; Zhang et al., 2024).

Silvopasture is a livestock agroforestry, where ecological interactions between trees or shrubs, grasses, and grazing animals optimize resources and improve multiple ecosystem services. Incorporating trees and shrubs within open grassland and transforming them into silvopastoral systems (SPS) promote C sequestration in biomass and soils (Aryal et al., 2022; Jose et al., 2019; Melkani et al., 2024). The inclusion of trees in the grazing lands also plays an important role in adapting to climate change, as they regulate the micro-climate through shade and windbreaks (Kanzler et al., 2019; Swieter et al., 2022).

The presence of trees on pasturelands (as silvopastoral systems, SPS) can influence the soil CO<sub>2</sub> flux in a variety of ways (Rolo et al., 2023). Silvopastoral systems differ from full-sun pasturelands in terms of plant species composition, vegetation structure, micro-environmental conditions, SOC concentration, and soil physicochemical properties which may affect soil CO<sub>2</sub> fluxes (Jacobs et al., 2022; Rybchak et al., 2024). For example, an ambient temperature of 31.1–31.9°C is reported in silvopastoral systems but 33.4°C in full-sun pasturelands in southern Brazil, where the relative humidity was 55.2–57.2 % in silvopasture compared to 52.9 % in full-sun pasturelands (Deniz et al., 2020). Regarding plant species composition, C3 plants were more abundant under tree canopy in silvopastoral systems in Paysandú and Tacuarembó, Uruguay, while C4 grasses were dominant in full or partial-sun pasturelands (Pizarro et al., 2024). In Brazilian grasslands, silvopastoral systems improved soil

enzymatic activity of β-glucosidase and arylsulfatase while increasing the soil organic carbon content (16 versus 20 g kg<sup>-1</sup>) (dos Santos et al., 2022). A land surface temperature difference of 2.3°C between loblolly-pine silvopasture and full-sun pasture is reported in Florida, where silvopastoral systems made the micro-climate milder (Karki and Goodman, 2015). The lower land surface and soil temperatures (especially in tropical regions) are also linked to the reduction in soil microbial activities related to organic matter decomposition, and thus the release of CO<sub>2</sub> from the soil to the atmosphere (Dacal et al., 2022). By reducing ambient temperature, silvopastoral systems regulate heat stress during afternoon hours and improve the overall animal performance than full-sun pasturelands (Thomsen et al., 2024). Silvopastoral systems can have higher soil moisture contents and relative humidity, but lower soil temperature than in full-sun pasturelands (Casanova-Lugo et al., 2022; López-Santiago et al., 2023). For instance, the average available soil water at 1 m depth was 47 mm in full-sun pastureland of *Urochloa brizantha*, while it was 51 mm in silvopastoral systems with Eucalyptus trees in São Paulo, Brazil (Bosi et al., 2020). Such differences in soil moisture content between silvopasture and full-sun pasture have a fundamental role in regulating drought effect and gas exchange between land and atmosphere. This is due to a strong relationship between tree canopy characteristics such as tree density, biomass stock, and microclimatic variables (Adams et al., 2021; Matías et al., 2021). Depending on the type, density of the trees per unit of land area, canopy cover, tree basal area, and vertical stratification make silvopastoral systems different from each other and from full-sun pasturelands in terms of vegetation structure (Pezzopane et al., 2024). Such differences in vegetation structure lead to changes in distribution, density, and biomass of the plant roots between silvopastoral systems and full-sun pasturelands, resulting in differences in autotrophic respiration (Morales Ruiz et al., 2021).

Bahru and Ding, (2020) reported a direct relationship between vegetation structure and litter production that influences soil organic matter accumulation. The changes in vegetation structure, species composition, and biomass stocks above and belowground also trigger changes in environmental factors such as relative humidity, temperature, and soil moisture contents and SOC content, that modify the amount of CO<sub>2</sub> produced or consumed in the soil (Agbohessou et al., 2023; Aryal et al., 2024; Oertel et al., 2016). The land use mediated changes in net primary productivity and the differences in above and belowground carbon allocation between grasses and trees lead to the variation in soil CO<sub>2</sub> flux. For example, carbon input, output, and the overall balance were improved by tree cover in a Mediterranean silvopasture in Sardinia, Italy, where the maximum C balance was obtained at about 24 % tree cover (Pulina et al., 2022). Full-sun pasture had higher carbon emissions (0.10 Mg ha<sup>-1</sup> yr<sup>-1</sup>) while the silvopastoral system of 25 % tree cover sequestered 1.67 Mg C ha<sup>-1</sup> yr<sup>-1</sup> in North-eastern Amazonia, highlighting the role of these land uses in accumulation of above and belowground organic matter and the reduction of soil CO<sub>2</sub> emissions (Lustosa Filho et al., 2024). Vegetation-mediated changes in soil organic matter decomposition also influence the amount rate of CO<sub>2</sub> fluxes from the soil to the atmosphere (Wallwork et al., 2023). The abundance of fast-growing trees may increase readily decomposable litter on the soil surface, thereby improving nutrient cycling but may also increase soil respiration (Metcalfe et al., 2011). Furthermore, land use mediated differences in the availability of dissolved or recalcitrant organic carbon and the structure of microbial community also control the rate of CO<sub>2</sub> fluxes from the soil (Zhang et al., 2020). Trees can stabilize soil CO<sub>2</sub> fluxes through shade and increase aeration and soil porosity due to their deeper rooting systems than monoculture grasslands (Haaf et al., 2021; Jewell et al., 2017; Montejo-Martínez et al., 2020). For example, soil CO<sub>2</sub> emissions were highest in full-sun pasture compared to silvopasture and secondary forests in New York and New Hampshire, USA, where the relationship between temperature and CO<sub>2</sub> emissions was mediated by vegetation, suggesting that silvopasture may offer the climate benefits of forests while

providing the services of the grasslands for livestock production (Contosta et al., 2022). Soil silt and clay contents negatively affected CO<sub>2</sub> flux while sand content had an unimodal relation with a maximum flux at 68 % sand (Tang et al., 2020). SOC and N contents affected soil CO<sub>2</sub> fluxes negatively in a tropical silvopastoral system in the Philippines while soil temperature affected it positively (Bae et al., 2013).

However, the relative contribution of vegetation attributes, soil properties, and micro-climatic variables on soil CO<sub>2</sub> fluxes are not studied widely in tropical SPS. Furthermore, the spatial variability in land and climatic conditions, the diversity of pastureland management practices, and the differences in vegetation structure and species composition highlight the importance of studying the interplay between soil, vegetation, and micro-climate parameters on soil CO<sub>2</sub> emissions (Haaf et al., 2021).

The presence of woody vegetation makes SPS sequester and store more C in plant biomass than in full-sun pasturelands (FSP), but how much C can be mitigated via soil CO<sub>2</sub> flux mediation remains elusive, especially in SPS such as dispersed trees in pasturelands (DTP), live fences around pasture (LFP), grazing under forest plantation (GFP). It is necessary to understand how different silvopastoral arrangements affect the interplay between vegetation structure, soil properties, including SOC content, and micro-climate that regulate soil CO<sub>2</sub> fluxes. Specifically, an in-depth study of the relative contribution of different vegetation attributes in modifying soil and microclimatic variables helps design best management practices for climate-smart agroforestry systems. On one hand, animal production is considered one of the important sources of greenhouse gas emissions thereby causing climate change. On the other hand, climate change is affecting the functioning and productivity of animal grazing systems (Godde et al., 2020). Agroforestry systems, such as silvopasture, are crucial both in mitigating greenhouse gas emissions through carbon sequestration and climate change adaptation and via micro-environment regulation. Understanding how different silvopastoral systems affect CO<sub>2</sub> emissions from the soil helps farmers identify resilient practices to enhance carbon sequestration, lower GHG emissions, and improve animal welfare by modulating micro-climate within pasturelands.

Thus, the main objective of this study was to evaluate the role of diverse silvopastoral systems on soil CO<sub>2</sub> fluxes and decipher the relative contribution of the vegetation attributes, soil properties, and micro-climatic variables on soil CO<sub>2</sub> fluxes. Soil CO<sub>2</sub> fluxes were assessed between three different SPS: dispersed trees on pasturelands, live fences around pastureland, and grazing under forest plantations, and compared with full-sun pasturelands in a humid tropical region. In the context of accelerated deforestation and the expansion of pasturelands (Villanueva-Lopez et al., 2019), comparing native forests would provide better insights into the changes in soil CO<sub>2</sub> fluxes. However, we did find grazed natural forests with conditions comparable to silvopastoral systems and considered full-sun pastureland as a reference. We hypothesized that silvopastoral systems minimize soil CO<sub>2</sub> emissions and store more soil organic carbon compared to full-sun pasturelands because tree cover modulates micro-environmental conditions.

## 2. Materials and methods

### 2.1. Study area and the characteristics of the pastoral systems

The study was conducted in the Usumacinta River basin, in Tabasco, Mexico (Fig. 1). The climate of the region is classified as warm-humid with abundant rainfall in summer with an average annual temperature of 26.6°C and precipitation of 1600 mm (INEGI, 2017). Study sites are found within the elevation range of 100–200 m above sea level where Phaeozems are the dominant soil types (Palma-López et al., 2017). The sampling plots were distributed in six localities (ejidos): Redención del Campesino, Bejucal, Francisco Villa, Allende, Repasto, and Miguel Hidalgo of the municipality of Tenosique, Tabasco (Fig. 1).

