Journal of Soil Science and Plant Nutrition
https://doi.org/10.1007/s42729-025-02985-w

ORIGINAL PAPER

Spatial Pattern of Litter Decomposition and Soil Carbon and Nitrogen Stocks in an Agrosilvopastoral System in the Cerrado Biome

Jaqueline de Cássia de Oliveira[1] · Igor Costa de Freitas[1] · Evander Alves Ferreira[1] · Ana Clara Santos Duarte[1] · Juliana Martins Ribeiro[1] · Demerson Luiz de Almeida Barbosa[2] · Warley Rodrigues Oliveira[1] · Diana Signor[3] · Miguel Marques Gontijo Neto[4] · Elaine Cristina Teixeira[5] · Luiz Arnaldo Fernandes[1] · Leidivan Almeida Frazão[1]

Received: 2 May 2025 / Accepted: 29 December 2025

Abstract

Purpose This study evaluated the effects of eucalyptus trees in an agrosilvopastoral (ASPS) system on litter dynamics, CO_2 efflux, soil fertility, and soil carbon (C) and nitrogen (N) stocks, in order to understand how these factors contribute to nutrient cycling and the restoration of soil quality, comparing it with nominal pasture (NP) and native vegetation (NV).

Methods Five treatments were assessed, including three locations within a nine years-old ASPS established with double-row eucalyptus planting, based on proximity to the trees: P1 (area between the double rows), P2 (2.5 m), and P3 (7.0 m). Litter deposition and decomposition and CO_2 efflux were monitored monthly for one year. Soil samples collected up to 50 cm depth were analyzed for bulk density, fertility attributes, and carbon and nitrogen stocks.

Results Annual litter deposition was highest at P1 (5.85 Mg ha^{-1} yr^{-1}), decreasing with distance from trees. Decomposition rates were highest at P3 and P1, with faster turnover (half-life ~ 203–224 days), and lowest at P2 (279 days). CO_2 efflux was highest at P1 (6.798 µmol m^{-2} s^{-1}), likely due to increased soil moisture near the trees. Litter input contributed to maintaining K and P levels, despite no fertilisers being applied after the first five years of ASPS establishment. Soil C and N stocks were highest in NV (115.4 and 11.3 Mg ha^{-1}, respectively), and similar between NP (92.4 and 8.7 Mg ha^{-1}) and ASPS (89.9 and 8.9 Mg ha^{-1}). The findings highlight the role of litter in nutrient cycling and maintaining soil C and N in ASPS.

Conclusion Our findings highlight the significant potential of agrosilvopastoral systems to enhance soil fertility and boost carbon and nitrogen stocks in tropical environments. However, these benefits are strongly contingent upon the effective and integrated management of both tree and pasture components. Without appropriate management practices, the full benefits of such systems may not be achieved, limiting their potential to enhance soil quality over time compared to conventional pastures and native vegetation.

✉ Leidivan Almeida Frazão
lafrazao@ufmg.br

1 Instituto de Ciências Agrárias, Universidade Federal de Minas Gerais, Av. Universitária 1000, Montes Claros, MG 9400-090 , Brazil

2 Universidade Federal dos Vales do Jequitinhonha e Mucuri, Rod. MGT 367 km 583, Diamantina, MG 39100-000 , Brazil

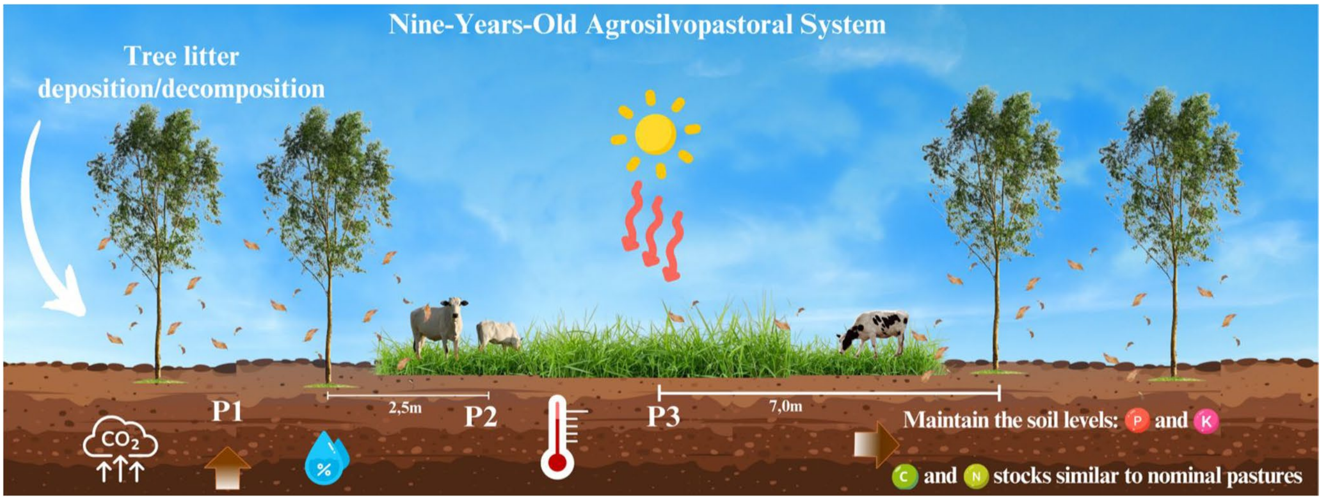
3 Empresa Brasileira de Pesquisa Agropecuária, Embrapa Semiárido, Rodovia BR 428 km 152, Petrolina, PE 56302-970, Brazil

4 Empresa Brasileira de Pesquisa Agropecuária, Embrapa Milho e Sorgo, Rodovia MG 424 km 45, Sete Lagoas, MG 35701-970, Brazil

5 Universidade Federal de São João Del-Rey, Rodovia MG-424- km 47, Sete Lagoas, MG, Brazil

Published online: 12 January 2026

Graphical Abstract



Keywords Litter deposition · CO_2 efflux · Livestock-forest integration · Luminous intensity

1 Introduction

With the increase in the concentration of greenhouse gases (GHG) in the atmosphere, several countries, during the 21 st United Nations Climate Change Conference (COP21) in Paris, committed to adopting measures to limit the average increase in global temperature to 1.5 °C (WMO, 2018). Soils, as the largest terrestrial carbon reservoir, play a fundamental role towards achieving these goals, acting as a potential long-term carbon sink and helping to reduce GHG emissions into the atmosphere (Breidenbach et al. 2022; Wehrle et al. 2022). The carbon sink capacity of agricultural soils can be improved with management practices that increase the input of organic matter and reduce decomposition rates. Although agricultural systems can be a carbon sink, they may also suffer the negative consequences of global climate change (Davidson and Janssens 2006; Tao et al. 2023).

The implementation of integrated agricultural production systems is strategic for increasing the resilience of these systems and for recovering degraded areas due to the positive impact they have on the physical and chemical quality of the soil. These impacts include improving fertility and increasing carbon (C) and nitrogen (N) stocks, especially in the surface layers, due to the accumulation of soil organic matter (SOM) (Ramakrishnan et al. 2021; Vásquez et al. 2021; Olaya-Montes et al. 2021). However, in addition to the type of climate and soil, several factors influence the efficiency of an integrated system, such as soil management practices, the plant species involved, and the arrangement and spacing between them.

Given the role of the soil as a source and reservoir of C, the inclusion of tree components in pasture areas affects nutrient cycling in integrated systems. This influence varies depending on the spatial arrangement and tree spacing, which alter litter input and exposure to solar radiation, both of which affect the decomposition of plant residues (Schinato et al. 2023). Tree species in silvopastoral systems also impact the soil C sink potential through variations in nutrient uptake, canopy structure, and litter quality (Hoosbeek et al. 2016).

Soil CO_2 efflux is a key component of the carbon cycle and is strongly influenced by both biotic and abiotic factors, including temperature, soil moisture, root biomass, and land management practices. These factors stimulate organic matter decomposition by enhancing microbial activity, which plays a central role in soil respiration (Koncz et al. 2015; Sun and Chang, 2019; Sanna et al. 2021). In silvopastoral systems, changes in microclimate and organic inputs especially near tree rows can modulate CO_2 emissions and affect soil carbon dynamics.

Defining the type and arrangement of integrated systems must consider the socioeconomic and environmental context of rural properties. Therefore, studies are needed to support decision-making and policies that promote sustainable land use, aiming to enhance soil carbon sequestration and mitigate GHG emissions (Lecegui et al. 2022; Sarto et al. 2020). In this context, silvopastoral systems demonstrate a synergistic effect: pastures promote C accumulation in surface layers, while tree species such as eucalyptus contribute to deeper C storage (Oliveira et al. 2024). Additionally, nutrient cycling in these systems is driven by plant uptake, litter deposition, and the transformation of organic residues into SOM (Sena et al. 2025).

Considering these aspects, we hypothesized that the inclusion of tree components in an integrated agricultural system enhances soil fertility and soil C and N stocks due to higher input of plant residues, microclimatic modifications, and greater accumulation of organic matter in the soil surface layers. Thus, this study aimed to evaluate the effects of eucalyptus trees in a nine-years-old agrosilvopastoral system on litter dynamics, soil CO_2 efflux, fertility, and C and N stocks, in order to understand how these factors contribute to nutrient cycling and the restoration of soil quality, comparing it with nominal pasture (NP) and native vegetation (NV).

