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Soil organic carbon stock and litter mass in silvopastoral systems with *Eucalyptus*

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Abstract The objective of this study was to evaluate the soil organic carbon stock and litter mass in silvopastoral systems (SSP) implemented with *Urochloa decumbens* and different *Eucalyptus* spatial arrangements. The SSP was implemented in 2008 with the spatial arrangements of (3×2)+20 m (434 trees ha^{-1}), (2×2)+9 m (909 trees ha^{-1}) and 9×2 m (556 trees ha^{-1}) formed by the *Eucalyptus* cultivars GG100, I144 and VM 58. Soil samples at 0 to 20 and 0 to 40 cm depths were collected in SSP in 2011 and 2015 to determine soil organic carbon stock. The soil organic carbon stock was 38.5% higher in 2015 compared to 2011 (111 vs. 80.7 Mg ha^{-1}), which represented an annual sink of 6.22 Mg ha^{-1} and indicates an increase in carbon stock over years. Litter mass was greater under the canopy than between trees, probably due to the greater drop in biomass in this location. The silvopastoral systems showed similar volumes of litter and soil organic carbon, which indicates that the evaluated arrangements have similar capacities to store carbon.

Keywords Agroforestry · Carbon sequestration · Integration livestock-forest · Production system · Tropical forage

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Introduction

The increase in the world's human population and consumption pattern has increased the pressure for greater food production and to preserve natural resources for future generations (IPCC 2020). In this context, Brazil plays a central role due to its large area of agricultural land and food production capacity. Meanwhile, Brazil is still recognized for its poor environmental indicators due to the conversion of native vegetation areas to agricultural production using conventional management. The large area with degraded pastures in Brazil is one of the main negative factors for the national agriculture sustainability. It is estimated that approximately 70% of the pasture areas show some degradation degree (Dias-Filho 2014), mainly due to the unsuitable stocking rate and the lack of soil fertility maintenance. In this context,

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the silvopastoral system (SSP) is an alternative for degraded pastures recovery and increasing production systems profitability (Braz et al. 2013; Torres et al. 2017).

The native vegetation conversion into conventionally managed agricultural areas reduces soil organic carbon stocks due to the greater soil plowing and higher organic matter exposure (Tivet et al. 2013). Sá et al. (2015) observed a reduction in soil organic carbon stock from 0.58 to 0.67 Mg C ha year^{-1} with the conventional planting use compared to conservationist systems, probably due to less breakdown of macroaggregates and exposure of organic matter for microbial oxidation. However, Tivet et al. (2013) showed that higher biomass decomposition, lower exposure of organic matter to oxidation, higher interaction of carbon with sesquioxides, lower turnover of macroaggregates and higher presence of polysaccharides from plants (shoot and root) result in greater aggregation of particles in the soil, favoring the formation of macro and microaggregates and increasing the stability of carbon in the soil. Thus, the present study can provide more information about carbon dynamics in SSP, such as the soil organic carbon mass of these systems, which can support the planning of carbon credit payment programs and the elaboration of national reports on greenhouse gases management and global warming mitigation.

The SSP is an efficient strategy to restore soil organic carbon stocks in these degraded areas. The soil non-disturbance, nutrients cycling from deeper layers, tree and forage robust root system, microclimate alteration and greater litter mass are the main factors that increase soil organic carbon stocks in SSP (Vicente et al. 2016; Cardinael et al. 2018; Almeida et al. 2021). Moreira et al. (2022) observed soil organic carbon stock 44.8% (194 vs. 134 Mg ha^{-1}) higher in silvopastoral systems implemented with *U. brizantha* cv. Piatâ and *Eucalyptus* with compared to native vegetation in the Brazilian Cerrado biome. However, there is still little information on the effect of different arrangements and *Eucalyptus* cultivars on soil organic carbon stocks in SSP in Brazil. Thus, the objective of this study was to evaluate the soil organic carbon stock and litter mass in SSP implemented with *U. decumbens* and different *Eucalyptus* spatial arrangements.