Four livestock grazing systems (Fig. 2, Table 1) were selected for the study: a) Grazing under forest plantations (GFP), b) Dispersed trees in pastureland (DTP), c) Live fences around pastureland (LFP), and d) Full-sun pasture (FSP). Twenty plots, five for each pastoral system, of 1000 m<sup>2</sup> each were used for sampling soil CO<sub>2</sub> fluxes, vegetation properties, and soils. Soil type and topographical conditions were similar for forest plantations and other grazing systems. Predominantly they are

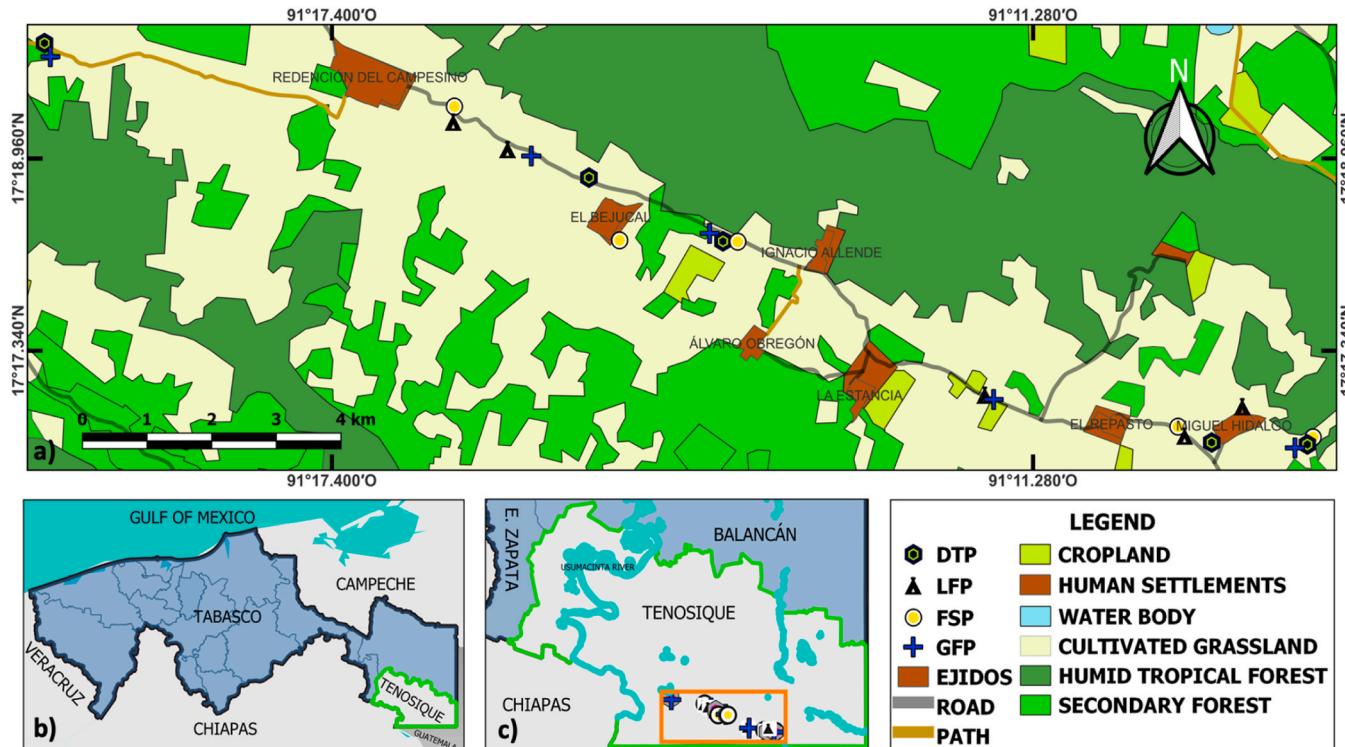
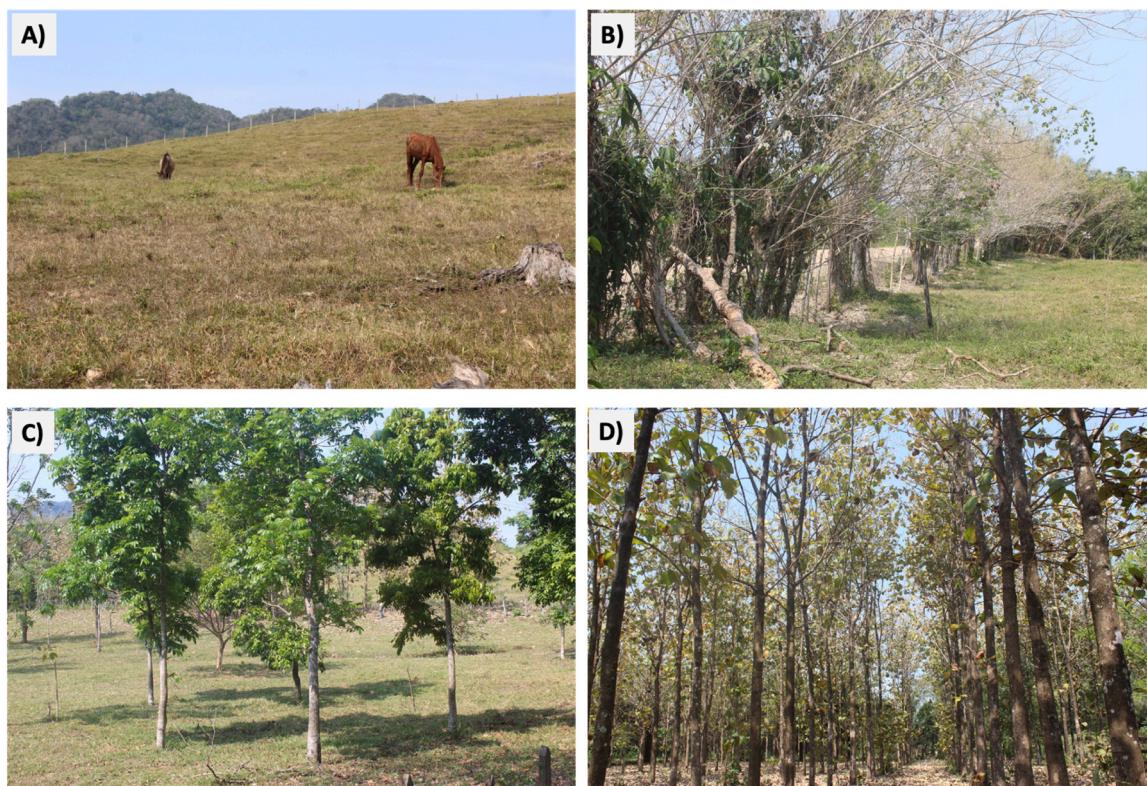


Fig. 1. Study region and distribution of the sample plots (a) in Tenosique municipality of the state of Tabasco (b) within the Usumacinta River Basin (c), Mexico.



**Fig. 2.** Representation of four pastoral systems studied. A) Full-sun pastureland (FSP), B) Live fences around pasture (LFP), C) Dispersed tree in pasture (DTP), and D) forest plantation (GFP).

**Table 1**

Characteristics of the pastoral systems: FSP = full-sun pasture, LFP = live fences around pasture, DTP = dispersed in pastureland, and GFP = grazing under forest plantation.

Systems	Characteristics
FSP	The full-sun pasture system is composed of only grasses without trees, where fences are made of wooden or concrete poles and metal wires. The dominant grasses are <i>Urochloa decumbens</i> and <i>Cynodon plectostachys</i> with about 30 years of establishment.
LFP	This system consists of the linear planting of trees on the perimeter of the pasturelands. The most common trees are <i>Gliricidia sepium</i> and <i>Tectona grandis</i> with 80–90 % of the basal area. The systems had a tree density of about 120–150 $\text{ha}^{-1}$ with an average height of 10–15 m and basal area of 8–12 $\text{m}^2 \text{ha}^{-1}$ .
DTP	Trees are found scattered randomly without any specific arrangement on the pasturelands. It had on average 100–150 trees $\text{ha}^{-1}$ with a basal area of 10–15 $\text{m}^2 \text{ha}^{-1}$ and a tree height of 10–15 m. These silvopastoral systems are 30–35 years old, where the most common tree species include <i>Tabebuia rosea</i> , <i>Cedrela odorata</i> , <i>Swietenia macrophylla</i> , and <i>Lonchocarpus rugosus</i> with about 70–90 % of the total basal area.
GFP	The grazing under the forest plantation system is composed of a high density of trees with <i>Tectona grandis</i> , <i>Platymiscium dimorphandrum</i> , and <i>Tabebuia rosea</i> with 80–90 % of the basal area. The system had an average tree density of 600–700 trees $\text{ha}^{-1}$ , with an average basal area of 15–20 $\text{m}^2 \text{ha}^{-1}$ , and tree height of 16–20 m. A thin layer of grasses and forbs are present in alleys between tree rows for cattle grazing.

sandy clay soils.