2 Materials and Methods

2.1 Location of the Study Area and Climate Data

The study was carried out at the Fazenda da Barra Ranch in the district of Francisco Sá, Minas Gerais, Brazil (16º38’44.02” S and 43º 42’ 43.77” W) (Fig. A1 A). The soil in the area was classified as a eutrophic Haplic Cambisol with a clayey texture (Almeida et al. 2021). These soils predominantly derive from parent materials of the Bambuí Group—such as limestone, siltstone, and slate—which impart higher base saturation and lower acidity relative to the typically acidic soils of the Cerrado biome. The area has a mean altitude of 590 m, flat relief, and is located in a transition area between the Cerrado (Brazilian Savanna) and a semideciduous seasonal forest. The average temperature is 23.4 °C, while the average rainfall is 1,105 mm. According to the Köppen classification, the climate is type Aabrol

w, with well-defined seasons, featuring hot and humid summers and cold and dry winters. The average annual rainfall for the northern mesoregion of the State of Minas Gerais, obtained between February 2022 and March 2023 from the Montes Claros-A506 weather station close to the study area, was 955.40 mm (Fig. A1 B). November 2022, December 2022 and January 2023 had the greatest rainfall, with a depth of 266.40 mm, 252.40 mm and 314.00 mm, respectively. No rainfall was recorded in June, July or August 2022, nor in March 2023; low rainfall was also seen in March 2022 (1.2 mm) and February 2023 (2.60 mm).

The average annual temperature for 2022, obtained from the same weather station as the rainfall data, was 23 °C (Fig. A1 B). The coldest months were from May to July 2022, with temperatures ranging from 20.13 °C to 20.72 °C. October had the highest temperature, reaching 25.92 °C. With the exception of January (23.73 °C), the first few months of 2023 had an average temperature greater than 25 °C. The average annual relative humidity was 56.41%. The wettest months were February, December and January of 2023, while August, September and October of the same year were the driest.

Luminous intensity was monitored over one year, and the mean values were 328.00 µmol m^{-2} s^{-1} in the agrosilvopastoral systems, 110.00 µmol m^{-2} s^{-1} in the native vegetarian and 1037.22 µmol m^{-2} s^{-1} in the nominal pasture. Seasonal variation was observed in the native vegetation due to the deciduous forest canopy, with greater light penetration in the dry season (August–November) and lower values in the rainy season. Nominal pasture consistently exhibited the highest luminous intensities, with peaks in January–March and reductions in May–July (Fig. A5).

2.2 Land-use History

In 1998, approximately 10 ha of native vegetation were converted to a pasture of *Urochloa brizantha* ‘Marandu’ (marandu grass), which for 13 years was used for dairy farming. From 2011 onwards, there was no management in the area, and the pasture was gradually replaced by spontaneous vegetation, reducing the productivity of the forage. In 2012, 3.2 ha of the area were converted to an agrosilvopastoral system, formed by double rows of eucalyptus (at a spacing of 2 × 3 m) with 14 m between the rows (alleys), of which 1.6 ha were planted with eucalyptus urograndis (*E. urophylla* x *E. grandis*), the area used for the present study, and 1.6 ha were planted with eucalyptus cloeziana (*Eucalyptus cloeziana* F. Muell). After a soil analysis, 190 g per hole of reactive natural phosphate was applied. Initial fertilisation of the eucalyptus seedlings included the application of 7.2 g N, 36 g P, 7.2 g K and 1.0 g B, Cu and Zn per plant. The same doses were then applied during the early development of the plants up to 24 months after transplanting. Seedlings were irrigated at planting and again at two and three months of growth, with four litres of water applied per plant each time. In December of the same year, sorghum (*Sorghum bicolor*) was planted in the alleys, which was harvested in May 2013 for silage. The sorghum was reseeded in November 2013, together with the planting of marandu grass. The second sorghum harvest for silage took place in April 2014, however the pasture remained poorly established due to the long dry season.

In November 2014, heavy harrowing, reseeding of the Marandu grass, and pruning of the eucalyptus were carried out. Following these management operations, the integrated production system was maintained as an arrangement of eucalyptus and Marandu grass. The sequence of operations can be seen in Fig. A1 C.

From 2015 onwards, the grass in the integrated system was managed by mowing during the rainy season only, without applying chemical fertilisers to replenish the nutrients, thereby causing gaps in the planting alleys leaving strips of exposed soil. After this period, the tree component did not undergo any pruning, selective thinning, or pest and disease control. The area of pasture used as reference, which has the same prior land use history, and located to the side of the integrated production system was also managed only by mowing during the rainy season, with no maintenance fertilisation. However, due to the increase in rainfall between 2020 and 2022 compared to the previous 6 years, the pasture produced a greater volume of forage and was classified as nominal. An average of 15 calves and 10 adult cows per month were rotated annually in the areas of agrosilvopasture and nominal pasture during the rainy season (instantaneous 4.34 animal units per hectare (AU), where one AU corresponds to an adult bovine weighing 450 kg live weight).

2.3 Description of the Treatments

The following land-use and management systems were considered for the study:

− Native vegetation (NV): reference area, characterised by vegetation typical of transition areas between the Cerrado and semideciduous seasonal forest. The following species were found in the area of NV: *Deguelia costata*, *Talisia esculenta*, *Senna multijuga*, *Senna spectabilis*, *Anadenanthera macrocarpa*, *Machaerium stipitatum*, *Machaerium scleroxylon*, *Machaerium* sp., *Aspidosperma* sp., *Senegalia polyphylla*, *Aspidosperma* sp. 2, *Astronium urundeuva*, *Pterogyne nitens*, *Piptadenia viridiflora and Sclerolobiu*m sp.

− Nominal pasture (NP): area cultivated during 23 years with *Urochloa brizantha*, managed on occasion by mowing and with a low stocking rate (< 1 AU/ha) during the dry season.

− Agrosilvopastoral System (ASPS): nine years of age, with double rows, using the hybrid eucalyptus urograndis (*E. urophylla* x *E. grandis*) intercropped with marandu grass (*Urochloa brizantha*), at a spacing of (2 × 3 m) + 14 m.

2.4 Production and Decomposition of Litter from the Tree Component in SPS

To analyse the litter, points of influence of the arboreal component in the integrated system were selected, taking into account the projection of the tree canopy: between the eucalyptus trees (P1), 1 m from the trees (P2), and 4 m from the trees (P3). Five replications were used at each point (Fig. A2 A).

In February 2022, litter traps of 0.16 m² (0.4 × 0.4 m), with a 1-mm mesh nylon bottom were installed at a height of 50 cm from the ground to assess the aerial litter of the eucalyptus in the SPS. The traps were fixed at three points in the SPS (P1, P2, P3), each with 5 replications, giving a total of 15 traps (Fig. A2 B).

The intercepted litter was collected monthly from March 2022 to February 2023, and the micro- and macronutrient content in leaves and branches of eucalyptus trees were determined (Table 1). After each collection, the litter was separated into leaves, stem, reproductive material (RM) and amorphous material (AM: of unidentified plant or animal origin). The fractions were then dried in a forced air circulation oven at 65 °C to constant weight. At the end of the evaluation period, the accumulated litter biomass (in Mg ha^{-1}) and the percentage of each fraction (leaf, stem, RM and AM) were determined.

To evaluate the decomposition, 12 nylon litterbags measuring 20 × 15 cm and with a 1 mm mesh, containing 30 g of eucalyptus litter collected at random in the

Table 1 Macronutrient and micronutrient concentrations in leaves and branches of Eucalyptus trees in a agrosilvopastoral system at Barra Ranch, Francisco Sá district, Minas Gerais, Brazil

Treatment	……… Leaves ………										
	N	*P*	K	Ca	Mg	S	Cu	Fe	Zn	Mn	B
	------g kg^{-1}------						------mg kg^{-1}------				
ASPSP1	7.15ns	0.47a	5.54a	8.33a	2.47a	0.73a	0.73ns	119.47ns	5.22ns	888.04ns	26.15ns
ASPSP2	7.04ns	0.43b	5.04b	8.58a	2.42a	0.72a	0.68ns	114.79ns	5.16ns	945.77ns	25.01ns
ASPSP3	7.20ns	0.48a	5.41a	7.93b	2.32b	0.74a	0.70ns	116.35ns	5.45ns	966.46ns	24.41ns
CV (%)	7.76	4.43	3.29	3.06	2.94	2.59	10.19	4.66	5.38	6.89	4.75
	……… Branches ………										
	------g kg^{-1}------						------mg kg^{-1}------				
ASPSP1	1.99ns	0.22b	6.10b	10.43a	2.13a	0.19	1.03a	29.97a	6.07a	715.70a	6.63a
ASPSP2	1.94ns	0.36a	6.62a	9.40b	1.63c	0.18	1.04a	24.92b	6.03a	630.82b	4.24b
ASPSP3	1.91ns	0.23b	6.57a	9.12b	1.97b	0.19	0.60b	23.58b	5.06b	722.13a	3.15b
CV (%)	9.27	3.22	3.89	5.00	4.62	5.14	5.76	12.86	4.83	5.71	27.68

ASPS agrosilvopastoral system; P1 = point between eucalyptus rows; P2 = point 1 m from eucalyptus trees; P3 = point 4 m from eucalyptus trees. Means followed by the same letter in the column do not differ significantly by Tukey's test ($p < 0.05$). "ns" indicates no significant difference agrosilvopastoral system, were distributed on soil surface near each litter trap. The litterbags were collected monthly together with the litter intercepted by the traps. After each collection, the litterbags were taken to the laboratory, washed to remove any soil, and dried in a forced air circulation oven at 65 °C (to constant weight) to determine the dry weight. The remaining biomass (%) was then determined using the mathematical equation: remaining biomass (%) = (final weight/initial weight) x 100. The rate of decomposition (K) was also determined, using the equation: $C = C_0\, e^{-kt}$, where C: final weight of the samples; C_0: initial weight; t: time elapsed during the experiment; and k: decomposition constant (Pardo et al. 1997). Finally, the time required for 50% of the litter to decompose ($t_{0.5}$) was determined using the following equation: $t_{0.5} = \ln 2/k$, where $t_{0.5}$: half-life or the time needed to transform 50% of the biomass (Costa and Atapattu 2001).

2.5 Soil CO_2 Efflux between the Different Types of Land Use and Management

The soil CO_2 efflux (μmol m^{-2} s^{-1}) was determined monthly using a bell jar (ADC Soil Hood) fixed to the ground and coupled to a portable IRGA device (Infra-Red Gas Analyser). The assessments were made in the vicinity of each litter trap (Fig. A2 B) and also at five random points in the reference areas (nominal pasture and native vegetation). Water flow (mmol m^{-2} s^{-1}) and surface temperature (°C) were also determined at each assessment.