Material e methods

Experimental area characterization

The experiment was carried out in the Cerrado biome at the Minas Gerais Agricultural Research Corporation (Epamig) Santa Rita Experimental Field. This experimental field is located in the Prudente de Morais municipality, Minas Gerais, Brazil (19° 27′ 15″ S; 44° 09′ 11″ W; 732 m altitude) (Fig. 1). The climate is Cwa type, with humid subtropical averages with hot and rainy summer and dry winter (warmer temperature over 22 °C) (Alvares et al. 2013). The climatological data during the experiment and last 30 years historic are shown in Fig. 2. The soil is classified as red ferralsols (WRB 2006).

Historic of experimental area and treatments

A 10 ha pasture area of *U. decumbens* implanted in 1993 was converted into an integrated

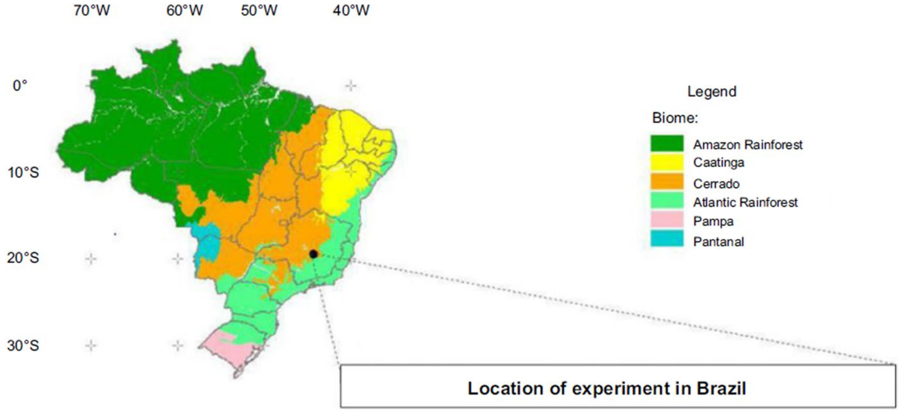

Fig. 1 Location of experiment in the Brazilian Cerrado biome at Prudente de Morais municipality