## 2.2. Soil respiration measurement

Soil respiration was measured *in situ* using an EGM-5 gas analyzer (PP Systems, USA), connected with an SRC-2 cylindrical soil respiration chamber of 150 mm (height) x 100 mm (diameter), which capture and carry the air to the analyzer, where soil CO<sub>2</sub> emissions are calculated. Sampling was done for twelve months from December 2022 to

November 2023. At the beginning of the study, three PVC collars with an inner diameter of 10 cm were installed in the soil leaving 2.5 cm above ground level in each sampling plot and randomly distributed within the sampling area. Collars in silvopastoral systems were located under the canopy in a way they received sunshine and shade for at least one part of the day. These collars were placed at 1–3 m distance from tree trunks. A total of 60 PVC collars, 15 for each system were set up. The distance between the collars within the plot was about 15–20 m. In DTP and FSP, sample plots were circular with a radius of 17.80 m, while for GFP, the plots were rectangular with 20 m wide by 50 m long. For LFP, a linear transect of 100 m was measured where PVC collars were distributed in a zigzag order. The shape of the plots was different for each system because of the spatial distribution and arrangement of the trees (Ibrahim and Andrade, 2003). PVC collars were installed in the soil 15 days before starting CO<sub>2</sub> flux measurement.

During each measurement of soil CO<sub>2</sub> flux, the soil respiration chamber was connected with EGM-5 gas analyzer and deployed on the ground surface fitting on the PVC collars. On each sampling date (each month), measurements were taken for four consecutive days from 11:00–15:00 h, resulting in four repeated measurements for each plot every month. During each sampling, grasses or plants within the collars, if any, were trimmed just before mounting the chambers to avoid aboveground respiration or photosynthesis. Only aboveground portion was removed to place the chamber, without disturbing roots. Simultaneously, a Hydra probe was used to measure soil moisture and temperature. At the same time, the ambient temperature, atmospheric humidity, dew point temperature, and light intensity were measured at a height of one meter from the soil surface using a data logger (HOBO H8 and U12 Onset Computer). Dew point temperature was a derived variable calculated automatically by the data logger using relative humidity and temperature data. Linear regression functions were used to calculate the CO<sub>2</sub> flux rate ( $\text{g m}^{-2} \text{hr}^{-1}$ ) from gas concentrations recorded by the EGM-5 analyzer for 120 s.

### 2.3. Soil sampling and analysis

Soil samples were collected by digging vertical pits ( $1 \times 1 \times 1 \text{ m}^3$ ) and taking samples for SOC analysis and another for bulk density, the latter with a cylindrical metal probe of 10 cm height and 5.4 cm diameter (Hazarika et al., 2024). From each of 20 plots, soil samples were collected separately at fixed depth intervals of 0–10, 10–20, 20–30, 30–40, 40–50, and 50–100 cm. Soil samples were shade-dried, sieved on 2 mm mesh, and proceeded to the laboratory for analysis. The SOC (%) analysis was carried out using chemical digestion, followed by spectrophotometric reading (Heanes, 1984; Walkley and Black, 1934). The pH and redox potential were also analyzed using the potentiometer method (Bates, 1964). Soil bulk density was calculated using cylinder volume and oven-dried soil mass after the coarse fragment correction.

### 2.4. Vegetation sampling

We sampled all the trees within a rectangular area ( $20 \times 50 \text{ m}$ ) in GFP, along a 100 m transect in LFP, and within a circular area of  $1000 \text{ m}^2$  (17.80 m radius) in DTP and FSP (Ibrahim and Andrade, 2003). The differences in the shape of the sampling area among pastoral systems are due to the differences in tree arrangements. To obtain a representative number of trees within the sampling area, rectangular plots are recommended for planned row plantations (such as GFP) while circular plots are better in the systems where trees are randomly distributed without any specific arrangement (such as DTP). The transect method was used in LFP due to the linear planting of the trees on borderlines of the square-shaped paddocks (Aryal et al., 2022). Tree diameter at breast height (DBH) was measured with a diametric tape and the total height with a Criterion RD 1000 laser gun (Laser technology). Tree species were identified and wood density data was collected from published literature (Chan-Coba et al., 2022; Zanne et al., 2009). Subsequently, aboveground biomass was quantified using an allometric equation [ $\text{AGB} = 0.0673 \times (\rho D^2 H)^{0.976}$ ] for tropical trees (Chave et al., 2014). Grass biomass and ground litter were sampled by direct harvesting within four  $0.25\text{-m}^2$  quadrats in each plot, oven-drying, and weighing.

### 2.5. Data analysis

The response variable data such as soil  $\text{CO}_2$  flux, SOC content, and biomass stocks were tested for normality using the Shapiro-Wilk test ( $p < 0.05$ ). Where applicable, we used log10 transformation of data before analysis. The normal data were subjected to the generalized linear mixed model (GLMM) procedure to determine the effect of the system or the interaction between systems and sampling months using the "lme4" package in R (R Core Team, 2024).  $\text{CO}_2$  flux data was taken as the response variable, pastoral systems and sampling months as predictor variables (fixed effects), while repeated measurements were considered as random effects. One-way analysis of variance was used to test the effect of pastoral systems on soil  $\text{CO}_2$  emissions, biomass stocks, micro-climatic variables, and SOC stocks. Two-way ANOVA was used to test the effect of pastoral systems and soil depths on SOC concentrations. Tukey's HSD tests were used respectively to declare statistical differences of means between pastoral systems. Non-normal data were analyzed with non-parametric methods (Kruskall-Wallis test). Furthermore, Spearman correlation analyses were performed to evaluate the bivariate relationships between multiple pairs of variables on soil  $\text{CO}_2$  fluxes, soil moisture, soil temperature, air temperature, ambient temperature, atmospheric humidity, dew point temperature, light intensity, and soil chemical properties such as SOC content, bulk density, pH, and redox potential using the "tab\_corr" function of the "sjPlot" package in the R (R Core Team, 2024).

For the structural equation model (SEM), we developed three latent variables (constructs): 1) soil properties; 2) vegetation components that include tree density, and 3) micro-climate within the pastoral systems.

Soil construct was developed using the manifest variables SOC, pH, oxidation-reduction potential, bulk density, soil moisture, and soil temperature. The vegetation construct was developed using tree density per hectare, total tree biomass, grass biomass, and litter mass. The micro-climate construct was developed using air temperature, diffuse light, atmospheric humidity, and dew point temperature as the manifest variables. To develop the model diagram, the "semPath" function was used with standardized path coefficients. Structural equation modeling was performed using the "lavaan" package in R (R Core Team, 2024; Rosseel, 2012).