2.6 Soil Sampling and Preparation of the Samples

In February 2022, soil samples were collected in trenches from the 0–5, 5–10, 10–20, 20–30, 30–40 and 40–50 cm layers, with five replications in the areas of native forest and pasture. To sample the soil in the ASPS, three points were selected based on the distance from the rows of eucalyptus, the first between the trees (P1), the second 2.5 m from the trees (P2), and the third 7 m from the trees (P3). In the agrosilvopastoral system, there were five replications per sampling point (P1, P2, P3), giving a total of 15 trenches (Fig. A2 B). After collection, the soil samples were air-dried and passed through 2-mm sieves. Samples up to a depth of 30 cm (0–5, 5–10, 10–20, 20–30) were separated for chemical and physical analysis. After the initial preparation, the roots were removed, and the samples were macerated and passed through 0.150-mm sieves to determine the contents of total organic carbon (TOC) and total nitrogen (TN). Undisturbed samples of each depth were also collected to determine the apparent density of the soil.

2.7 Assessing the Fertility and Density of the Soil

Soil fertility was analysed as per the method of Teixeira et al. (2017). The apparent density of the soil was determined using the volumetric ring method (stainless steel rings, ±5 cm in diameter) for each of the depths under evaluation (Teixeira et al. 2017).

2.8 Determining the Contents and Stocks of Soil Carbon and Nitrogen

The levels of TOC and TN were obtained by dry combustion using an elemental analyser (Leco CN-2000®, St. Joseph, MI, USA) that determines the carbon content by infrared absorption and the nitrogen content by thermal conductivity. The C/N ratio of each soil sample was calculated from these results.

To determine the carbon (SC) and nitrogen (SN) stocks, in Mg ha^{-1}, the TC or TN content (%) was multiplied by the apparent density of the soil (g cm^{-3}) and by the thickness of the respective layer (cm). The values were then corrected for the same volume of soil in the area of native vegetation (reference area), as per the methodology proposed by Ellert and Bettany (1995) and Moraes et al. (1996).

2.9 Statistical Analysis

Generalised linear models (glm) were used to describe the pattern of litter decomposition. Principal component analysis was used to describe the pattern of litter deposition and the constituent parts of the litter (stems, leaves, amorphous material and reproductive material).

To analyse the CO_2 efflux, luminous intensity and soil C and N stocks, time series were generated, and the Shapiro-Wilk test was used to check for normal distributions, and Bartlett's test was used to check for homogeneity of variances. Due to the CO_2 efflux and light intensity data did not meet the assumptions of ANOVA, the nonparametric Kruskal-Wallis test and the Dunn-Bonferroni multiple comparison test were applied at a level of 5%. To compare the soil C and N stocks between the different land-use systems and sampling points in the integrated systems, an analysis of variance was carried out in a completely randomised design, with five replications. The mean values were compared using the t-test (LSD) at 5% significance.

Soil data regarding density and chemical attributes (pH, P, Ca, Mg, K, Al, C, N, density, CEC and V%) were analysed for each layer of soil (0–5, 5–10, 10–20, 20–30 cm) using multivariate statistical methods and applying principal component analysis. Each analysis was carried out using the R Core Team software (2023).

3 Results

3.1 Litter Production and Decomposition in the Forest Component

Monthly variations in litter deposition were observed across the different sampling points within the agrosilvopastoral system (ASPS) (Fig. 1A). The highest average annual litter deposition occurred at P1 (between double rows of eucalyptus), with 5.85 Mg ha^{-1} yr^{-1}, followed by P2 (1.0 m from the tree row) with 5.20 Mg ha^{-1} yr^{-1}, and P3 (4.0 m from the tree row) with 4.17 Mg ha^{-1} yr^{-1}. Peaks in litter deposition were recorded in March and May 2022, and again in January and February 2023. Conversely, a marked reduction in litter input was observed from June to December 2022.

The composition of the accumulated plant material also exhibited a clear seasonal pattern across the leaf, stem, reproductive material (RM), and amorphous material (AM)

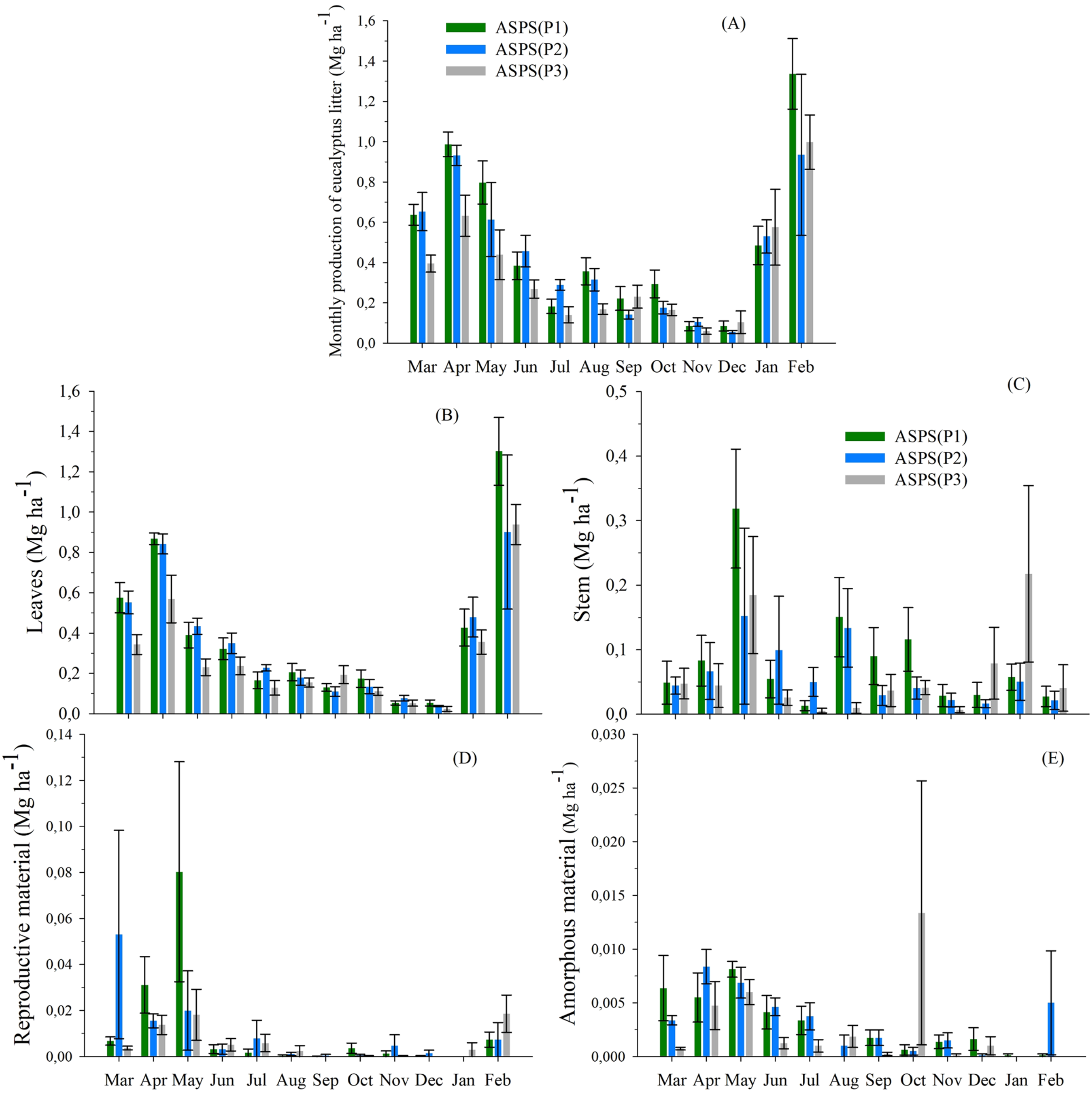


Fig. 1 Monthly production of eucalyptus litter (**A**) and its components: leaves (**B**), stems (**C**), reproductive material (**D**), and amorphous material (**E**) in a agrosilvopastoral system at Barra Ranch, Francisco Sá district, Minas Gerais, Brazil. ASPS(P1) = point between trees in the row; ASPS(P2) = point 1 m from the row of trees; ASPS(P3) = point 4 m from the row of trees. Values represent means (n = 5) ± standard error

fractions (Fig. 1B and E). The leaf fraction accounted for the largest proportion of total litter mass, contributing 69.20%, followed by stems (27.86%), RM (1.81%), and AM (1.13%) (Fig. 2).

Regarding the litter decomposition, the pattern of biomass reduction (% remaining biomass) in the litterbags was monitored throughout the year (Fig. 3). The highest decomposition rates were observed at P3 and P1, with final remaining biomass of approximately 28.71% and 32.33%, respectively. In contrast, decomposition was slower at P2, where 40.44% of the original biomass remained after one year.

The decomposition constant (K) was similar at P1 and P3, with values of 0.00309 and 0.00342 g g^{-1} day^{-1}, corresponding to half-lives ($t_{0.5}$) of 224 and 203 days, respectively. P2, on the other hand, showed a lower decomposition constant (0.00248 g g^{-1} day^{-1}) and a longer half-life of 279 days.

3.2 Soil CO_2 Efflux

In the agrosilvopastoral system, the highest soil CO_2 effluxes were recorded at point P1 (Fig. 4A) during the months of December, January, and February, reaching values of 4.735 µmol m^{-2} s^{-1}, 6.798 µmol m^{-2} s^{-1}, and 3.778 µmol m^{-2} s^{-1}, respectively. At point P2, peak CO_2 effluxes coincided with the rainy season (November, December, and January), with values of 2.521 µmol m^{-2} s^{-1}, 3.629 µmol m^{-2} s^{-1}, and 3.994 µmol m^{-2} s^{-1}, respectively. A similar temporal pattern was observed at point P3. The native vegetation (NV) exhibited the highest CO_2 effluxes between November and February, with values of 3.316 µmol m^{-2} s^{-1}, 4.371 µmol m^{-2} s^{-1}, 9.424 µmol m^{-2} s^{-1}, and 4.106 µmol m^{-2} s^{-1}, respectively. In contrast, the nominal pasture (NP) showed its greatest efflux values from November to January (Fig. 4B).

