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Research article

Implications of converting native forest areas to agricultural systems on the dynamics of CO_2 emission and carbon stock in a Cerrado soil, Brazil

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ABSTRACT

The conversion of native vegetation to agricultural areas leads to a natural process of carbon loss but these systems can stabilize in terms of carbon dynamics depending on the management and conversion time, presenting potential to both store and stabilize this carbon in the soil, resulting in lower soil respiration rates. In this context, this study aimed to investigate the effect of converting native Cerrado forest areas to agricultural systems with a forest planted with *Eucalyptus camaldulensis* and silvopastoral systems on the dynamics of CO_2 emission and carbon stock at different soil depths. The experimental sites are located in the Midwest of Brazil, in the coordinates 20°22′31″ S and 51°24′12″ W. Were evaluated soil CO_2 emission (FCO_2), soil organic carbon, the degree of humification of soil organic matter (HLIFS), soil temperature, soil moisture, and soil chemical and physical attributes. The soil of the area is classified as an Oxisol (Haplic Acrustox). Soil samples were collected at depths of 0.00–0.10, 0.10–0.20, 0.20–0.30, and 0.30–0.40 m. The lowest FCO_2 values were found in the silvopastoral system (1.05 μmol m^{-2} s^{-1}), followed by the native forest (1.65 μmol m^{-2} s^{-1}) and the eucalyptus system (1.96 μmol m^{-2} s^{-1}), indicating a 36% reduction in FCO_2 compared to the conversion of the native forest to the silvopastoral system and an increase of 19% when converting the native forest to the eucalyptus system. The soil chemical attributes (N, K^+, Ca^{2+}, H^++Al^{3+}, CEC, and organic carbon) showed a decrease along the profile. The shallowest depths (0.00–0.10 and 0.10–0.20 m) presented no differences between systems but the subsequent depths (0.20–0.30 and 0.30–0.40 m) had a difference (95% confidence interval), relative to N, Ca^{2+}, H^++Al^3, CEC, and organic carbon stock (OCS), and the soil under silvopastoral system showed a higher concentration of these attributes than the native forest. The multivariate analysis showed that the eucalyptus and silvopastoral systems did not differ from the forest in the shallowest soil layer but differed from each other. This behavior changed from the second assessed depth (0.10–0.20 m), in which the silvopastoral system stands out, differing both from the eucalyptus system and from the native forest, and this behavior is maintained at the following depths (0.20–0.30 and 0.30–0.40 m). OCS, H^++Al^3, CEC, and nitrogen are strongly related to land use change for silvopastoral system. Regarding the behavior/relationship of attributes as a function of depth, the silvopastoral system contributed to soil carbon accumulation and stability over consecutive years.

1. Introduction

Brazil has a prominent position in the world ranking relative to the emission of greenhouse gases (CO_2, N_2O, and CH_4), ranking fourth in the world in cumulative emissions (Cerri et al., 2007; IPCC, 2022). The intensification of global warming due to the high concentration of

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greenhouse gases (GHG) in the atmosphere is mainly related to an increase in deforestation and fires, which have been worsening as a result of the expansion of agricultural activities, especially in regions located in biomes such as the Cerrado and Amazon Forest (IPCC, 2022).

The Cerrado, also known as the Brazilian Savanna, is the second largest biome in South America and covers a vast area in Brazil, is mainly located in the Central Highlands of Brazil. This biome has around 10,000 plant species, in each hectare, approximately 400 plant species can be found. The fauna is extremely rich and diverse, 199 species of mammals, 864 of birds, 180 of reptiles, 210 of amphibians, and 1200 of fish inhabit the biome (Brazilian Forestry Institute, 2022).

The Brazilian Cerrado nestles the most biodiverse tropical savannas in the world, representing more than 5% of the world's biodiversity. The biome is also home to 25 million people, about 100 indigenous peoples, and countless traditional communities (WWF, 2022). Approximately 50% of the original 2 million kilometers of the Cerrado area is under agricultural use (Sano et al., 2008; Beuchle et al., 2015), compromising around 80% of its primary vegetation. According to data from the World Wildlife Fund (WWF, 2022), this biome is projected to lose tens of millions of additional acres of native vegetation by 2030. Thus, the world will lose an irreplaceable biome, which is fundamental to preserving nature and facing the climate crisis.