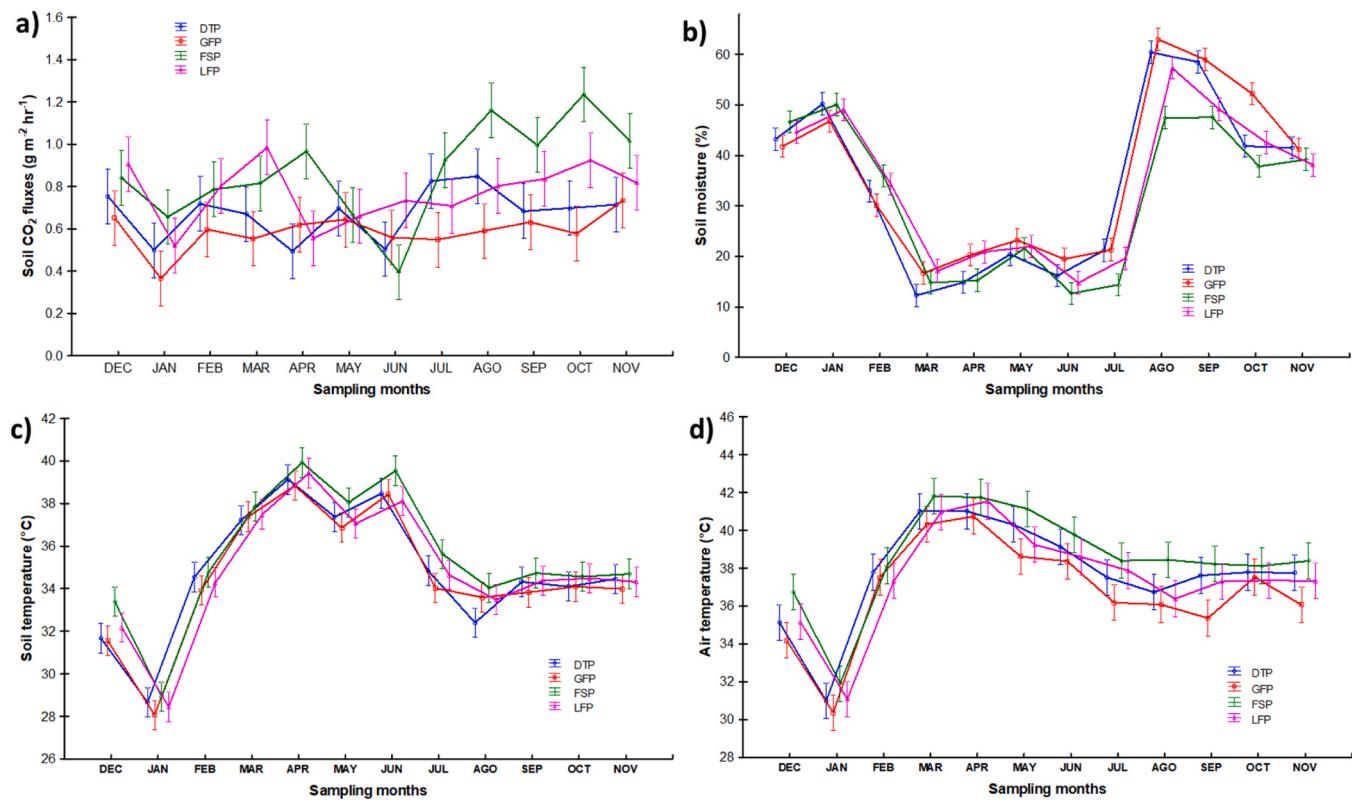
## 3. Results

### 3.1. Monthly variation in soil $\text{CO}_2$ flux, soil temperature, and moisture

The soil  $\text{CO}_2$  fluxes fluctuated between  $0.36$  and  $1.24 \text{ g m}^{-2} \text{ hr}^{-1}$  during the year (from December 2022 to November 2023) across pastoral systems. FSP showed consistently higher fluxes in most of the months compared to silvopastoral systems. In the dry months of March and April, FSP, a system with no trees, and the LFP, a system with low tree density, showed a higher  $\text{CO}_2$  flux compared to the systems with a greater tree density such as DTP and GFP. FSP showed higher fluxes during the summary rainy period (July - October) too. It was noted that the monthly mean of soil  $\text{CO}_2$  fluxes in FSP was more sensitive to micro-meteorological changes between months, particularly during the rainy season, while the silvopastoral systems showed more stable fluxes irrespective of the time of year (Fig. 3a). Although all the systems followed the seasonal trend, soil moisture, soil temperature, and air temperature at ground level (Fig. 3b-d) presented a significant interaction between months of the year and pastoral systems ( $P < 0.01$ ). The greatest presence of soil moisture occurred in August in the GFP, followed by DTP, and LFP. In the FSP, the highest percentage of soil moisture occurred in January, with 50.1 %, while the lowest amount was found in June, with 12.7 %. FSP tended to be drier than silvopastoral systems in hotter months and soil moisture increased from June to August (Fig. 3b). The highest soil temperature (Fig. 3c) occurred in April in FSP, followed by LFP, DTP, and GFP with an average of 39.9, 39.4, 39.1, and  $38.8^\circ\text{C}$  respectively. After July, the temperature decreased due to the precipitation events but the soil  $\text{CO}_2$  fluxes in FSP continued to be higher than other systems. The lowest temperature was observed in January for all the pastoral systems. Grazing under forest plantations had the lowest temperature in January followed by live fences, dispersed tree silvopasture, and full-sun pasture monoculture with an average of 28.1, 28.4, 28.6, and  $28.9^\circ\text{C}$  respectively. In most months, full-sun pasture had the highest soil temperature compared to silvopastoral systems. The highest air temperature occurred in March in the FSP, followed by LFP while the lowest air temperature was recorded in GFP and DTP in January (Fig. 3d). Air temperature tended to be higher in full-sun pasture than in silvopastoral systems in most of the months, reaching up to  $41.7^\circ\text{C}$  in April.

### 3.2. Soil $\text{CO}_2$ flux, moisture, and temperature among pastoral systems

The overall average soil  $\text{CO}_2$  flux across the four pastoral systems was  $0.73 \text{ g m}^{-2} \text{ hr}^{-1}$ , ranging from  $0.59$  to  $0.87 \text{ g m}^{-2} \text{ hr}^{-1}$  (Fig. 4a). The year-round averages of soil  $\text{CO}_2$  fluxes differed significantly among pastoral systems ( $F = 32.2$ ,  $p < 0.001$ ). Soil  $\text{CO}_2$  flux had a statistically significant interaction between pastoral systems and months of the year (Table 2). Pastoral systems with higher tree density such as forest plantations (GFP) and dispersed trees in paddocks (DTP) had a lower soil  $\text{CO}_2$  flux compared to systems with less tree cover or without trees such as FSP. The GFP system had the lowest mean with  $0.59 \text{ g m}^{-2} \text{ hr}^{-1}$  followed by DTP with a mean of  $0.68 \text{ g m}^{-2} \text{ hr}^{-1}$ , while LFP and FSP also presented significant differences with a mean of  $0.77$  and  $0.87 \text{ g m}^{-2} \text{ hr}^{-1}$  respectively (Fig. 4a). Depending upon the type, silvopastoral systems were able to reduce  $\text{CO}_2$  flux by 12 – 32 % compared to FSP.



**Fig. 3.** a) Monthly variation of carbon dioxide fluxes ( $\text{CO}_2 \text{ g m}^{-2} \text{ hr}^{-1}$ ), b) soil moisture (%), c) soil temperature ( $^{\circ}\text{C}$ ), and d) air temperature at ground level ( $^{\circ}\text{C}$ ) during a year of measurement in four pastoral systems within the Usumacinta River basin in Tabasco. GFP: grazing under forest plantations, DTP: trees dispersed in paddocks, LFP: living fences around pastureland, and FSP: full-sun pasturelands. Error bars indicate the respective 95 % confidence intervals.

The average annual soil temperature differed significantly between pastoral systems (Kruskal-Wallis  $H = 32.59$ ,  $P < 0.01$ ), FSP being the one with the highest temperature ( $35.5^{\circ}\text{C}$ ) and GFP ( $34.5^{\circ}\text{C}$ ) with the lowest soil temperature (Fig. 4b). Similarly, the annual average in soil moisture differed significantly between pastoral systems ( $H = 22.72$ ,  $P < 0.01$ ). The systems with high tree density, such as GFP and DTP (672 and 114 trees  $\text{ha}^{-1}$ , respectively), presented higher soil moisture content (36.3 and 34.5 % respectively) than those with lower tree cover or without trees, such as LFP (154 trees  $\text{ha}^{-1}$ ) and FSP (no trees) with 34.1 and 32.0 % respectively (Fig. 4c).

### 3.3. Monthly variation of micro-climatic variables

The monthly variation of ambient temperature readings taken one meter above ground level showed a statistically significant interaction between months by systems ( $F = 2.1$ ;  $P < 0.00$ ) (Fig. 5a). The highest temperature is observed in March in the tree systems dispersed in pastures and monoculture grass with an average of  $39.5$  and  $39.2^{\circ}\text{C}$ , respectively. Forest plantations and live fences showed the lowest ambient temperatures with values of  $27.0$  and  $27.2^{\circ}\text{C}$ , respectively. The highest environmental temperature presented by silvopastoral systems occurs in March with an average of  $38.9^{\circ}\text{C}$  compared to full-sun pasturelands with an average of  $39.2^{\circ}\text{C}$ , observing that full-sun pasture from March onwards remains with an average ambient temperature above the silvopastoral systems, observing a total of 10 months with this trend (Fig. 5a).

The dew point temperature (Fig. 5b) and light intensity (Fig. 5c) had a statistically significant interaction ( $F=1.55$ ;  $P < 0.02$  and  $F=3.24$ ;  $P < 0.00$ , respectively) between months and pastoral systems. The highest light intensity was observed in June in FSP with an average of 694 lum/sqf, while the lowest occurred in November in GFP with 183 lum/sqf (Fig. 5d). GFP experienced a trend of low light intensity for 10

months, while the FSP experienced a greater light intensity for 6 months (April, Major, June, August, October, and December).

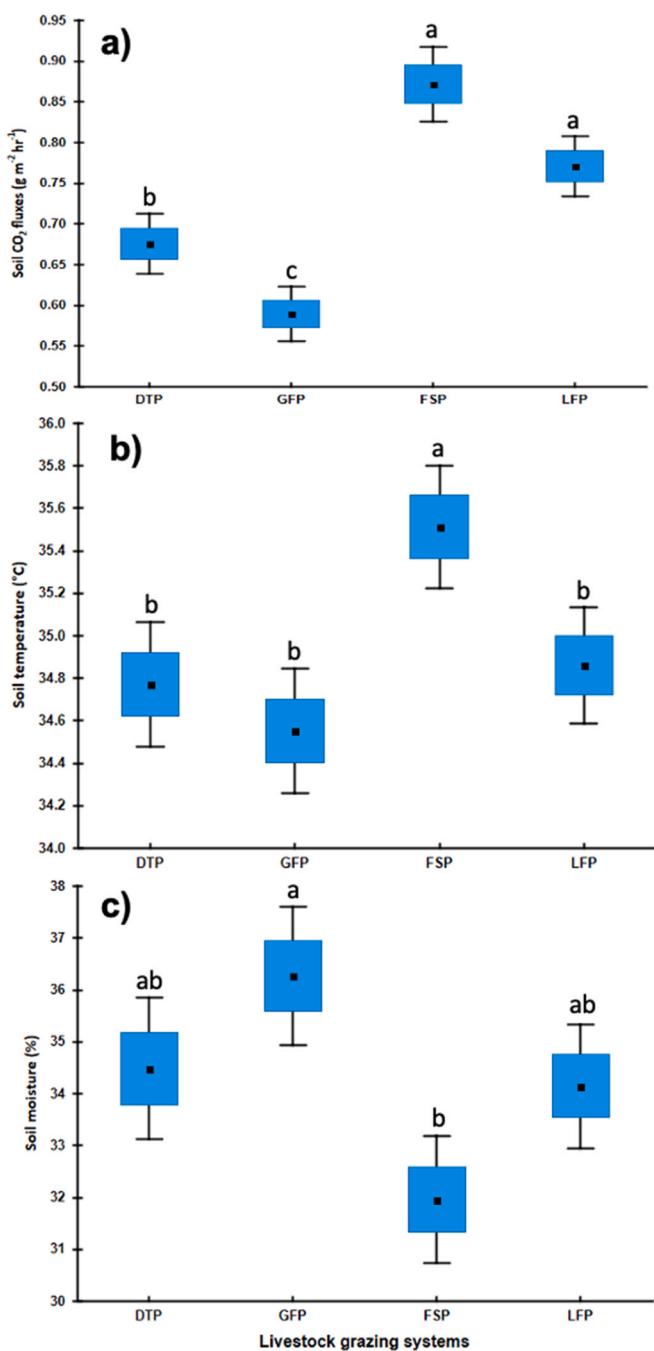
### 3.4. Micro-climatic variables among pastoral systems

Significant differences in micro-climatic variables were observed between silvopastoral systems and FSP (Table 3). Air temperature at one meter from the ground level and dew point temperature were higher in FSP than in all the silvopastoral systems. Relative humidity was the lowest in FSP. Diffused light was significantly greater in DTP and FSP compared to LFP and GFP (Table 3).