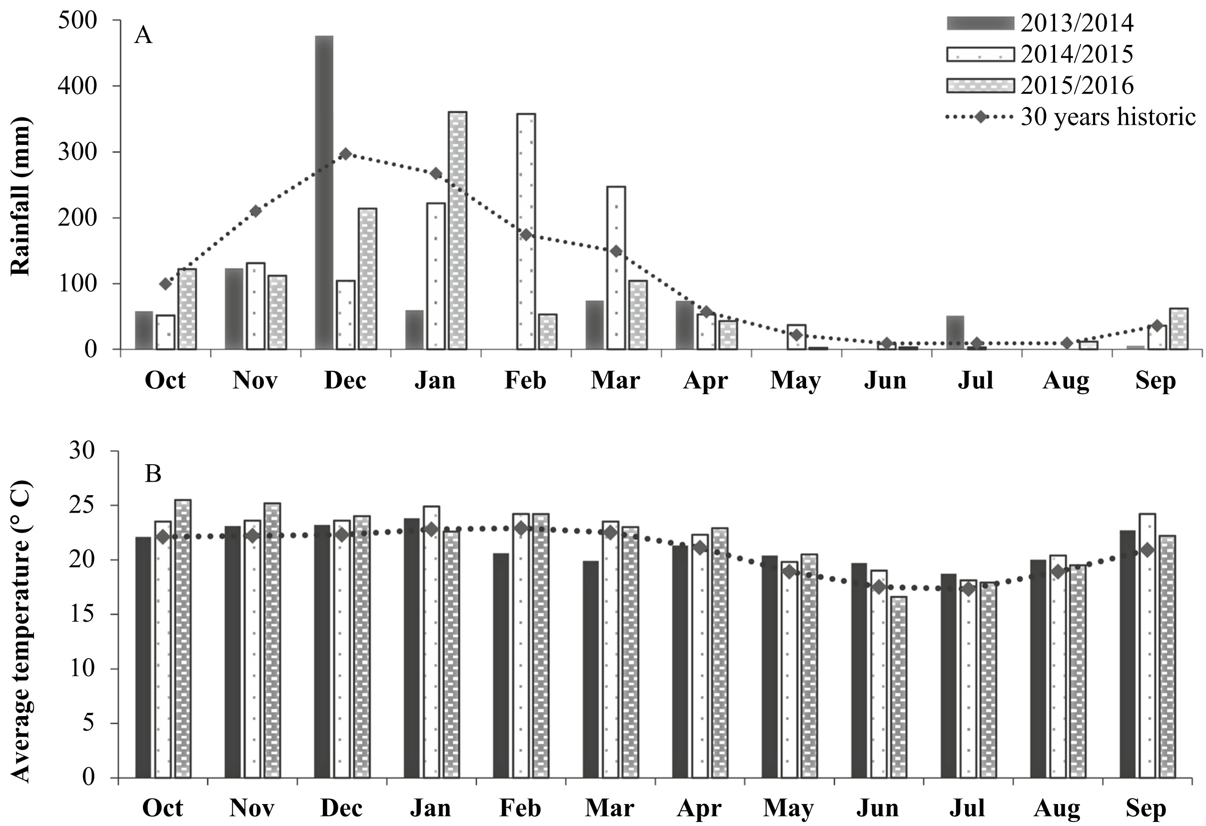

Fig. 2 Monthly rainfall (**A**) and average temperature (**B**) during the experimental period and last 30 years climatological historic in the experimental area Source: National Institute of Meteorology (INMET)

crop-livestock-forest system (ICLFS) in 2008 as a strategy to recover pasture productivity. In the ICLFS implantation year, ants control, desiccation of the entire vegetation cover and the application of 2000 kg ha^{-1} of dolomitic limestone to correct the soil pH were performed. For planting, conventional preparation was carried out with plowing and harrowing the entire area and subsoiling in the *Eucalyptus* planting rows. An amount of 400 kg ha^{-1} of reactive natural phosphate was applied in the entire area soil.

The *Eucalyptus* was planted at the beginning of the system establishment. In the first three agricultural cycles (2009/2010, 2010/2011 and 2011/2012) maize (*Zea mays*) was grown intercropped with *U. decumbens* cv. Basilisk between *Eucalyptus* rows. The maize was planted 1.5 m from the *Eucalyptus* rows. In the fourth agricultural cycle, only the *U. decumbens* cv. Basilisk pasture was implemented and the system was converted to SSP.

During the evaluations, the system was characterized as SSP composed of *Eucalyptus* arranged in two double rows spatial arrangements [$(3\times2)+20$ m, with three meters between trees, two meters between rows and 20 m between ranks (434 trees ha^{-1}) and $(2\times2)+9$ m, with two meters between rows, two meters between trees and nine meters between ranks (909 trees ha^{-1})] and in a simple row spatial arrangement [9×2 m, with two meters between trees and nine meters between ranks (556 trees ha^{-1})]. The trees rows were established in the east–west direction. In each arrangement, rows were implanted with the *Eucalyptus* cultivars GG100, I144 (*E. grandis*×*E. urophylla*) and VM 58 (*E. grandis*×*E. camaldulensis*).

The pasture maintenance fertilization in SSP was carried out with 100 kg ha^{-1} of nitrogen (N) and 100 kg ha^{-1} of K_2O in the 2014/2015 agricultural cycle and 100 kg ha^{-1} of N, 40 kg ha^{-1} of K_2O and 50 kg ha^{-1} of P_2O_5 in the 2015/2016 agricultural cycle. The first fertilizations were made in December. The amount of N used was divided into two applications and the second application was carried out in March 2015 and 2016. The correctives and fertilizers applications followed the recommendations described by Ribeiro et al. (1999).