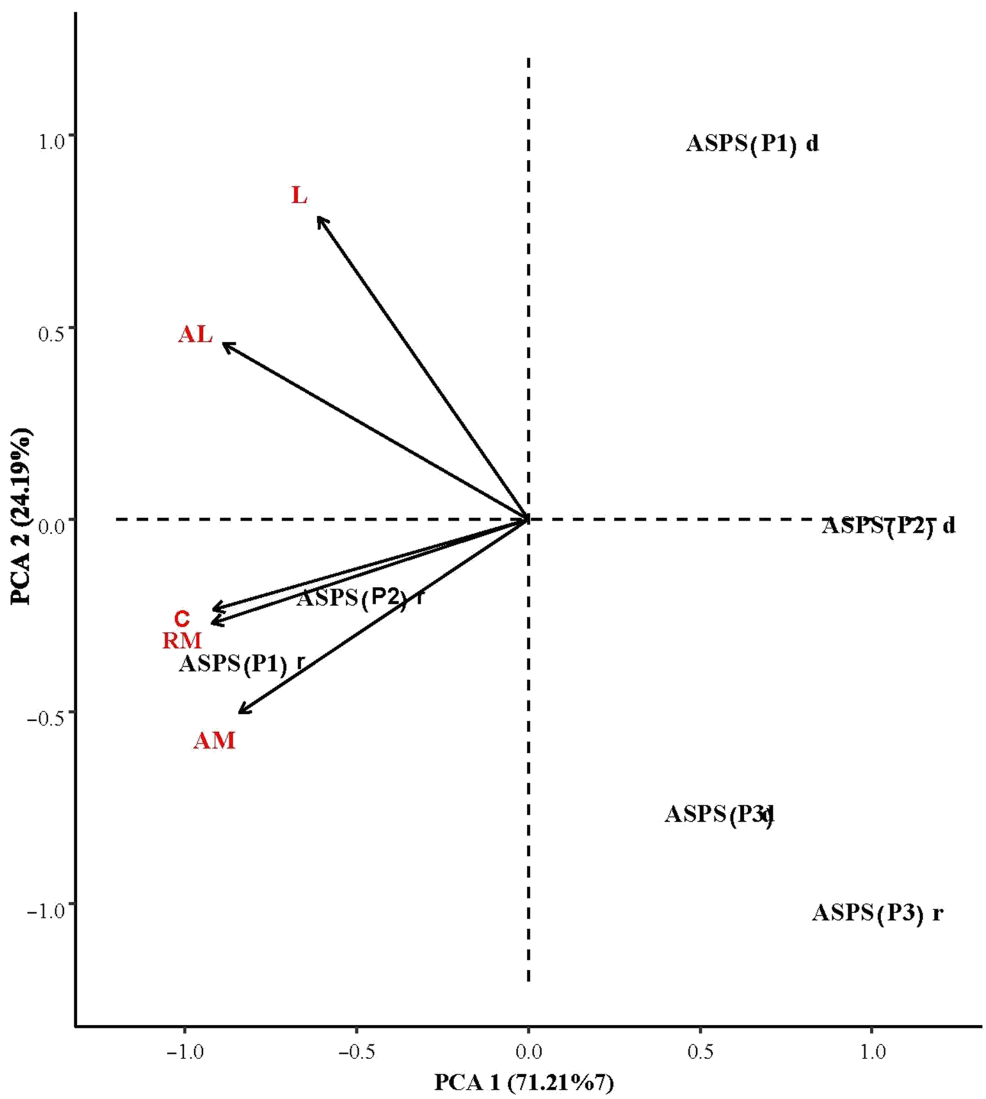


Fig. 2 Principal component analysis (PCA) of total accumulated litter (AL) and its fractions: leaves (L), stems (S), reproductive material (RM), and amorphous material (AM) in a Agrosilvopastoral system at Barra Ranch, Francisco Sá district, Minas Gerais, Brazil. ASPS(P1) = point between trees in the row; ASPS(P2) = point 1 m from the row of trees; ASPS(P3) = point 4 m from the row of trees. "r" = rainy season; "d" = dry season

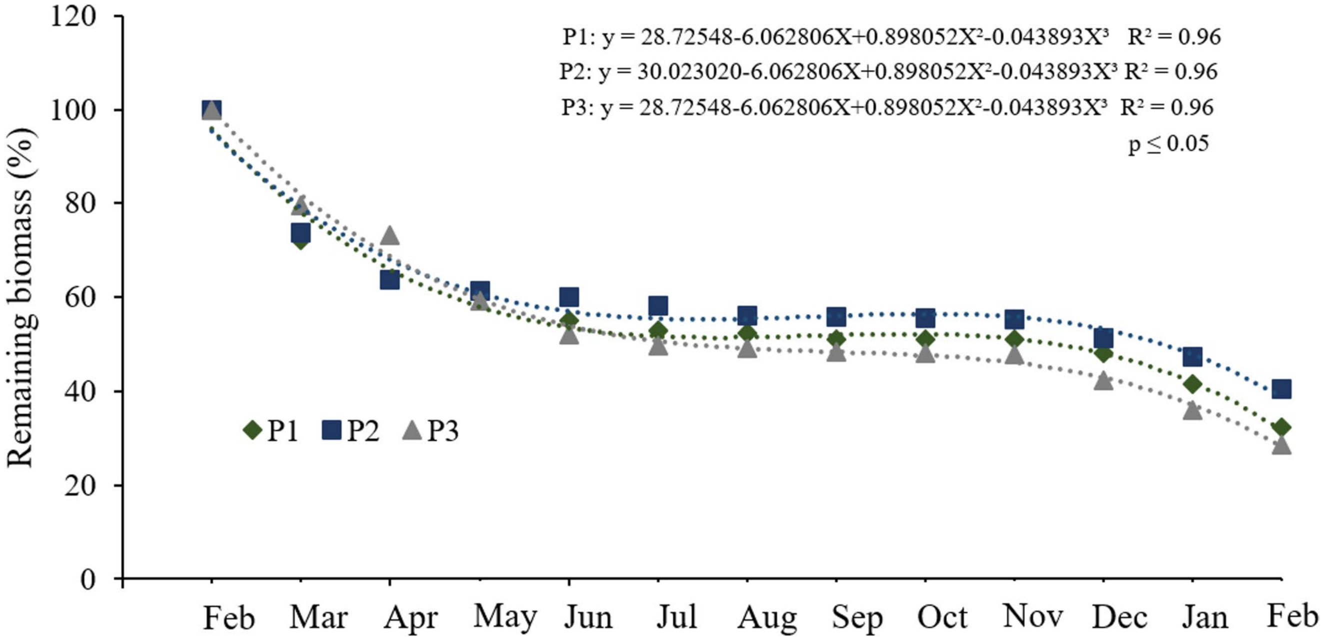


Fig. 3 Litter decomposition curve in a agrosilvopastoral system at Barra Ranch, Francisco Sá district, Minas Gerais, Brazil. ASPS(P1) = point between eucalyptus trees in the row; ASPS(P2) = point 1 m from the row of trees; ASPS(P3) = point 4 m from the row of trees. The dotted lines represent the fitted polynomial regression models (shown in the figure), with $R^2 = 0.96$ and $p \leq 0.05$. Values represent mean ± standard error ($n = 5$)

3.3 Soil Fertility and Bulk Density

The results for soil nutrient content and bulk density are presented in Table A1. The principal component analysis (PCA) revealed that PC1 and PC2 together explained over 80% of the variability in soil attributes across all evaluated layers (Fig. 5). Native vegetation (NV) consistently exhibited the highest values of calcium (Ca), carbon (C), nitrogen (N), and cation exchange capacity (CEC) at all depths, with these variables contributing most significantly to the soil analysis (Table A1, Fig. 7). Bulk density also influenced the results, except in the 5–10 cm layer (Fig. 5B), where it did not show a negative correlation with Ca, C, N, or CEC. These findings suggest that increased bulk density tends to reduce soil fertility. The highest magnesium (Mg) levels and base saturation (V% = (K + Ca + Mg)/CEC) were likewise observed in NV, likely reflecting the absence of fertilisation and nutrient replenishment in the agrosilvopastoral system (ASPS) and nominal pasture (NP). Additionally, aluminum (Al), phosphorus (P), and potassium (K) concentrations were elevated in the top two soil layers at point P3 and in the two deepest layers at P1, influenced by nutrient inputs from litterfall (Table A1). Bulk density varied with depth: it was higher at P2 and in the pasture area in the 0–5 cm (Fig. 5A) and 20–30 cm layers (Fig. 5D), while in the 10–20 cm layer, density peaked at P3.

3.4 Content and Stocks of Soil Carbon and Nitrogen

There was no difference in soil carbon (C) content among the sampling points within the integrated system. However, point P1 showed higher nitrogen (N) values in the 30–40 cm and 40–50 cm layers (Table 2). Additionally, the C and N contents in the agrosilvopastoral system (ASPS) were similar to those in the nominal pasture (NP), but lower than in the native vegetation (NV). No significant differences were observed between treatments in the 20–30 cm, 30–40 cm, and 40–50 cm layers (Table 3).