### 3.5. Soil organic carbon, tree density, and biomass stocks among pastoral systems

The average SOC concentration varied among pastoral systems ( $F = 0.84$ ,  $p = 0.01$ ), and soil depth categories ( $F = 19.7$ ,  $p < 0.01$ ) but there was no significant interaction between pastoral systems and soil depth ( $F = 0.56$ ,  $p = 0.89$ ). The lack of interaction between two predictor variables indicates that the depth-related decrease in SOC content was not affected by pastoral systems. However, in the individual depth category, the most notable differences were observed in the 40–50 cm and 50–100 cm. The highest SOC concentration was found in the topsoil (36.8, 34.2, 29.0, and 24.3 g  $\text{kg}^{-1}$  respectively for GFP, DTP, LFP, and FSP) and decreased gradually in the deeper layers (Fig. 6). SOC concentrations in 40–50 and 50–100 cm depths were significantly higher in silvopastoral systems such as DTP (20.7 and 12.7 g  $\text{kg}^{-1}$ ) than FSP (9.4 and 8.0 g  $\text{kg}^{-1}$ ).

Tree density was high in forest plantations followed by live fences and dispersed trees in pasturelands. The highest tree basal area and biomass stock was estimated in GFP followed by DTP and LFP (Table 4). Grass biomass did not differ statistically among pastoral systems but full-



**Fig. 4.** a) Soil CO<sub>2</sub> flux, b) soil temperature, and c) moisture in four pastoral systems. DTP: dispersed trees in paddocks, GFP: grazing under forest plantations, LFP: live fences around pasture, and FSP: full-sun pasture monoculture. The letters above the boxes indicate statistically significant differences between pastoral systems (Tukey HSD,  $p < 0.05$ ).

**Table 2**

Analysis of variance testing the effect of pastoral systems and sampling months on soil CO<sub>2</sub> emissions.

Sources of variance	Degrees of freedom	Sum of squares	Mean sum of squares	F-value	P-value
System	3	24.4	8.127	32.206	< 0.001
Month	11	32.4	2.943	11.662	< 0.001
System*Month	33	30.9	0.937	3.715	< 0.001
Residuals	2835	715.4	0.252		

sun pastureland tended to have a higher stock. DTP had the highest SOC stock followed by GFP, FSP and LFP (Table 4).

### 3.6. Relationship between CO<sub>2</sub> flux, soil properties, vegetation, and microclimate

The pairwise correlations indicated that soil CO<sub>2</sub> flux did not have statistically significant correlations ( $p = 0.05$ ) with soil properties, but it tended to correlate positively with soil temperature ( $r = 0.33$ ) and negatively with soil moisture and bulk density (Table 5). Although statistically non-significant, soil temperature tended to have a negative correlation with soil moisture content. Soil moisture showed a significant positive correlation with SOC content (Table 5).

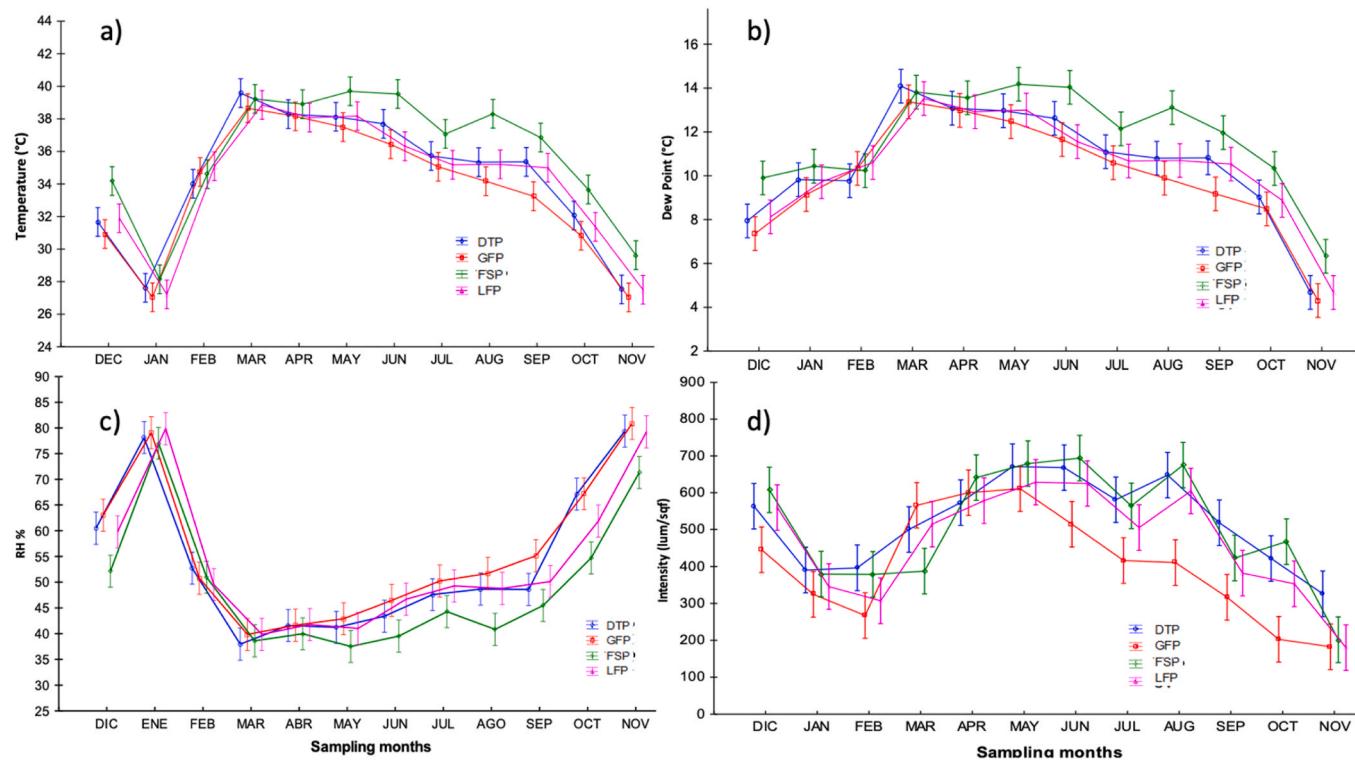
The CO<sub>2</sub> flux showed significant negative correlations with tree biomass and tree density per ha<sup>-1</sup>. Tree density showed significant negative correlations with air temperature and diffuse light, but positive correlations with relative humidity. Grass biomass correlated positively with diffuse light and dew point but negatively with ground litter mass and relative humidity (Table 6).

The structural equation model converged normally after 106 iterations and was statistically significant ( $\chi^2 = 143.2$ ,  $p < 0.01$ ,  $df = 85$ ), with a comparative fit index of 0.74 and a Tucker-Lewis index of 0.67. The SEM showed that the vegetation or plants as a latent variable had a significant negative effect on soil CO<sub>2</sub> flux (standardized path coefficient = -0.82,  $p = 0.03$ ). Tree density per hectare, tree biomass, grass biomass, and ground litter were the manifest variables used to construct vegetation as a latent variable, where the tree component had positive path coefficients while the grass biomass had a negative path coefficient (Fig. 7). The direct effect of micro-climatic variables on soil CO<sub>2</sub> flux was small (path coefficient = -0.26), but we observed that there was a negative covariance between vegetation and micro-climatic variables. Such a negative covariance indicates that trees on grazing lands modulate micro-climatic variables such as ambient temperature. The direct effect of soil properties on CO<sub>2</sub> flux was very low and non-significant (path coefficient = -0.03,  $p = 0.91$ ), but we noted that the vegetation construct had a positive covariance with soil properties. The positive relationship between soil moisture and SOC content indicates that the trees in silvopastoral systems improve SOC and water storage (Fig. 7).