The conversion of the Cerrado vegetation will continue to be a dominant process of land use change in Brazil (Lapola et al., 2013; Nóbrega et al., 2017), and the expansion of agriculture across Cerrado has implications for the global C cycle. The substitution of natural vegetation is usually followed by soil C loss, especially when soil or crop management reduces biomass input or increases soil organic carbon decomposition rate (Don and Freibauer, 2011; Mayer et al., 2020), making it essential to adopt conservationist management practices in these agricultural areas with the least possible change in their composition, structure, and natural biodiversity, as a strategy to restore and maintain the organic carbon stock (FAO, 2016), improve soil quality, and increase agronomic productivity relative to conventional farming (Sá et al., 2014; Ferreira et al., 2018).

RECSOIL (recarbonization of global soils) is one of the main movements that encourage the use of strategies for this sustainable soil management, to face the main challenges associated with agricultural production and soil degradation, whose main objective is to support and improve national and regional initiatives for GHG mitigation and soil carbon sequestration (FAO, 2019).

In this context, the Brazilian government established a low-carbon agriculture plan (ABC) to promote sustainable agriculture practices, reducing greenhouse gas (GHG) emissions and maintaining the profitability of the agricultural sector. This plan is based on practices such as the recovery of degraded pastures, integrated crop-livestock-forestry systems, no-till farming, biological nitrogen fixation, and forest and agroforestry systems aiming to maintain and increase carbon stocks in Brazilian soils (Brazil, 2011). Forests absorb the equivalent of approximately 2 Gt of CO_2 every year (FAO, 2018). Reforestation programs have been implemented in Brazil, since the 1970s, to direct actions that contribute to overcoming these challenges of reducing environmental impacts, implemented tax incentives for the planting of exotic species, and eucalyptus is the main forest species used in soils of low fertility and water deficit, being frequently used in the Brazilian Cerrado (Gama-Rodrigues et al., 2005), representing about 70% of the total area of planted forests (ABRAF, 2012). The Reforestation programs were the 1965 Forest Code with exemption from the *Imposto Territorial Rural* - ITR (Rural Land Tax); the Restructuring of the Forestry Sector (1965–1967), the forestry sector underwent a complete restructuring as part of the institutional reforms that affected the management of natural resources; Federal Law No. 5,106, of 1966, which regulated tax incentives granted to forestry enterprises and the Forestry Development and Research Project (Prodepef), this program contributed to the advancement of the forestry sector (ABRAF, 2012; Teixeira and Rodrigues, 2021).

Additionally, some studies have proven that these systems of food production and carbon sequestration by planting trees can help reduce deforestation in tropical countries (Oelbermann et al., 2004; Nair et al., 2011; Zomer et al., 2016; Reed et al., 2017; Santana et al., 2019; Costa et al., 2020). In this context, the silvopastoral system also consists of an excellent strategy in the purposeful association of trees, pastures, and cattle in the same space and time interval (Bungenstab, 2012).

Soil carbon plays a key role in terrestrial ecosystems, controlling numerous soil functions, such as increasing aggregate stability, improving infiltration rate and water storage, increasing nutrient supply and cation exchange capacity (Sá et al., 2014), and mainly acting as a substrate and energy source for soil microbiota (Primavesi, 2006). However, the conversion of native vegetation in agricultural systems based on conventional soil tillage leads to aggregate degradation, exposing the soil C content to microbial oxidation and decreasing the C stock (Sá et al., 2017), mainly in Cerrado soils (Santana et al., 2019; Costa et al., 2020). The improvement of macroaggregation in soils with conservation systems leads to an effective protection of carbon inside macroaggregates and, consequently, results in higher soil carbon storage, increasing the CO_2 sink capacity and the mitigation potential of the agricultural soil (Briedis et al., 2018). Carbon accumulation in the vegetation comes from CO_2 absorption and fixation from the atmosphere in the biomass. Subsequently, part of this biomass is transformed into soil organic matter through the decomposition of plant residues (Autret et al., 2016). This organic material remains for a period in the soil as particulate organic matter (not decomposed), goes through the decomposition process and incorporation into the soil, and a part of the carbon is released into the atmosphere as CO_2 during this process (Briedis et al., 2018).