In the ASPS, the stocks of C and N were similar across the sampling points (P1, P2, and P3) and between the evaluated systems (Fig. 6A and C; Table A.2), except in the 30–40 cm soil layer, where the nitrogen stock was higher at P1. In the 0–50 cm soil layer, the C and N stocks at P1 were 93.2 Mg ha^{-1} and 9.3 Mg ha^{-1}, respectively, followed by P2 with 89.9 Mg ha^{-1} and 8.8 Mg ha^{-1}, and P3 with 86.6 Mg ha^{-1} and 8.7 Mg ha^{-1} (Table A.2). When comparing the three land-use types (Fig. 6B and D; Table A.3), the highest C and N stocks in the 0–50 cm layer were observed in native vegetation (NV), with 115.4 Mg ha^{-1} and 11.3 Mg ha^{-1}, respectively, while the stocks in nominal pasture (NP) and ASPS were similar, with 92.4 Mg ha^{-1} and 8.7 Mg ha^{-1} in NP, and 89.9 Mg ha^{-1} and 8.9 Mg ha^{-1} in ASPS.

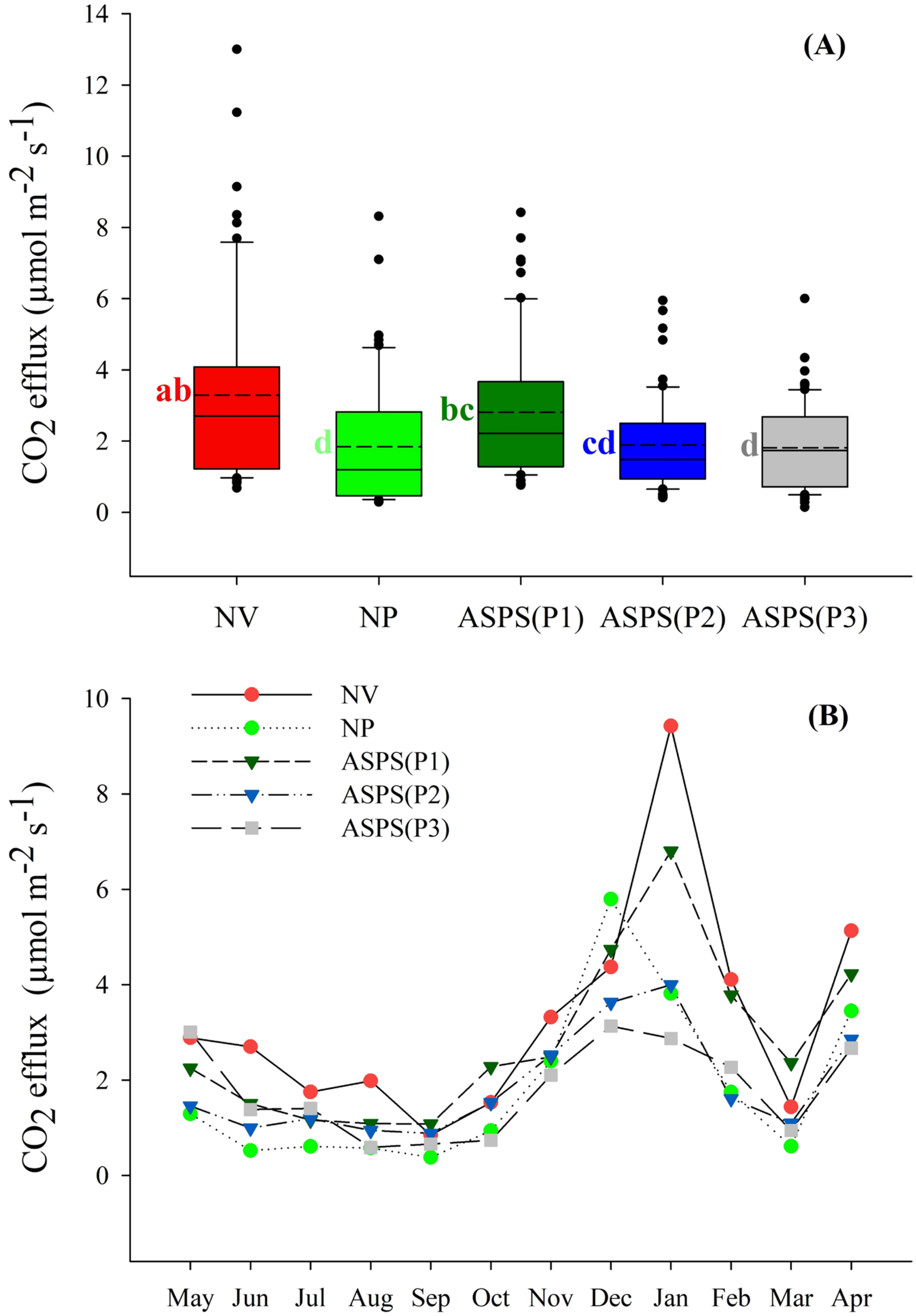


Fig. 4 Boxplot (**A**) and temporal dynamics (**B**) of soil CO_2 efflux (μmol m^{-2} s^{-1}) under different land-use systems at Barra Ranch, Francisco Sá district, Minas Gerais, Brazil. NV = native vegetation; NP = nominal pasture; ASPS = agrosilvopastoral system; ASPS(P1) = point between eucalyptus trees in the row; ASPS(P2) = point 1 m from the row of trees; ASPS(P3) = point 4 m from the row of trees. In (A), different letters indicate significant differences among treatments according to the Kruskal–Wallis test followed by the Dunn–Bonferroni multiple comparisons test ($p \leq 0.05$). Dashed horizontal lines within boxplots represent mean values; solid horizontal lines indicate medians. In (B), values represent mean ± standard error ($n = 5$)

4 Discussion

Our research provides comprehensive insights into eucalyptus litter deposition and decomposition, soil CO_2 efflux, soil fertility, bulk density, and soil carbon (C) and nitrogen (N) stocks within an agrosilvopastoral system established on a Haplic Cambisol in the Cerrado biome. By integrating these components, the study elucidates the main environmental drivers regulating nutrient cycling and carbon dynamics under an integrated land-use system, offering a robust reference for future studies conducted under different edaphoclimatic conditions.

Litter deposition exhibited marked seasonal variation, closely following the regional rainfall pattern, with higher inputs during the rainy months, when soil moisture and relative humidity were elevated. Soil temperature remained

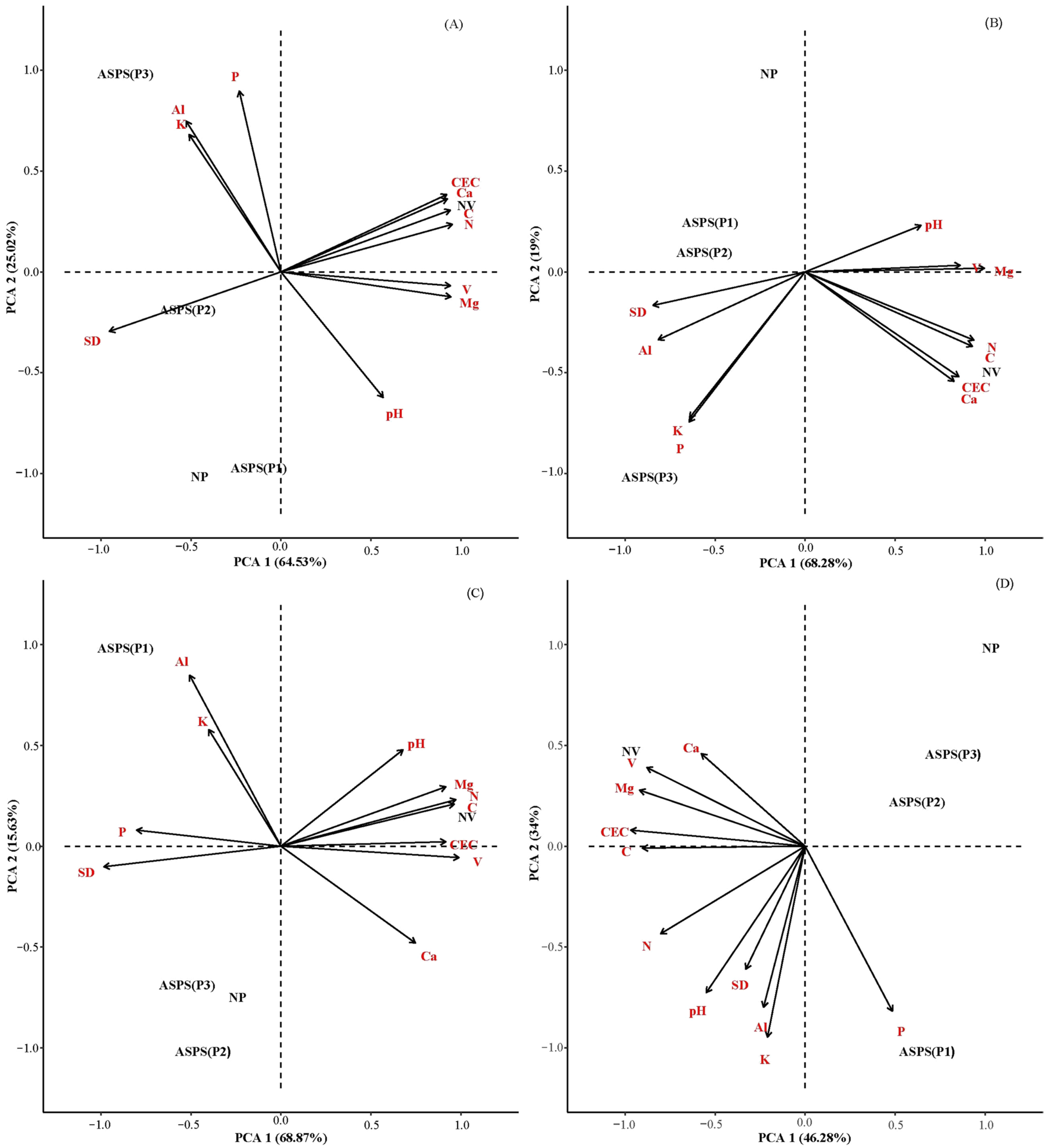


Fig. 5 Principal component analysis (PCA) of soil chemical attributes at different depths in the experimental area of Barra Ranch, Francisco Sá district, Minas Gerais, Brazil: (**A**) 0–5 cm, (**B**) 5–10 cm, (**C**) 10–20 cm, and (**D**) 20–30 cm. NV = native vegetation; NP = nominal pasture; ASPS = agrosilvopastoral system; ASPS(P1) = point between eucalyptus trees in the row; ASPS(P2) = point 1 m from the row of trees; ASPS(P3) = point 4 m from the row of trees. Soil variables included: pH, P, K, Ca, Mg, Al, sum of bases (SB), cation exchange capacity (CEC), base saturation (V), soil density (SD), and total nitrogen (N)

relatively stable throughout the year, creating favorable conditions for microbial activity and litter decomposition. These patterns indicate that litter dynamics in the system are strongly controlled by rainfall and microclimatic conditions, as also reported in other agrosilvopastoral systems (Ribeiro et al. 2022). Spatial variability in litter deposition