Soil organic carbon stock and litter mass

The soil and litter sampling site was delimited with a 1 m^2 (1 × 1 m) square metal frame. The experiment was conducted in random blocks with split-split-plot 3 × 2 × 2 design, with the SSP spatial arrangement in the plot, the sampling site or soil depth in the subplot and the agricultural cycle in the sub-subplot. The soil samples were collected in December 2011 and 2015 in the three SSP spatial arrangements. Sampling was carried out under trees canopy and between the tree rows (Fig. 3) in 0–20 and 20–40 cm layers. In each experimental unit, one subsample was collected in each row with the three *Eucalyptus* cultivars and the average of these three subsamples was considered a repetition.

The soil organic carbon content determination was carried out according to Nelson and Sommers (1982) in a carbon analyzer. The soil organic carbon stocks (Mg ha^{-1}) in each soil layer were estimated by the equation: Soil organic carbon stock = d × μ × e; Where: d = apparent soil density in the studied layer (g cm^{-3}); μ = soil C content (%); e = studied soil layer depth (cm). The undisturbed soil samples were dried in oven at 105 °C for 24 h, weighed and used to quantify soil density (EMBRAPA 1997). The average density obtained was of 1.05 g cm^{-3} for the 0–20 cm layer and 1.13 g cm^{-3} for 20–40 cm layer for all spatial arrangements.

Litter sampling was carried out in June 2014 and 2016 under trees canopy and between the tree rows (Fig. 3). The litter inside the area delimited by the metallic frame was collected, weighed, used to determine dry matter (DM) and considered the repetition. After DM determining, the litter mass per area was estimated by the equation: Litter mass (kg ha^{-1}) = (litter biomass collected in 1 ha × litter DM).

Statistical analysis

Three replicates per treatment were used and the data were analyzed in random blocks with split-split-plot 3 × 2 × 2 design, with the SSP spatial arrangement in the plot, the sampling site or depth in the subplot and the agricultural cycle in the sub-subplot. All data were submitted to the Lilliefors and Bartlett tests to verify the distribution of normality and homoscedasticity ($p > 0.05$), respectively. The litter mass was quadratically transformed for data analysis, but the data presented were the original. The data were submitted to variance analysis according to the statistical models: $Y_{ijkm} = \mu + B_m + A_i + l_{im} + S_j + (AS)_{ij} + \alpha_{ijk} + C_k + (AC)_{ik} + (SC)_{jk} + (ASC)_{ijk} + \gamma_{ijkm}$. Where: Y_{ijkm} = observation of arrangement i, sample site or depth j, of agricultural year k, in block m; μ = overall average effect; B_m = effect of block m, where m = 1, 2 and 3; A_i = effect of arrangement i, where i = (3 × 2) + 20 m,

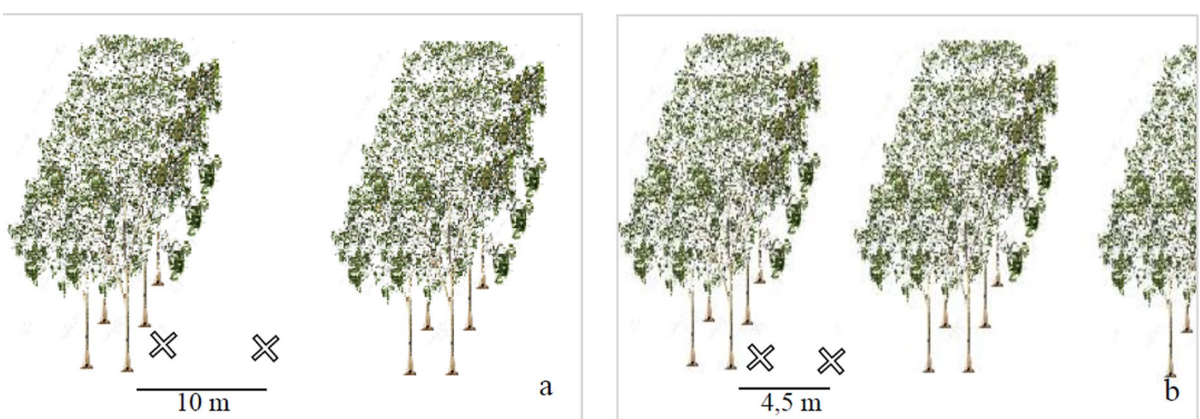

Fig. 3 Soil and litter sample collection scheme in the silvopastoral system in the arrangements (3 × 2) + 20 m (**a**) and in (2 × 2) + 9 m and 9 × 2 m (**b**)