The carbon stock is influenced by the decomposition rate, which depends on the organic matter composition and the recalcitrance of compounds. Technologies that allow identifying the degree or stage of soil organic matter (SOM) humification consist of important strategies in the mitigation processes (Santos et al., 2019; Xavier et al., 2020).

Considering the conversion of the Cerrado native forest to different agricultural uses, which include the silvopastoral system and eucalyptus plantation, and comparing both systems with the Cerrado native forest, this study hypothesized that, these agricultural systems can stabilize in terms of carbon dynamics, as the soil vegetation cover, characteristic of these systems, provides material at different levels of decomposition and complexity of plant residues, resulting in lower soil respiration rates. In this context, this study aimed to investigate the effect of converting native forest areas to agricultural systems with eucalyptus plantations and silvopastoral systems on the dynamics of CO_2 emission and carbon stock at different depths in soil from the Cerrado biome.

2. Material and methods

2.1. Characterization of the study area

The sites are located on the experimental farm of the School of Engineering of State University of São Paulo in Selvíria, Mato Grosso do Sul, Midwest of Brazil, with coordinates 20°22′31″ S and 51°24′12″ W at 354 m above sea level. The regional climate is classified as C1dAa' by the Thornthwaite system (Rolim et al., 2007), indicating a dry sub-humid region with summer evapotranspiration below 48% of the potential annual evapotranspiration, with an average annual temperature of 23.5 °C and an average annual precipitation of 1300 mm. The soil is classified as an Oxisol (Haplic Acrustox), with 542.38 g kg^{-1} sand, 65.21 g kg^{-1} silt, and 392.39 g kg^{-1} clay.

The evaluation sites were chosen because they portray the characteristics of typical land uses in the region where land use changes occurred in nearby areas with the same soil type, temperature variations, and rainfall regime. The areas consisted of native Cerrado vegetation until the 1970s, followed by deforestation in 1978 and cultivation with annual crops (corn, soybean, cotton, and green manures) until 1986 (Cavenage et al., 1999; Souza and Alves, 2003). The areas were converted to different uses in 1986: planted forest of *Eucalyptus camaldulensis* (PE), Cerrado native forest (CE), and silvopastoral system (SPS) implemented with Brazilian peppertree (*Schinus terebinthifolius* Raddi), by using 3 × 3 m spacing with a total area of 1 ha and spreading liverseed grass (*Brachiaria decumbens* Stapf) for pasture formation. The two conservationist systems PE and SPS were evaluated together with the native vegetation forest area (preserved intact since the 1970s), which is the reference for comparing the effects of conversion.

2.2. Measurements of soil CO_2 emission, soil temperature, and soil moisture

The silvopastoral system and the eucalyptus plantation had been converted for 32 years at the time of the evaluations. Measurements were conducted from May 22 to July 11, 2018, from 7 a.m. to 9 a.m., totaling sixteen evaluations for 50 days. The measurements were performed at 15 points marked with PVC collars (10 cm in diameter), which were previously installed in each area at a depth of 3 cm, totaling 45 points for evaluating soil CO_2 emission, soil temperature, and soil moisture. Soil CO_2 emissions (FCO_2) were measured using a portable LI-8100 system (LICOR, Inc., Lincoln, NE, USA). This system monitors the levels of CO_2 concentration inside the soil chamber by optical absorption spectroscopy in the infrared spectral region. We determined a time of 90 s to measure FCO_2 at each point, and the concentration of CO_2 inside the chamber was determined every 2.5 s. Furthermore, soil temperature (Ts) and soil moisture (Ms) were measured at the same time as FCO_2. Ts values were collected using a temperature sensor, while Ms was recorded with a time-domain reflectometry device (Hydrosense, Campbell Scientific Inc., Logan, UT, USA).