Table 2 Soil carbon (C) and nitrogen (N) content at different sampling points in an integrated production system in the experimental area of the Barra ranch in the district of Francisco Sá, Minas Gerais, Brazil

Treatment	Depth (cm)						
	0–5	5–10	10–20	20–30	30–40	40–50	40–50
	………………… Carbon content (g kg^{-1}) …………………						
ASPSP1	22.1ns	16.8ns	15.0ns	11.7ns	10.1ns	8.4ns	14.0ns
ASPSP2	22.1ns	17.0ns	15.0ns	12.0ns	8.2ns	7.8ns	13.7ns
ASPSP3	21.9ns	17.7ns	14.2ns	10.3ns	8.3ns	7.3ns	13.3ns
CV (%)	25.3	15.4	23.6	26.2	19.1	21.8	17.2
	………………… Nitrogen content (g kg^{-1}) …………………						
ASPSP1	1.9ns	1.6ns	1.4ns	1.2ns	1.1a	1.1a	1.4ns
ASPSP2	1.9ns	1.6ns	1.4ns	1.2ns	0.9b	0.9b	1.3ns
ASPSP3	1.8ns	1.5ns	1.4ns	1.1ns	1.0ab	1.0ab	1.3ns
CV (%)	23.7	13.9	20.4	14.6	8.9	8.9	11.5

ASPS agrosilvopastoral system; ASPS(P1) = point between eucalyptus trees in the row; ASPS(P2) = point 3 m from the row of trees; ASPS(P3) = point 7 m from the row of trees. Mean values followed by "ns" in the same column are not significantly different according to the t-test ($p \leq 0.05$)

Table 3 Soil carbon (C) and nitrogen (N) content in different land-use systems in the experimental area of the Barra Ranch in the district of Francisco Sá, Minas Gerais, Brazil

Treatment	Depth (cm)						
	0–5	5–10	10–20	20–30	30–40	40–50	40–50
	………………… Carbon content (g kg^{-1}) …………………						
NV	39.6a	27.2a	21.5a	14.1ns	9.2ns	7.4ns	19.8a
NP	22.9b	17.4b	16.9ab	11.3ns	8.4ns	6.9ns	14.0b
ASPS	22.0b	17.2b	14.7b	11.3ns	8.9ns	7.8ns	13.7b
CV (%)	14.9	12.9	18.7	19.5	19.3	18.8	10.3
	………………… Nitrogen content (g kg^{-1}) …………………						
NV	2.1a	1.8a	2.7a	1.8a	1.3ns	1.5a	1.9a
NP	1.8ab	1.6b	2.2b	1.6ab	1.2ns	1.0b	1.5b
ASPS	1.6b	1.2c	1.4c	1.1b	1.0ns	0.9b	1.3b
CV (%)	15.8	9.2	14.6	26.4	32.5	20.7	5.6

NV native vegetation, *NP* nominal pasture, *ASPS* agrosilvopastoral system. Mean values followed by "ns" in the same column are not significantly different according to the t-test ($p \leq 0.05$)

was evident, with higher inputs near the eucalyptus rows, reflecting the influence of tree architecture and spacing. The extension of branches beyond the tree rows allowed litterfall to reach intermediate positions, highlighting the importance of tree arrangement in regulating organic residue inputs and nutrient cycling in integrated systems (Ribeiro et al. 2022; Deniz et al. 2021).

Principal component analysis reinforced this spatial pattern, showing greater litter deposition and a higher contribution of leaf material close to the tree component, particularly at P1. As eucalyptus stands mature, reduced light penetration promotes natural pruning, increasing the deposition of leaves and fine branches, especially during the dry season (Valadão et al. 2021; Almeida et al. 2021). This continuous input of organic material favors organic matter accumulation and stimulates soil microbial activity, extending its influence beyond the immediate tree rows and affecting adjacent areas within the system.

Litter decomposition rates varied with distance from the trees, reflecting differences in microclimatic conditions, organic inputs, and light availability. Faster decomposition at P1 and P3 was associated with higher soil moisture during the rainy season and greater understory development at P3, which likely increased root activity and microbial stimulation. In contrast, slower decomposition at P2 may be explained by intermediate light conditions combined with lower organic inputs, resulting in reduced microbial activity. Soil moisture emerged as a key driver of decomposition, as periods of higher moisture coincided with increased CO_2 efflux, corroborating previous findings that identify moisture as a primary regulator of microbial processes in tropical systems (Shvaleva et al. 2014; Santos et al. 2018; Sanna et al. 2021).

The chemical composition of eucalyptus litter further influenced decomposition dynamics. Branches, characterized by higher lignin and structural nutrient contents, decomposed more slowly, whereas leaves, richer in labile nutrients such as K and P, contributed to faster nutrient release. This combination promotes both short-term nutrient availability and long-term organic matter accumulation, enhancing

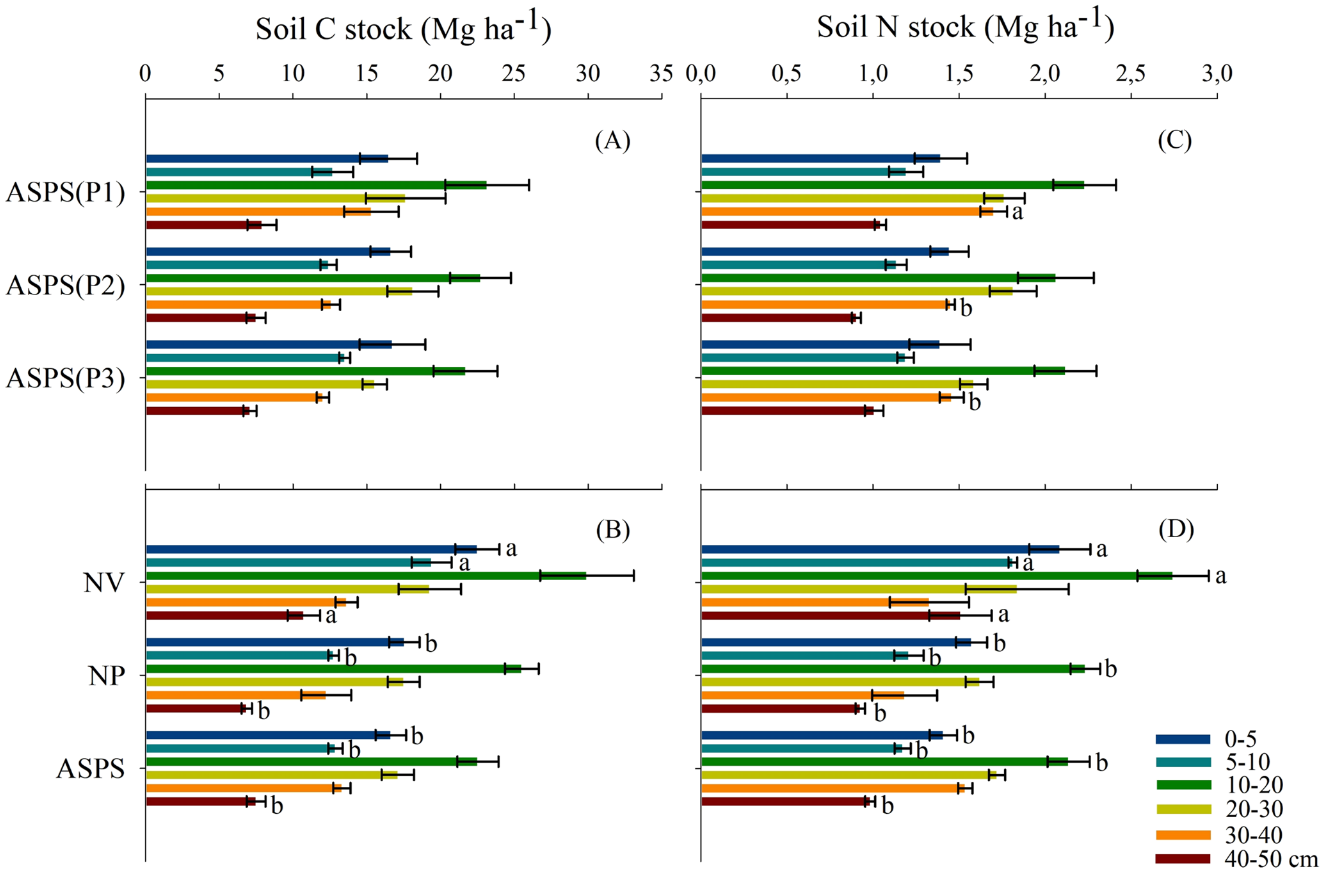


Fig. 6 Soil carbon stocks (**A**, **B**) and total nitrogen stocks (**C**, **D**) at different depths in the experimental area of Barra Ranch, Francisco Sá district, Minas Gerais, Brazil. NV = native vegetation; NP = nominal pasture; ASPS = agrosilvopastoral system; ASPS(P1) = point between eucalyptus trees in the row; ASPS(P2) = point 1 m from the row of trees; SPS(P3) = point 7 m from the row of trees. Depth intervals: 0–5, 5–10, 10–20, 20–30, 30–40, and 40–50 cm. Bars followed by the same letter within each depth are not significantly different according to the LSD test at 5% probability

nutrient cycling efficiency and soil health (Valadão et al. 2019; Carvalho et al. 2019; Ferreira et al. 2020; Mendham et al. 2003; Kulman et al. 2024). Thus, litter in agrosilvopastoral systems functions not only as a nutrient source but also as a regulator of soil physical and biological processes.