$(2\times2)+9$ m and 9×2 m; l_{im} = effect of random error attributed to the portion of arrangement i in block m; S_j = sample site or depth, where j = the center of the plot and under the tree canopy or—0–20 and 20–40; $(AS)_{ij}$ = effect of the arrangement and sample site interaction or depth; α_{ijm} = random error attributed to the sub-portion of arrangement i, the sample site or the depth j of block m; C_k = effect of year k, where k = 2011 and 2015 (carbon) and 2014 and 2016 (litter); $(AC)_{ik}$ = effect of arrangement and year interaction; $(SC)_{jk}$ = effect of interaction between sample site or depth and year; $(ASE)_{ijk}$ = effect of the interaction between arrangement, sample site or depth and year; γ_{ijkm} = random error attributed to the sub-subplot of arrangement i, at the sample site or depth j, year K of block m. To compare the treatment means in the SSP, the Student–Newman–Keuls test (SNK) at 5% probability of error was used. All analyzes were performed using the R Core Team (2019) software.

Results

The experimental area soil chemical characteristics at 0–20 and 20–40 cm depths in 2008 when the *Eucalyptus* was implemented are shown in Table 1.

The litter mass did not show normal distribution and homoscedasticity ($p<0.05$) and after quadratic transformation it had normal distribution ($p=0.25$) and homoscedasticity ($p=0.12$). The litter mass showed a significant interaction between year and sampled site in the SSP ($p=0.01$). The litter mass increased 59.7% from 2014 to 2016 in the two sampled sites (2390 vs. 5960 kg ha^{-1}). In addition, in 2014 the litter mass was 58.6% higher under the canopy compared to between tree rows (2940 vs. 1850 hg ha^{-1}) (Fig. 4).

The soil organic carbon content and stock normal distribution ($p=0.63$ and $p=0.41$) and homoscedasticity ($p=0.32$ and $p=0.69$). The soil organic carbon content and stock were 38.7% (2.58 vs. 1.86 dag (decagram) kg^{-1}) and 38.5% (111 vs. 80.7 Mg ha^{-1}) higher ($p<0.001$) in 2014 compared to 2011, which represented a sink of 6.22 Mg ha^{-1} year^{-1} (Fig. 5).

The soil organic carbon content and stock were not influenced ($p>0.05$) by the SSP arrangements and sampled site (Table 2). The mean values of soil organic carbon content was 22.1 g kg^{-1} and carbon stock was 96.1 Mg C ha^{-1} in the 0–40 cm layer.

Discussion

The SSP was efficient in increasing the soil organic carbon stock (6.22 Mg ha^{-1} year^{-1}) (Fig. 5). Increases in the soil organic carbon stock in SSP were also observed in Latin America by Torres et al. (2017) in red-yellow latosol soil using *Eucalyptus* aged 3–4 years, Almeida et al. (2021) in haplic Cambisol soil (particle-size distribution ranged from 52 to 53% sand, 24 to 27% silt, and 21 to 24% clay) using *Eucalyptus* aged 4 years and Moreira et al. (2022) in red ferralsol soil using *Eucalyptus* aged 5 to 7 years and by Haile et al. (2010) in North America in spodosol and ultisol soils (particle-size distribution ranged from 87 to 96% sand, 2 to 4% silt, and 3 to 9% clay) using *Pinus* aged 8–40 years and Howlett et al. (2011) in Europe in gleyic umbrisols and inceptisols soils using *Pinus* aged 13 years. Although there are many differences in soil biochemical processes between

Table 1 Experimental area soil chemical characteristics at 0 to 20 and 20 to 40 cm depth