## 4. Discussions

### 4.1. Soil CO<sub>2</sub> flux between silvopastoral systems and full-sun pasture

The lower soil CO<sub>2</sub> emissions in silvopastoral systems than in conventional full-sun pasturelands shows the potential of reducing greenhouse gas emissions with silvopasture, contributing to the retention of sequestered SOC for a longer time (de Souza Almeida et al., 2021; Pulina et al., 2022; Schinato et al., 2023). The decrease in soil CO<sub>2</sub> flux in silvopastoral systems compared to full-sun pastureland was primarily attributed to the reduction in soil heterotrophic respiration (Baah-Acheamfour et al., 2020; de Carvalho Gomes et al., 2016). Studies show an increase in heterotrophic respiration and net CO<sub>2</sub> efflux with increasing soil temperature (Naidu and Bagchi, 2021; Peri et al., 2015; Wang et al., 2014). The reduction of soil respiration and increase in SOC storage is possible by the integration of trees on grazing lands because it leads to the addition of organic matter through litter production, fine root turnover in the deeper soil horizons, improvement in the microbial metabolic quotient, and the regulation of micro-environmental conditions (Amorim et al., 2023; Lira Junior et al., 2020; Morales Ruiz et al., 2021). For example, DTP and LFP stored a greater amount of total C (387.0 and 362.6 Mg ha<sup>-1</sup> respectively) compared to FSP (312.5 Mg ha<sup>-1</sup>), tree biomass contributed 6.3 % and 8.4 % in DTP and LFP respectively (De la Cruz-López et al., 2023). DTP added 10.1 Mg C ha<sup>-1</sup> through tree litterfall, storing 58 % more C than FSP (Valenzuela Que et al., 2022). In this same region, LFP stored 119.8



**Fig. 5.** Monthly variation in ambient temperature a), dew point b), relative humidity c), and light intensity d) measured one meter above the ground during a year in four pastoral systems within the basin of the Usumacinta River in Tabasco. GFP: grazing under forest plantations, DTP: dispersed trees in paddocks, LFP: living fences around the pasture, and FSP: full-sun pasture monoculture. Error bars indicate the respective 95 % confidence intervals.

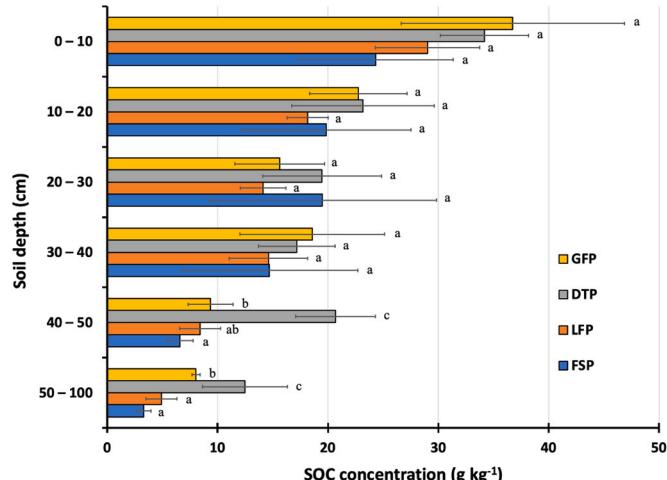
**Table 3**

Micro-climatic variables (mean and 95 % confidence intervals) measured at one-meter height from the ground level among pastoral systems with and without trees. FSP: full-sun pasture monoculture, LFP: live fences around pasture, DTP: dispersed trees in paddocks, and GFP: grazing under forest plantations.

Micro-climatic variables	FSP	LFP	DTP	GFP
Air Temperature (°C)	35.8 <sup>c</sup> (35.4 – 36.2)	34.2 <sup>b</sup> (33.8 – 34.5)	34.4 <sup>b</sup> (34.0 – 34.8)	33.6 <sup>a</sup> (33.3 – 34.0)
Dew point (°C)	11.7 <sup>b</sup> (11.4 – 12.0)	10.4 <sup>a</sup> (10.1 – 10.7)	10.6 <sup>a</sup> (10.3 – 10.7)	10.0 <sup>a</sup> (9.7 – 10.3)
Relative humidity %	49.4 <sup>a</sup> (48.1 – 50.7)	54.0 <sup>b</sup> (52.7 – 55.2)	53.9 <sup>b</sup> (52.5 – 55.3)	55.7 <sup>b</sup> (54.4 – 57.0)
Light Intensity (lum/sqft)	508 <sup>b</sup> (487 – 529)	465 <sup>a</sup> (445 – 486)	521 <sup>b</sup> (502 – 541)	405 <sup>a</sup> (385 – 425)

Mg C ha<sup>-1</sup> compared to 113.34 Mg C ha<sup>-1</sup> stored in FSP (Villanueva-López et al., 2015).

Trees in grazing lands are reported to improve soil physical, chemical, and hydric properties that favor a reduction in C output through soil respiration (Alcidia-Aguilar et al., 2024; Pinheiro et al., 2021; Simões et al., 2023). Improvements in soil biological properties in silvopastoral systems are also reported to influence the soil respiration rates (de Abreu et al., 2020; dos Santos et al., 2022; Gargaglione et al., 2022). The differences in soil CO<sub>2</sub> production between silvopastoral systems and full-sun pasture are potentially linked to the changes in the composition and diversity of soil organisms due to the variation in tree species composition and litter quality (Adams et al., 2021; Bai and Cotrufo, 2022). Full-sun pasture litter is characterized by a higher C:N ratio because of the organic residues from sole grasses compared to mixed species litter in silvopasture, which can partially contribute to a higher



**Fig. 6.** Average soil organic carbon (SOC) concentrations (g kg<sup>-1</sup>) among three different silvopastoral and one full-sun pasture system. GFP = grazing under forest plantation, DTP = dispersed trees on pastureland, LFP = Live fences around pastureland, and FSP = full-sun pasturelands. Error bars indicate respective 95 % confidence intervals. Different letters above the bars denote statistically significant differences among grazing systems (Tukey HSD, p < 0.05).

release of CO<sub>2</sub> from FSP (Pessoa et al., 2024). The variance of plant traits due to the differences in species composition, canopy cover, and the differences in tree vertical structure lead to the differences in CO<sub>2</sub> emissions among silvopastoral systems (Jewell et al., 2017). Though not specifically in the study plots but in the same region, the abundance of arbuscular mycorrhizal fungi was higher in pasturelands and grazing under forest plantations, while the richness of their morphospecies was

**Table 4**

Tree density, basal area, biomass, and SOC stocks among four pastoral systems. DTP = dispersed trees on pastureland, GFP = grazing under forest plantation, LFP = Live fences around pastureland, and FSP = full-sun pasturelands. CI indicate the respective 95 % confidence intervals. Lowercase letters followed by means denote the significant differences between pastoral systems (Tukey HSD,  $p < 0.05$ ).

	DTP	GFP	LFP	FSP
Tree-density (number of trees $\text{ha}^{-1}$ )				
Mean	114.00 <sup>a</sup>	672.00 <sup>b</sup>	153.60 <sup>a</sup>	0.00 <sup>a</sup>
Lower 95 % CI	55.37	220.59	38.42	
Upper 95 % CI	172.63	1123.41	268.78	
Tree basal area ( $\text{m}^2 \text{ha}^{-1}$ )				
Mean	12.88 <sup>bcd</sup>	19.90 <sup>c</sup>	5.50 <sup>b</sup>	0.00 <sup>a</sup>
Lower 95 % CI	6.30	10.32	2.45	
Upper 95 % CI	19.46	29.48	8.54	
Tree aboveground biomass ( $\text{Mg C ha}^{-1}$ )				
Mean	40.57 <sup>ab</sup>	71.57 <sup>b</sup>	15.99 <sup>a</sup>	0.00 <sup>a</sup>
Lower 95 % CI	18.52	19.46	6.55	
Upper 95 % CI	62.63	123.68	25.42	
Grass biomass ( $\text{Mg C ha}^{-1}$ )				
Mean	4.72 <sup>a</sup>	4.67 <sup>a</sup>	5.48 <sup>a</sup>	8.21 <sup>a</sup>
Lower 95 % CI	3.21	0.58	2.66	3.82
Upper 95 % CI	6.23	8.77	8.31	12.60
Leaf litter mass ( $\text{Mg C ha}^{-1}$ )				
Mean	1.71 <sup>b</sup>	4.79 <sup>b</sup>	2.12 <sup>b</sup>	0.00 <sup>a</sup>
Lower 95 % CI	0.09	-1.26	-0.07	
Upper 95 % CI	3.33	10.84	4.31	
SOC stock to 1 m depth ( $\text{Mg C ha}^{-1}$ )				
Mean	215.12 <sup>b</sup>	187.18 <sup>ab</sup>	140.21 <sup>a</sup>	167.13 <sup>a</sup>
Lower 95 % CI	148.88	127.85	106.34	114.78
Upper 95 % CI	281.36	246.50	174.08	219.49

**Table 5**

Pairwise correlation (Spearman) between multiple variables such as soil  $\text{CO}_2$  fluxes  $\text{g m}^{-2} \text{ hr}^{-1}$ , soil temperature  $^{\circ}\text{C}$  ( $T_{\text{soil}}$ ), soil moisture % ( $M_{\text{soil}}$ ), SOC content % (SOC), bulk density  $\text{g cm}^{-3}$  (BD), hydrogen potential in soil (pH), redox potential (Eh). P-values are presented in parentheses.