Soil CO_2 efflux exhibited clear seasonal patterns across all systems, with higher values during the rainy season, reinforcing the central role of soil moisture in regulating soil respiration. In the silvopastoral system, higher CO_2 efflux near the tree rows was associated with greater shading, litter accumulation, and root biomass, which together created a more stable microclimate conducive to microbial activity. In contrast, areas farther from the trees and the nominal pasture exhibited lower moisture retention and greater thermal variability, resulting in reduced CO_2 emissions. These findings align with previous studies demonstrating that soil respiration is strongly controlled by the interaction between moisture, temperature, root activity, and surface residue cover (Koncz et al. 2015; Sun et al. 2019; Sanna et al., 2021; Nielsen et al., 2024).

Light intensity played a critical role in shaping soil microclimate within the silvopastoral system, influencing soil moisture, temperature, and biological activity. Shaded areas maintained higher moisture levels and moderated temperatures, favoring microbial respiration, while more exposed areas experienced greater fluctuations that limited biological processes. In native vegetation, despite lower light availability, dense ground cover and extensive root systems contributed to stable microclimatic conditions and higher CO_2 efflux compared to the nominal pasture, emphasizing the importance of vegetation structure in regulating soil carbon fluxes (Silva et al. 2024; Carvalho et al. 2020).

Soil physical and chemical attributes reflected the combined effects of vegetation structure, animal behavior, and management practices. Higher bulk density observed at intermediate positions within the silvopastoral system was likely associated with increased animal trampling, as cattle tend to concentrate in shaded areas (Deniz et al. 2021). Although the presence of a tree component generally enhances nutrient cycling and soil fertility through organic residue inputs (Vásquez et al. 2021), the absence of adequate management practices in the studied system since 2014 limited the full expression of these benefits. Even so, higher P and K contents compared to the nominal pasture suggest that continuous litter deposition and gradual decomposition partially compensated for the lack of fertilization, as also observed by Kulmann et al. (2024) and Sena et al. (2025). Long-term studies reinforce that well-managed silvopastoral systems consistently improve soil chemical, physical, and biological attributes over time (Silva-Olaya et al. 2021; Lecegui et al. 2022).

Across all land-use systems, soil C and N contents decreased with depth, reflecting greater organic matter inputs at the surface. Although integrated systems have strong potential to increase soil C and N stocks through enhanced litterfall, root biomass, and microclimatic regulation (Conceição et al. 2017; Oliveira et al. 2016, 2021; Guillot et al. 2019), the lack of proper management in the silvopastoral system limited gains in C and N stocks, even after nine years of establishment. Overgrazing and insufficient nutrient replenishment restricted organic inputs, resulting in soil C and N stocks comparable to those of the continuously grazed pasture. In contrast, pasture reestablishment and vigorous grass root systems contributed to sustained carbon inputs in the nominal pasture, partially offsetting the absence of a tree component.

Nevertheless, agrosilvopastoral systems remain a promising strategy for restoring degraded pastures and enhancing soil carbon sequestration when appropriately managed. As eucalyptus trees mature, increased litter production and root biomass can further promote soil C and N accumulation and atmospheric CO_2 removal through both soil and biomass pools (Valadão et al. 2021; Shvaleva et al. 2014). Evidence from long-term studies highlights that adjustments in grazing intensity, nutrient management, and tree management practices are essential to maximize the environmental and productive benefits of these systems (Freitas et al. 2022; Varela et al. 2022; Oliveira et al. 2025). Thus, the results of this study demonstrate both the potential of agrosilvopastoral systems in the Cerrado and the critical role of sustained, integrated management in enhancing soil quality, carbon sequestration, and agroecosystem sustainability.

5 Conclusions

Eucalyptus trees in the integrated production system contribute to litter input and modify microclimatic conditions, thereby enhancing the accumulation of soil organic matter. However, the absence of ongoing silvicultural and agronomic interventions limited long-term improvements in soil quality, resulting in soil carbon and nitrogen stocks comparable to those of continuously grazed pastures after nine years of establishment. These findings highlight the importance of appropriate management practices—such as controlled grazing, residue retention, and nutrient supplementation—for soil quality maintenance in integrated production systems.

Therefore, further research is needed to confirm the viability of well-managed eucalyptus-based integrated production systems as a sustainable approach to livestock intensification, while also contributing to the recovery of degraded areas and the mitigation of greenhouse gas emissions in the Cerrado biome.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s42729-025-02985-w.

Acknowledgements We thank Stephen Hocken for providing language help and the Barra Farm for all the logistic support given during this study. We gratefully acknowledge the support of the RCGI – Research Centre for Greenhouse Gas Innovation (23.1.8493.1.9), hosted by the University of São Paulo (USP) and sponsored by FAPESP – São Paulo Research Foundation (2020/15230-5) and Shell Brasil, as well as the strategic importance of the support given by ANP (Brazil's National Oil, Natural Gas and Biofuels Agency) through the R&DI levy regulation.

Funding The Article Processing Charge (APC) for the publication of this research was funded by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES) (ROR identifier: 00x0ma614). This work was supported by Bayer S.A; Fundação de Amparo à Pesquisa do Estado de Minas Gerais - Fapemig [Grant number PPM-00617, 2018]; Conselho Nacional de Desenvolvimento Científico e Tecnológico – CNPq [Grants number 316873, 2021-7 and 406635, 2022-6]; Coordenação de Aperfeiçoamento de Pessoal de Nível Superior [Finance Code 001]; RCGI - Research Centre for Greenhouse Gas Innovation (FAPESP processes 2014/50279-4 and 2020/15230-5) and Shell Brazil.

Data Availability Data transparency complies with the journal's requirements. All data is available in this article and the raw data will be made available by the authors upon request.

Declarations

Competing interests The authors declare no competing interests.

References

Almeida LL, de Frazão S, Lessa LA, Fernandes TAM, Veloso LA, de Lana ÁL, de Souza AMQ, Pegoraro IA, Ferreira RF EA (2021) Soil carbon and nitrogen stocks and the quality of soil organic matter under silvopastoral systems in the Brazilian Cerrado. Soil Tillage Res 205:104785. https://doi.org/10.1016/j.still.2020.104785

Breidenbach A, Schleuss P-M, Liu S et al (2022) Microbial functional changes mark irreversible course of Tibetan grassland degradation. Nat Commun 13:2681. https://doi.org/10.1038/s41467-022-30047-7

Carvalho HCdeS, Ferreira JLS, Calil FN, Silva-Neto CDM (2019) Estoque de nutrientes na serapilheira acumulada em quatro tipos de vegetação no Cerrado em Goiás, Brasil. (In portuguese). Rev Ecol Nutr Florest - ENFLO 7:06. https://doi.org/10.5902/2316980x37296

Carvalho RP de, Heid DM, Davide LMC, Piletti LMM da S, Jesus FLF de, Viegas Neto AL (2020) Microclimate and thermal comfort indices in silvopastoral systems under different planting directions and seasons. Rev Bras Eng Agric Ambient 24:266–273. https://doi.org/10.1590/1807-1929/agriambi.v24n4p266-273

Conceição MCG, da S, Matos E, Bidone ED, Rodrigues R, de Cordeiro AR RC (2017) Changes in soil carbon stocks under integrated crop-livestock-forest system in the Brazilian Amazon region. Agric Sci 08:904–913. https://doi.org/10.4236/as.2017.89066

De Costa WAJM, Atapattu AMLK (2001) Agrofor Syst 51:201–211. https://doi.org/10.1023/a:1010772209966

de Freitas IC, Alves MA, Magalhães JR, Dias RF, Albuquerque CJB, Ferreira EA, Fernandes LA, Pegoraro RF, Frazão LA (2022) Soil carbon and nitrogen stocks under agrosilvopastoral systems with different arrangements in a transition area between Cerrado and Caatinga biomes in Brazil. Agron (Basel) 12:2926. https://doi.org/10.3390/agronomy12122926

de Oliveira WRD, Ramos MLG, de Carvalho AM, Coser TR, Silva AMM, Lacerda MM, Souza KW, Marchão RL, Vilela L, Pulrolnik K (2016) Dynamics of soil Microbiological attributes under integrated production systems, continuous pasture, and native Cerrado. Pesqui Agropecu Bras 51:1501–1510. https://doi.org/10.1590/s0100-204x2016000900049

de Oliveira JdeC, de Freitas IC, Duarte ACS, Moreira JGF, Couto AJS, Lessa MFG, Gontijo Neto MM, Santos MV, Cherubin MR, Cerri CEP, Frazão LA (2025) Fertility and carbon stocks in oxisols under *Urochloa* pastures and *Eucalyptus* based agrosilvopastoral systems established in the Brazilian Cerrado. Soil Tillage Res 253:106663. https://doi.org/10.1016/j.still.2025.106663

Davidson EA, Janssens IA (2006) Temperature sensitivity of soil carbon decomposition and feedbacks to climate change. Nature 440:165–173. https://doi.org/10.1038/nature04514

Deniz M, Sousa KTF, Moro MF, Do Vale MM, Dittrich JR, Machado Filho LCP, Hötzel MJ (2021) Social hierarchy influences dairy cows' use of shade in a silvopastoral system under intensive rotational grazing. Appl Anim Behav Sci 244–105467. https://doi.org/10.1016/j.applanim.2021.105467

Ellert BH, Bettany JR (1995) Calculation of organic matter and nutrients stored in soils under contrasting management regimes. Can J Soil Sci 75:529–538. https://doi.org/10.4141/cjss95-075