2.3. Soil chemical and physical analysis

Soil sampling was conducted after recording the measurements of FCO_2, Ts, and Ms. The samples were taken from the 0.00–0.10, 0.10–0.20, 0.20–0.30, and 0.30–0.40 m layers in all 15 points where the FCO_2 was evaluated in the three areas. The samples were analyzed at the Laboratory of Soil Chemistry at Unesp (Ilha Solteira Campus), where they were air-dried, ground, homogenized, and passed through a 2-mm mesh sieve. The following routine analyses were conducted: pH, soil organic matter (SOM) (Raij et al., 1987), available phosphorus (P), potassium (K^+), calcium (Ca^{2+}), magnesium (Mg^{+2}), the sum of bases (SB) ($Ca^{2+} + Mg^{+2} + K^+$), and potential acidity ($H^+ + Al^3$). The ion exchange resin method (Raij et al., 2001) was used to extract exchangeable calcium, magnesium, potassium, and available phosphorus (Embrapa, 2011). Cation exchange capacity (CEC) and alkaline saturation (V%) were also calculated. The nitrogen content was determined by the sulfuric acid digestion method (Malavolta et al., 1997).

Organic carbon stock (OCS) was adjusted for changes in soil density (Ds) that occurred after land use changes (LUC) in the area. For this purpose, the method described by Ellert and Bettany (1995) was used to correct carbon storage in the soil at an equivalent mass depth, that is, the soil depth of the management area (PE and SPS) in the corresponding soil layers (0.00–0.10, 0.10–0.20, 0.20–0.30, and 0.30–0.40 m). The calculation of the equivalent soil layer (ESL) was proposed by Carvalho et al. (2010) and Segnini et al. (2013).

$$ESL\ (cm) = \frac{M_{CE}}{M_{Area}} \times 10 \quad (1)$$

where M_{CE} is the weighted mean of the soil density in the respective soil layers in the Cerrado native forest (CE) and M_{Area} is the weighted mean of the soil density in the topsoil layer in each area (SPS, PE, and CE). OCS ($Mg\ ha^{-1}$) of each soil layer was calculated according to Equation (2) (Bayer et al., 2000).

$$OCS = \frac{(OC \times Ds \times T)}{10} \quad (2)$$

in which OC is the oxidizable organic carbon content ($g\ kg^{-1}$), Ds is the soil density ($g\ dm^{-3}$), T is the thickness of the studied layer of 0.40 m.

The sampler used to determine the soil density of an undisturbed sample is suitable for cylinders with a mean internal diameter of 5.0 cm and a height of 4.0 cm. Soil density of undisturbed soil sample was determined by metodology proposed by Embrapa (2011). The total pore volume was calculated based on the density value. The porous plate funnel was used to determine the pore size, macroporosity, and microporosity distribution of the samples, which were previously saturated under a 60-cm water column. The amount of water retained in the sample corresponded to the micropores, while the macropores were calculated by difference (Embrapa, 2011).

The soil carbon stability potential was estimated by decay constant k as $k = C–CO_2/CS$, where $C–CO_2$ is the labile carbon emitted into the atmosphere in the form of CO_2 and CS is the soil carbon stock. The decay constant k allowed for estimating the carbon half-life ($t_{1/2}$), that is, the time required for 50% of the $C–CO_2$ to be decomposed. It is calculated as $t_{1/2} = 1/k \times \ln(2)$.

2.4. Degree of humification of organic matter

The degree of humification of organic matter was determined by laser-induced fluorescence spectroscopy (LIFS). The basic principle of laser-induced fluorescence technology is to use a laser to excite soil samples in the ultraviolet/blue region to produce fluorescence of functional groups of organic substances related to the humification process. LIFS works with a diode laser emitting at the 405-nm range, with a maximum power of 50 mW. Milori et al. (2006) determined the equation HLIFS = fA/tC to establish the degree of humification of organic matter, in which fA corresponds to the area of fluorescence under the spectrum and tC is the total carbon content.

The LIFS spectrum was captured using a system implemented by Embrapa Instrumentação Agropecuária. The LIFS spectral area of each soil sample is divided by the corresponding carbon content, which is obtained by the wet combustion method or dichromate measurement to calculate the normalized fluorescence signal, thus defined as the degree of humification of soil organic matter. Importantly, the HLIFS index characterizes system properties arising from the ratio of quantity quotients whose units cancel each other out, being a dimensionless measure.