Soil depth (cm)	pH[a]	H + Al[b]	Al[c]	Ca[3]	K[d]	P[d]	OM[e] (dag kg^{-1})	Granulometry (g/kg)			
		Cmol$_c$ dm^{-3}			Mg dm^{-3}			Coarse sand	Fine sand	Silt	Clay
0–20	5.4	7.5	0.2	3.2	70.3	3.7	4.3	169	111	128	595
20–40	5.3	7.6	0.6	2.5	56.7	3.7	4.3	97	89	115	693

[a]pH in water suspension at a rate of 1:2.5

[b]Extractor Ca $(OAc)_2$ 0.5 mol pH 7.0

[c]Extractor KCl 1 mol L^{-1}

[d]Extractor Merlich-1

[e]Method Walkley and Black, reported in decagrams per kilogram

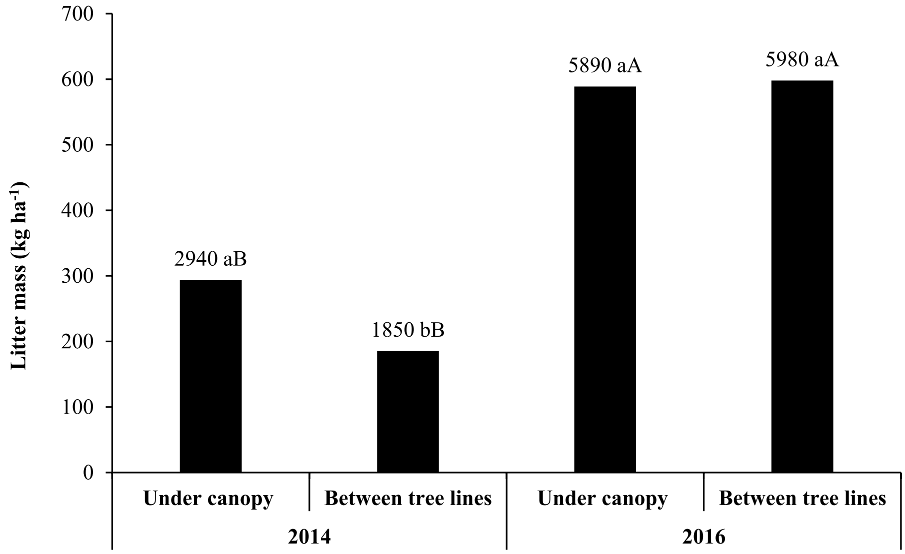

Fig. 4 Litter mass (kg ha^{-1}) in silvopastoral system under canopy and between the *Eucalyptus* rows in 2014 and 2016 Lowercase letters compare the site within the same year and uppercase letters compare the year within the same site by SNK test Standard error of mean = 1.17 and coefficient of variation = 31.2% (from transformed data) *p* value = 0.01