Ferreira NCF, Ramos TV, Ferreira RJ Júnior, Carvalho IA (2020) Decomposição de serapilheira Em Mata nativa do bioma Cerrado e Eucalyptus urograndis. Biotecnol Ciênc 9:1–8. https://www.revista.ueg.br/index.php/biociencia/article/view/10047 (In portuguese)

Guillot E, Hinsinger P, Dufour L, Roy J, Bertrand I (2019) With or without trees: resistance and resilience of soil microbial communities to drought and heat stress in a mediterranean agroforestry system. Soil Biol Biochem 129:122–135. https://doi.org/10.1016/j.soilbio.2018.11.011

Hoosbeek MR, Remme RP, Rusch GM (2016) Trees enhance soil carbon sequestration and nutrient cycling in a silvopastoral system in south-western Nicaragua. Agrofor Syst. https://doi.org/10.1007/s10457-016-0049-2

Koncz P, Balogh J, Papp M, Hidy D, Pintér K, Fóti S, Klumpp K, Nagy Z (2015) Higher soil respiration under mowing than under grazing explained by biomass differences. Nutr Cycl Agroecosyst 103:201–215. https://doi.org/10.1007/s10705-015-9732-3

Kulmann MS, de Dick S, Schumacher G MV (2024) Litter decomposition in *Eucalyptus Saligna* Smith plantation in Pampa biome in Southern of Brazil. Sci for 52:1–11. https://doi.org/10.18671/scifor.v52.01

Lecegui A, Olaizola AM, Varela E (2022) Disentangling the role of management practices on ecosystem services delivery in mediterranean silvopastoral systems: synergies and trade-offs through expert-based assessment. Ecol Manage 517:120273. https://doi.org/10.1016/j.foreco.2022.120273

Mendham DS, O'Connell AM, Grove TS, Rance SJ (2003) Residue management effects on soil carbon and nutrient contents and growth of second rotation eucalypts. Ecol Manage 181:357–372. https://doi.org/10.1016/s0378-1127(03)00007-0

Moraes JFL, Volkoff B, Cerri CC, Bernoux M (1996) Soil properties under Amazon forest and changes due to pasture installation in Rondônia, Brazil. Geoderma 70:63–81. https://doi.org/10.1016/0016-7061(95)00072-0

Nielsen UN, Bristol D, Blyton M, Delroy B, Powell JR (2024) Elevated CO_2 enhances decomposition and modifies litter-associated fungal assemblages in a natural *Eucalyptus* woodland. Funct Ecol 38:1751–1764. https://doi.org/10.1111/1365-2435.14598

Olaya-Montes A, Llanos-Cabrera MP, Cherubin MR, Herrera-Valencia W, Ortiz-Morea FA, Silva-Olaya AM (2021) Restoring soil carbon and chemical properties through silvopastoral adoption in the Colombian Amazon region. Land Degrad Dev 32:3720–3730. https://doi.org/10.1002/ldr.3832

Oliveira JdeCde, Azevedo AM, Ribeiro JM, Freitas IC, Dias RF, Duarte ACS, Melo PF, Veloso ÁL, Frazão LA (2021) Sampling representativeness of soil carbon and physiological parameters of marandu palisadegrass in a tropical silvopastoral system. Sci Agric. https://doi.org/10.1590/1678-992x-2020-0176

Oliveira PPA, Bernardi ACC, Pezzopane JRM, Bosi C, Júnior FP, Tadini AM, Martin-Neto L, Rodrigues PHM (2024) Potential of integrated trees-pasture-based systems for GHG emission mitigation and improving soil carbon dynamics in the Atlantic forest biome, southeastern of Brazil. Eur J Agron 158:127219. https://doi.org/10.1016/j.eja.2024.127219

Pardo F, Gil L, Pardos JA (1997) Field study of Beech (Fagus sylvatica L.) and Melojo oak (Quercus pyrenaica Willd) leaf litter decomposition in the centre of the Iberian Peninsula. Plant Soil 191:89–100. https://www.jstor.org/stable/42948032

Ramakrishnan S, Kumar S, Chaudhary M, Govindasamy P, Yadav M, Prasad M, Srivastava R, Kumari B, Prajapati K (2021) Silvopastoral system for resilience of key soil health indicators in semi-arid environment. Arch Acker Pflanzenbau Bodenkd 67:1834–1847. https://doi.org/10.1080/03650340.2020.1814954

R Core Team (2023) R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. https://www.r-project.org/. Accessed 15 january 2024

Ribeiro FP, Pulrolnik K, Vilela L, Gatto A (2022) Deposição, decomposição e conteúdo de nutrientes de serapilheira Em área de integração lavoura-pecuária-floresta Na região do Cerrado. (In portuguese). Pesqui Florest Bras 42. https://doi.org/10.4336/2022.pfb.42e201902072

Sanna F, Campesi G, Deligios P, Ledda L, Piluzza G, Sulas L, Re GA (2021) Combined effects of microenvironment and land use on C fluxes in a Mediterranean agro-silvopastoral system. Eur J Agron 130:126348. https://doi.org/10.1016/j.eja.2021.126348

Santos DdeC, Guimarães Júnior R, Vilela L, Maciel GA, França AFdeS (2018) Implementation of silvopastoral systems in Brazil with *Eucalyptus urograndis* and *Brachiaria brizantha*: productivity of forage and an exploratory test of the animal response. Agric Ecosyst Environ 266:174–180. https://doi.org/10.1016/j.agee.2018.07.017

Sarto MVM, Borges WLB, Sarto JRW, Pires CAB, Rice CW, Rosolem CA (2020) Soil microbial community and activity in a tropical integrated crop-livestock system. Appl Soil Ecol 145:103350. https://doi.org/10.1016/j.apsoil.2019.08.012

Schinato F, Munka MC, Olmos VM, Bussoni AT (2023) Microclimate, forage production and carbon storage in a eucalypt-based silvopastoral system. Agric Ecosyst Environ 344:108290. https://doi.org/10.1016/j.agee.2022.108290

Sena KN, Maltoni KL, Barbosa MC, Araujo EGde (2025) Nutrient release and decomposition time of *Eucalyptus urograndis* harvest residues practices under Brazil tropical conditions. For Ecol Manage 582:122558. https://doi.org/10.1016/j.foreco.2025.122558

Shvaleva A, Costa e Silva F, Costa JM, Correia A, Anderson M, Lobo-do-Vale R, Fangueiro D, Bicho C, Pereira JS, Chaves MM, Skiba U, Cruz C (2014) Comparison of methane, nitrous oxide fluxes and CO2 respiration rates from a Mediterranean cork oak ecosystem and improved pasture. Plant Soil 374:883–898. https://doi.org/10.1007/s11104-013-1923-6

Silva-Olaya AM, Olaya-Montes A, Polanía-Hincapié KL, Cherubin MR, Duran-Bautista EH, Ortiz-Morea FA (2021) Silvopastoral systems enhance soil health in the Amazon region. Sustainability 14:320. https://doi.org/10.3390/su14010320

Silva B de O, Moitinho MR, Panosso AR, Oliveira DM da S, Montanari R, Moraes MLT de, Milori DMBP, Bicalho E da S, La Scala N Jr (2024) Implications of converting native forest areas to agricultural systems on the dynamics of CO2emission and carbon stock in a Cerrado soil, Brazil. J Environ Manage 358:120796. https://doi.org/10.1016/j.jenvman.2024.120796

Sun S, Lei H, Chang SX (2019) Drought differentially affects autotrophic and heterotrophic soil respiration rates and their temperature sensitivity. Biol Fertil Soils 55:275–283. https://doi.org/10.1007/s00374-019-01347-w

Tao F, Huang Y, Hungate BA et al (2023) Microbial carbon use efficiency promotes global soil carbon storage. Nature 618:981–985. https://doi.org/10.1038/s41586-023-06042-3

Teixeira PC, Donagemma GK, Fontana A, Teixeira WG (2017) Manual de Métodos de Análise de Solo. (In portuguese) Rio de Janeiro: Embrapa Solos. https://www.embrapa.br/en/busca-de-publicacoes/-/publicacao/1085209/manual-de-metodos-de-analise-de-solo

Varela E, Olaizola AM, Blasco I, Capdevila C, Lecegui A, Casasús I, Bernués A, Martín-Collado D (2022) Unravelling opportunities, synergies, and barriers for enhancing silvopastoralism in the Mediterranean. Land Use Policy 118:106140. https://doi.org/10.1016/j.landusepol.2022.106140

Vásquez HV, Valqui L, Bobadilla LG, Arbizu CI, Alegre JC, Maicelo JL (2021) Influence of arboreal components on the physical-chemical characteristics of the soil under four silvopastoral systems in northeastern Peru. Heliyon 7:e07725. https://doi.org/10.1016/j.heliyon.2021.e07725

Valadão MBX, Carneiro KMS, Inkotte J, Ribeiro FP, Miguel EP, Gatto A (2019) Litterfall, litter layer and leaf decomposition in *Eucalyptus* stands on Cerrado soils. Sci for 47. https://doi.org/10.18671/scifor.v47n122.08

Valadão MBX, Carneiro KMS, Inkotte J, Ribeiro FP, Rodrigues MI, Hodecker BER, Miguel EP, Gatto A (2021) Litter layer removal and implications on decomposition in a *Eucalyptus* stand in the Cerrado. Sci for 49. https://doi.org/10.18671/scifor.v49n131.08

WMO (World Meteorological Organization) (2018) The state of greenhouse gases in the atmosphere based on global observations through 2017. WMO Greenh Gas Bull Nº 14 https://wmo.int/publication-series/wmo-greenhouse-gas-bulletin-no14-state-of-greenhouse-gases-atmosphere-based-global-observations

Wehrle R, Coulouma G, Pätzold S (2022) Portable mid-infrared spectroscopy to predict parameters related to carbon storage in vineyard soils: model calibrations under varying geopedological conditions. Biosyst Eng 222:1–14. https://doi.org/10.1016/j.biosystemseng.2022.07.012