	CO <sub>2</sub> flux	T <sub>soil</sub>	M <sub>soil</sub>	SOC	BD	pH	Eh
CO <sub>2</sub> flux							
T <sub>soil</sub>	0.326 (.160)						
M <sub>soil</sub>	-0.397 (.084)	-0.444 (.052)					
SOC	-0.320 (.168)	-0.269 (.250)	0.477 (.035)				
BD	-0.389 (.091)	-0.071 (.767)	0.170 (.472)	-0.018 (.942)			
pH	0.125 (.599)	0.242 (.302)	0.078 (.743)	0.066 (.782)	0.409 (.075)		
Eh	-0.077 (.748)	-0.165 (.484)	-0.310 (.183)	-0.174 (.460)	-0.376 (.103)	-0.836 (<.001)	

Computed correlation used the Spearman-method with listwise-deletion.

higher in native forests (Ricárdez-Pérez et al., 2024). Livestock agroforestry systems such as live fences, dispersed trees on pasture, and grazing under forest plantations showed a higher diversity of macro-arthropods compared to monoculture systems in the region (Lara-Pérez et al., 2023; Villanueva-López et al., 2019). The reduced soil  $\text{CO}_2$  fluxes under tree cover compared to full-sun pastures are reported in some other regions too. For example, soil heterotrophic respiration was lower beneath the tree cover in native evergreen forests than in full-sun pastures in Sardinia, Italy (Sanna et al., 2021). Total soil respiration as well as soil and near-surface air temperatures were lower in silvopastoral systems than in full-sun pastures in New Hampshire and New York, USA (Contosta et al., 2022). However, some studies reported no significant effect of silvopasture on soil  $\text{CO}_2$  fluxes (Villanueva-López et al., 2016), while others showed a higher soil  $\text{CO}_2$  flux in silvopastoral systems than in full-sun pastures (Ibañez et al.,

2020; Matías et al., 2021).

To compare with earlier studies, we converted  $\text{g CO}_2 \text{ m}^{-2} \text{ hr}^{-1}$  values to  $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$  by multiplying with 6.313 and found that our results in soil  $\text{CO}_2$  fluxes ( $3.7 - 5.5 \mu\text{mol m}^{-2} \text{ s}^{-1}$ ) were within the reported ranges. However, a high variation in soil  $\text{CO}_2$  fluxes was noted depending on the system and the region of study. For example, in the humid tropical regions of Mexico, a significant difference was observed in soil  $\text{CO}_2$  fluxes between dispersed tree silvopasture ( $4.3 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ ) and full-sun pasture ( $6.7 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ ) (López-Santiago et al., 2023). However, a study in Quintana Roo reported that fluxes were indifferent between two silvopastoral systems with different grass species with an average of  $6.1 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$  (Adame-Castro et al., 2020). In the Mediterranean hot dry climate of Sardinia, Italy, soils of silvopastoral systems with *Quercus suber* trees emitted  $3.5 - 3.7 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$  compared to  $3.5 - 3.7 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$  from full-sun pasture (Sanna et al., 2021). In the humid tropics of Brazil, soil  $\text{CO}_2$  emissions from DTP were  $3.1 - 6.4 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$  compared to  $6.0 - 8.3 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$  from FSP (Cândido et al., 2024). In the humid temperate region of Fayetteville, USA, soil  $\text{CO}_2$  emissions in FSP was  $8.3 - 9.7 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$  (Adams et al., 2021), while in the humid temperate region of Texcoco, Mexico, it ranged between  $3.0$  and  $20.0 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$  (López-Teloxa and Monterroso-Rivas, 2020). In a subtropical semi-arid ecosystem of Nuevo Leon, Mexico, soil  $\text{CO}_2$  emissions were  $0.7 - 2.8$  times greater in silvopasture with *L. leucocephala* trees ( $8.4 - 14.4 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ ) compared to conventional FSP ( $3.5 - 5.0 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ ) (Cantú-Silva et al., 2010).

Differences in soil  $\text{CO}_2$  fluxes and the interaction between system and month highlight that the silvopastoral systems do not behave in the same way throughout the year. This is due to the differences in tree cover between systems that control micro-climatic factors modulated. The increase in rainfall from July to September and the differences in soil moisture retention among silvopastoral systems influence soil  $\text{CO}_2$  fluxes (Acosta et al., 2018). The differences in soil  $\text{CO}_2$  flux between silvopastoral systems can be attributed to the arrangement and density of trees that modify the local micro-climatic conditions (Fig. 7). For example, the shade and high soil moisture content in silvopastoral systems regulates soil microbial activity, increasing soil C accrual and stabilization (Adame-Castro et al., 2020; Viruel et al., 2021). The positive covariance between the vegetation component and soil component reflects that trees in silvopasture reduce soil  $\text{CO}_2$  fluxes and improve soil properties such as SOC storage (Alcidia-Aguilar et al., 2024; Aryal et al., 2022). However, the direct effect of soil properties on soil  $\text{CO}_2$  fluxes was not significant in our study.

#### 4.2. Trees in silvopastoral systems regulate micro-climate and reduce $\text{CO}_2$ fluxes

The inverse relationship between vegetation construct and soil  $\text{CO}_2$  flux in our study indicates that increasing tree density and biomass reduce soil respiration, with tree components being the strong predictor of soil  $\text{CO}_2$  emissions. A higher tree cover in silvopasture compared to full-sun pastureland regulates soil  $\text{CO}_2$  flux and micro-climate in multiple ways (Jacobs et al., 2022). For example, the shades from trees significantly reduced the soil and near-surface air temperatures in silvopastoral systems such as GFP and DTP which is reflected by a negative correlation between tree density and air temperature. Though the average annual difference in soil temperature was only  $1^{\circ}\text{C}$  between full-sun pasture and silvopasture, it reaches up to  $1.9^{\circ}\text{C}$  in some months, which potentially increases oxidative extra-cellular enzyme activities, resulting in higher  $\text{CO}_2$  emissions (Meng et al., 2020). Landuse-mediated changes in soil temperature and moisture also affect the structure and activities of soil microorganisms, declining the overall microbial diversity and thereby increasing soil  $\text{CO}_2$  fluxes (Nottingham et al., 2022). The drier soil in FSP than in the silvopastoral systems is because of the absence of trees that would otherwise regulate the loss of water through evapotranspiration (Joseph et al., 2020). Tree canopy in silvopasture

**Table 6**

Pairwise correlation (Spearman) between multiple variables such as soil CO<sub>2</sub> fluxes g m<sup>-2</sup> hr<sup>-1</sup>, total tree biomass Mg C ha<sup>-1</sup>, grass biomass Mg C ha<sup>-1</sup>, leaf litter mass Mg C ha<sup>-1</sup> (Litter), number of trees per ha<sup>-1</sup> (tree density), air temperature °C (T<sub>air</sub>), diffuse light (Light), relative humidity (RH), and dew point temperature. Respective p-values are presented in parentheses.

	CO <sub>2</sub> flux	Tree biom	Grass biom	Litter	Tree density	T <sub>air</sub>	Light	RH	Dew point
CO <sub>2</sub> flux									
Tree biom	<b>-0.612</b> (.004)								
Grass biom	0.168 (.476)	-0.415 (.069)							
Litter	-0.434 (.056)	<b>0.502</b> (.024)	-0.294 (.208)						
Tree density	<b>-0.534</b> (.015)	<b>0.773</b> (<.001)	-0.203 (.390)	<b>0.642</b> (.002)					
T <sub>air</sub>	0.430 (.060)	-0.464 (.039)	0.132 (.577)	-0.641 (.002)	<b>-0.621</b> (.003)				
Light	0.030 (.901)	-0.406 (.076)	0.361 (.119)	-0.225 (.341)	-0.594 (.006)	0.090 (.705)			
RH	-0.383 (.096)	<b>0.711</b> (<.001)	<b>-0.549</b> (.014)	0.402 (.079)	<b>0.689</b> (.001)	-0.331 (.154)	<b>-0.629</b> (.004)		
Dew point	0.346 (.136)	-0.644 (.002)	<b>0.487</b> (.031)	<b>-0.507</b> (.022)	<b>-0.720</b> (<.001)	0.352 (.129)	<b>0.665</b> (.002)	<b>-0.937</b> (<.001)	

Computed correlation used the Spearman-method with listwise-deletion.

improves the ambient relative humidity and soil moisture as revealed by a positive correlation between these variables and tree density in our results. A study in Mediterranean pasturelands reported that soil moisture, temperature, grazing legacy, and tree canopy were the main factors controlling soil CO<sub>2</sub> fluxes (Matías et al., 2021). Therefore, full-sun pasturelands are more vulnerable to climate extremes such as warming, drought, and flooding than silvopastoral systems, ultimately increasing soil CO<sub>2</sub> fluxes and losing carbon storage capacity (Haaf et al., 2021; Nissan et al., 2023; Villanueva-López et al., 2016).

The lack of tree cover on the ground in FSP leads to direct sunlight and soil warming (Zeppetello et al., 2022). This rise in temperature in the soil and near-surface air depends on the time of day and actual temperature (Cater et al., 2021). In this study, vegetation played an important role, as a regulating agent of soil moisture loss, soil and air temperature, light intensity, and dew point temperature in most months of the year. Some studies did not obtain significant differences between silvopasture and FSP in soil water content (Darenova et al., 2021a), which is different from our result where soil moisture was higher in silvopasture. We noted that air temperature peaked in March but soil temperature peaked in April in this study, which we attribute to the prolonged drought, as evidenced by soil moisture content. Our results of a strong positive correlation between SOC content and soil moisture reinforce that increasing SOC stocks through silvopasture also helps to improve soil water balance for pasture production, especially in dry seasons. The lower CO<sub>2</sub> emissions, reduced land-surface temperature, and higher SOC concentrations in silvopastoral systems than in full-sun pasturelands, especially in the soil horizons, make these agroforestry systems promising to develop sustainable and climate-smart livestock farming.