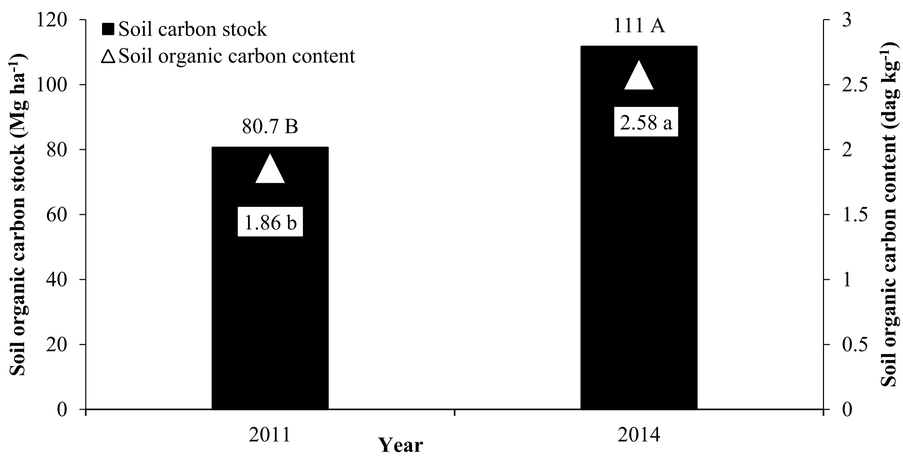

Fig. 5 Soil organic carbon content (dag kg^{-1}) and soil organic carbon stock (Mg ha^{-1}) in the 0–40 cm layer in 2011 and 2014 in different SSP spatial arrangements with *Urochloa decumbens* and *Eucalyptus* spp. Means followed by different letters differ by the SNK test Soil organic carbon content—Standard error of mean = 0.170 and coefficient of variation = 1.69% *p* value = 0.0001/Soil organic carbon stock—Standard error of mean = 2.51 and coefficient of variation = 16.3% *p* value = 0.0001

tropical and temperate regions, these results show a similar trend of increasing carbon stocks in different areas of the world. These increases in soil organic carbon stock in SSP usually are attributed to the soil protection against erosion, greater carbon cycling in litter, lower soil disturbance, greater root content mainly in the deeper layers and organic matter stabilization (Nair et al. 2009; Silveira et al. 2014).

Moreira et al. (2022) observed a carbon stock between 175 and 210 Mg ha^{-1} (up to 1 m deep) in SSP implemented in red ferralsol soil using *Eucalyptus* aged 5–7 years in the Brazilian Cerrado and that SSP had higher carbon stock than native vegetation. These results show that silvopastoral systems have high capacity to store carbon and can improve the indicators of Brazilian livestock. These authors also observed a higher stock and content of soil organic carbon in older systems. This increase was probably due to tree growth that increases the nutrient cycling from deeper layers, which increases the soil litter deposition (Oliveira et al. 2016; Cardinael et al. 2018). Another explanation is exudate release by tree

Table 2 Soil organic carbon content (g kg^{-1}) and soil organic carbon stock (Mg C ha^{-1}) in the 0–40 cm layer in different SSP spatial arrangements with *Urochloa decumbens* and *Eucalyptus* spp.

Parameter	SSP spatial arrangement			SEM	*p* value
	(3×2)+20 m	(2×2)+9 m	9×2 m		
Soil organic carbon content	22.2	23.0	21.0	0.600	0.563
Soil organic carbon stock	96.2	98.4	93.9	2.770	0.564
	Site				
	Between tree rows	Under tree canopy			
Soil organic carbon content	22.0	22.4		0.400	0.514
Soil organic carbon stock	97.0	95.4		1.710	0.520

(3×2)+20 m = spatial arrangements with three meters between trees, two meters between rows and 20 m between ranks (434 trees ha^{-1}) (2×2)+9 m = spatial arrangements with two meters between rows, two meters between trees and nine meters between ranks (909 trees ha^{-1}) 9×2 m = spatial arrangements with simple row, with two meters between trees and nine meters between ranks (556 trees ha^{-1}) SEM = standard error of mean Means followed by different letters on the line differ by the SNK test ($p < 0.05$)

roots (Baah-Acheamfour et al. 2015), which contribute to soil aggregate formation and to increase protection of organic matter against microbial decomposition (Nair et al. 2009).

Sarto et al. (2020) did not observe differences in soil organic carbon stocks among a SSP in arenic hapludult soil (particle-size distribution of 81.5% sand, 10.4% silt, and 8.1% clay) at 8 years after *Eucalyptus* planting, the monoculture of *U. brizantha* and the native vegetation. On the other hand, Almeida et al. (2021) observed higher SCS in a SSP in haplic Cambisol soil with 4 years of plantation with *U. brizantha* and *Eucalyptus cloeziana* or *Eucalyptus urograndis* with 14 m between ranks compared to degraded areas. This observation associated with the results of the present study indicates that SSP are able to increase SCS, offset emissions from other productive sectors and meet the low-carbon agriculture goals in tropical regions.

The soil carbon stock is one of the main ways to reduce global warming as it allows a large carbon removal from the atmosphere, in addition to making it possible to neutralize emissions from other commercial sectors. In the present study, the systems had an average of 95.9 Mg C ha^{-1} up to 40 cm deep, which would be capable of mitigating the enteric methane emissions of approximately 88 dairy cows for one year, considering the cattle emissions measured by Guimarães Jr et al. (2022). Moreira et al. (2022) observed an average of 175 Mg C ha^{-1} up to 100 cm deep in SSPs implemented in Brazil, which would be capable of mitigating the enteric methane emissions of approximately 160 dairy cows for one year. The study by Figueiredo et al. (2017), for example, evaluated carbon equivalent emissions for 10 years through a life cycle assessment and observed that the integration crop-livestock-forest system had carbon footprint of 12.6 kg CO_2 eq. kg^{-1} live weight without considering the carbon sink in trees (170 Mg CO_2 ha^{-1}) and in soil (16.1 Mg CO_2 ha^{-1}) and -28.1 kg CO_2 eq. kg^{-1} live weight considering carbon in trees and soil. Furthermore, in this study the increase in soil carbon stock (16.1 Mg CO_2 ha^{-1}) would be capable of neutralizing twice the emissions from cattle (8.00 Mg CO_2 eq. – from CH_4 from enteric fermentation, N_2O from manure, CH_4 from manure and emissions from pasture management).

The litter mass increase (Fig. 4) indicates that in SSP the increase in nutrient cycling and the greater carbon supply to the soil through litter are responsible for the increase in carbon stocks. In addition, the lower soil disturbance increases the organic matter protection against degradation, which increases the soil carbon permanence. The main mechanisms for soil carbon stabilization are physical protection of organic matter against decomposers due to inaccessibility in aggregates, selective preservation due to the organic compounds recalcitrance and the organomineral interaction on sesquioxides surface (Dieckow et al. 2009; Tivet et al. 2013).

The results of the present study showed that older systems have more litter, which increases the incorporation of carbon in the soil. Moreira et al. (2022) observed litter mass of 206 kg ha^{-1} in SSP with

Eucalyptus, values similar to those observed in the present study. In addition, the authors observed higher concentrations of particulate organic carbon (14.3 vs. 7.16 g kg^{-1}) and particulate organic nitrogen (0.686 vs. 0.319 g kg^{-1}) in 7-year-old SSP compared to SSP with 5 years; and higher concentrations of particulate organic carbon and nitrogen in 7-year-old SSP compared to native vegetation. The particulate organic carbon fractions are particles from fungi hyphae and plant residue decomposition recently formed. Increasing these fractions is important to increase soil carbon and these results show that in SSP there is frequent cycling of these nutrients in the soil.

Another important result of this study is the increase in the carbon stock in soils occupied with pastures. In Brazil, deforestation and pastures implantation without suitable management are responsible for the pasture degradation occurrence and carbon loss from the soil to the atmosphere (Braz et al. 2013; Carvalho et al. 2014). Therefore, the results of this study show that SSP is able to sink carbon from the atmosphere and mitigate greenhouse gas emissions. According to the 2017 Agricultural Census (IBGE 2017), 89.3% of Brazilian farms have an area of up to 100 ha. If 5% of the area of these farms were converted to SSP and obtained the same soil organic carbon increase as the present study, 151 tons of carbon could be stocked in the soil of each farm.

However, to really obtain this large carbon stock at the national level, it is necessary that SSPs are effectively implemented on commercial farms. The studies by Oliveira et al. (2022) and Oliveira et al. (2023) showed that the planning of tree arrangements in SSP, mainly considering tree density, distance between rows and planting orientation, needs to be done with technical criteria so as not to negatively impact the productivity and profitability of the systems.

Conclusion

The SSP is able to sink carbon from the atmosphere and increase the soil organic carbon stock. The SSP use makes it possible to reverse the carbon loss process in degraded pastures and to mitigate GHG emissions from livestock.

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Author contributions Oliveira AF = data analysis and writing Santos CA = data collection Gonçalves LC = review Viana MCM = data collection and conceptualization Gontijo Neto MM = data collection and conceptualization Silva EA = data collection and conceptualization Lana AMQ = conceptualization and review

Declarations

Competing interests The authors declare that there is no conflict of interest or specific funding in this study.

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