## 5. Conclusions

The full-sun pasture system emitted a higher amount of CO<sub>2</sub> from the soil to the atmosphere than silvopastoral systems such as grazing under forest plantations, dispersed trees in pastureland, and live fences around the pasture. Soil CO<sub>2</sub> emissions also varied among silvopastoral systems, grazing under forest plantations emitted the lowest CO<sub>2</sub>, followed by dispersed trees in pasturelands, and live fences around the pasture. Taking the full-sun pasture as a reference, GFP, DTP, and LFP respectively mitigated 32, 22, and 12 % of the soil CO<sub>2</sub> emissions. The monthly trends on soil CO<sub>2</sub> fluxes were lower and more stable in silvopastoral systems compared to full-sun pasturelands. This is attributed to the presence of trees as regulating agents in micro-climatic factors such as near-surface air temperature, relative humidity, and soil moisture. Soil

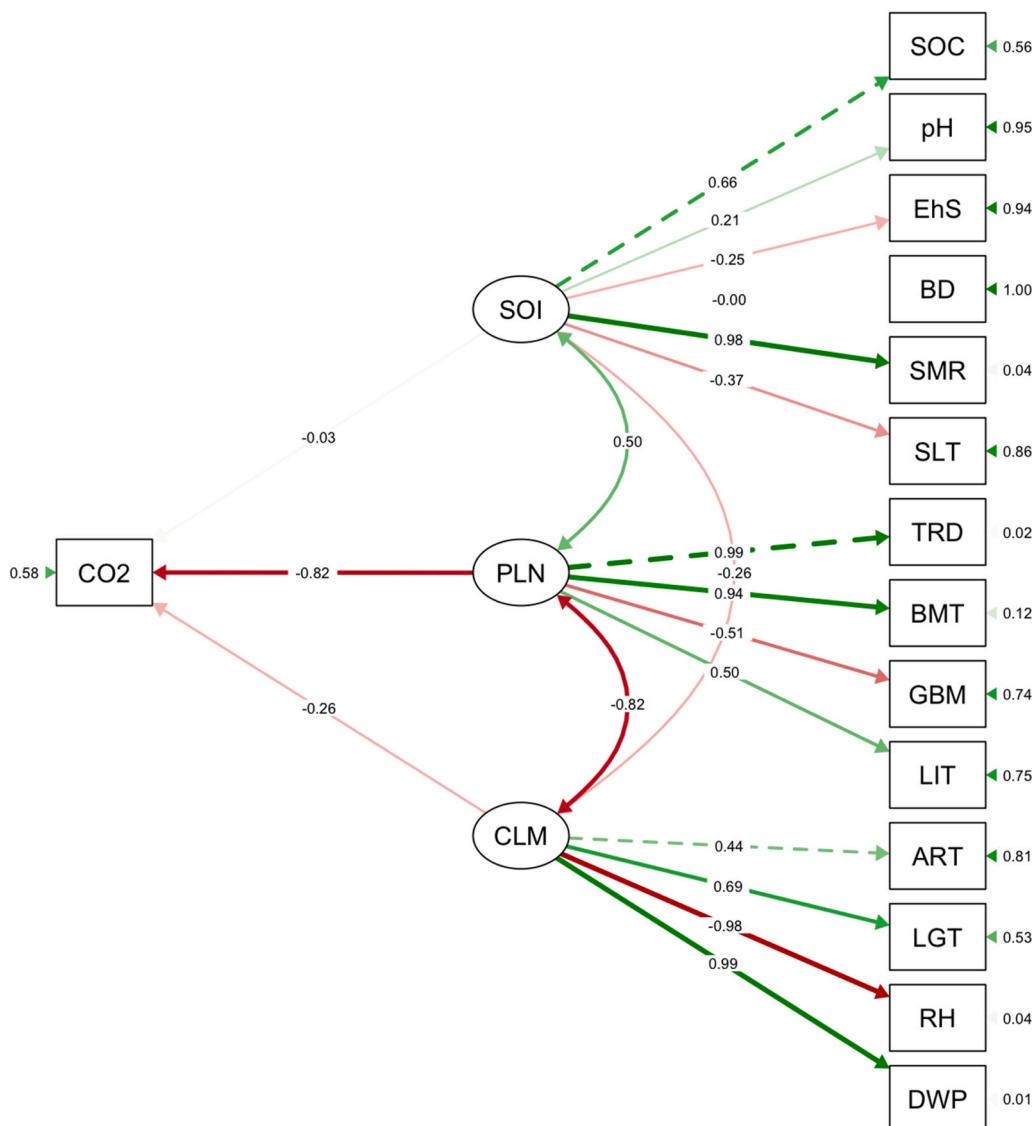
organic carbon concentrations were higher in silvopastoral systems than in full-sun pasturelands, specifically in the deeper soil horizons. The total C stocks, including tree biomass, were 50–53 % higher in DTP and GFP than in FSP. Our structural equation model untangled that the woody vegetation cover in grazing lands is fundamental in regulating micro-climatic variables and reducing soil CO<sub>2</sub> fluxes that ultimately enhance SOC concentrations. Although soil properties were a poor predictor of soil CO<sub>2</sub> flux, vegetation, and micro-climatic variables better explained the reduction in soil CO<sub>2</sub> fluxes in our study. Our findings demonstrate that silvopastoral systems contribute to climate change mitigation in grazing land by regulating micro-climate and ultimately reducing CO<sub>2</sub> emissions. Further studies on the composition and activities of microorganisms in the decomposition and mineralization of soil organic matter to better understand the differences in CO<sub>2</sub> fluxes from these grazing lands. Continuous measurement of soil greenhouse fluxes over multiple years would provide better insights into interannual variability and reduce the uncertainty of the estimates regarding soil atmosphere gas exchange under diverse land use and management practices. The results of this study have fundamental implications for promoting climate-smart and regenerative livestock production through the implementation of silvopastoral systems such as dispersed trees in pasturelands and live fences in the hotspots of deforestation led primarily by the expansion of open grasslands.

## Author contribution

DMR, DRA, GVL: conceptualization, fieldwork, lab work, data analysis, draft writing and search for funding, FCL, RPR, JAV, FGH, MRS, PMZ, RG: manuscript writing and revision

## CRediT authorship contribution statement

**René Pinto-Ruiz:** Resources, Writing – original draft, Writing – review & editing, Supervision. **José Apolonio Venegas-Venegas:** Resources, Writing – original draft, Supervision, Writing – review & editing. **Francisco Guevara-Hernández:** Writing – original draft, Supervision, Writing – review & editing, Resources. **Pablo Martínez-Zurimendi:** Resources, Writing – original draft, Project administration, Writing – review & editing. **Mariela Reyes-Sosa:** Supervision, Writing – original draft, Writing – review & editing. **Deb Raj Aryal:** Supervision, Conceptualization, Data curation, Writing – review & editing, Formal analysis, Writing – original draft. **Rajan Ghimire:** Methodology, Writing – review & editing, Writing – original draft. **Danilo Enrique Morales-Ruiz:** Writing – original draft, Methodology,



**Fig. 7.** Structural equation model that shows the relationship between soil  $\text{CO}_2$  fluxes (CO<sub>2</sub>), vegetation attributes (PLN), soil properties (SOI), and micro-climatic variables (CLM). Soil properties, vegetation and micro-climate are latent variables constructed from manifest (measured) variables such as soil organic carbon (SOC), hydrogen potential (pH), oxidation-reduction potential (EhS), bulk density (BD), soil moisture (SMR), soil temperature (SLT), tree density per hectare (TRD), total tree biomass (BMT), grass biomass (GBM), ground litter (LIT), air temperature (ART), diffuse light (LGT), relative humidity (RH), and dew point (DWP). The green colored arrows indicate the positive path coefficients, while the red colored arrows indicate the negative path coefficients. Thicker and darker color means stronger relationships.

Conceptualization, Investigation, Writing – review & editing, Data curation, Visualization, Formal analysis. **Fernando Casanova-Lugo:** Writing – original draft, Writing – review & editing, Methodology, Resources. **Gilberto Villanueva-López:** Project administration, Conceptualization, Writing – original draft, Investigation, Writing – review & editing, Methodology, Funding acquisition.

#### Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

#### Acknowledgment

We thank the landowners of Tenosique, Tabasco for allowing their land and ranches to carry out this study. Mexican National Council of Humanities Sciences and Technologies (CONAHCYT) provided the PhD

scholarship to the first author. The Science and Technology Council of the state of Tabasco (CCYTET) provided funding for field and lab work through the project PRODECTI-2022-01/21. The College of Southern Border (ECOSUR) provided laboratory facilities, vehicles, and equipment to carry out this project. Part of the lab analysis was carried out at the animal nutrition lab of the Autonomous University of Chiapas (UNACH).

#### Data availability

Data will be made available on request.

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