Pads were prepared with the samples to be used in the LIFS for analysis. The soil samples were previously ground and pressed using a hydraulic press, in which a load of 6 tons was applied for 3 min. Two pads of approximately 0.5 g each, weighed on a precision scale, were prepared per soil sample. Pads with 10 mm in diameter and 2 mm in thickness were obtained at the end of the process, thus standardizing the physical form of the samples. The samples were analyzed with two replications per pad, totaling four replications per sample for the mean degree of humification of each pad. The methodology proposed by Milori et al. (2006), consisting of a spectral region of 475–800 nm, with an intensity from 0 to 4000, an integration time of 500 m/s, and a box equal to 4, was used.

2.5. Data processing and analysis

Initially, the data were presented as plots to simulate the evaluated depths and visualize the conversion effect of the areas on soil attributes. The conservationist systems and the native forest area were compared using 95% confidence intervals. The analyses were conducted using the software Statistica 7.0 (StatSoft. Inc. Tulsa, OK, United States). Subsequently, multivariate analyses of principal components were conducted to summarize the number of variables and understand the attributes that best interact with FCO_2. The non-collinearity criterion was used to determine which attributes would remain and the attributes that presented correlation coefficients with an absolute value above 0.50 were considered for the interpretation. The eigenvectors (principal components) were built with the eigenvalues of the covariance matrix (Hair et al., 2005).

The interpretation of the meaning of each principal component considered the sign and the relative dimension of the coefficients of linear functions as an indication of the weight to be assigned to each variable. The analyses were performed using the Statistica 7.0 software (StatSoft Inc. Tulsa, OK, United States) after data standardization (zero mean and unitary variance). The first two principal components (PC1 and PC2), whose eigenvalues were higher than unity, according to the criteria established by Kaiser (1958), were considered in this study. Correlation ellipses and principal components were constructed to visualize and interpret the existing relationship between soil attributes as a function of different land uses. We carried out a multivariate approach based on principal component analysis (PCA), as soil CO_2 emissions have complex relationships with edaphoclimatic factors, and PCA can be used to investigate certain characteristics that allow the identification of natural correlations and multiple influences on behavior, being widely used to explain these structures of interdependencies.

3. Results

Soil CO_2 emission during the total period of 50 days of the study showed a significant difference between the areas when we observed the confidence interval bars, with the silvopastoral system differing from the eucalyptus plantation and native forest (Fig. 1). The lowest FCO_2 values were observed in the silvopastoral system (1.05 μmol m^{-2} s^{-1}), followed by native forest (1.65 μmol m^{-2} s^{-1}) and eucalyptus system (1.96 μmol m^{-2} s^{-1}), indicating a 36% reduction in soil CO_2 emissions compared to the conversion of native forest to the silvopastoral system and a 19% increase when converting native forest to the eucalyptus system. In addition, there was also less temporal variation of FCO_2 in the areas under the silvopastoral system and native forest.

Soil temperature presented a different pattern of management behavior over time. The temperature from the beginning to 28 days of evaluations was higher in the soil under the silvopastoral system and lower in the eucalyptus system and native forest, but this behavior was inverted after 28 days and remained so until the end of the experimental period. The accumulated mean values of soil temperature in the eucalyptus (19.8 °C) and silvopastoral systems (19.3 °C) were similar to those observed in the native forest (19.8 °C) (Fig. 1). Soil moisture in the silvopastoral system (2.30 VWC) showed similar values compared to the native forest (3.12 VWC). However, the silvopastoral and eucalyptus systems (1.97 VWC) had no differences from each other, but the eucalyptus system differed when compared to the native forest soil, presenting the lowest values (Fig. 1).

There was a trend towards an increase in micropores and a reduction in macropores along the soil profile up to the depth of 0.20–0.30 m, with higher microporosity in the silvopastoral system. The macropores showed only differences between systems at the depth of 0.00–0.10 m, with the native forest (0.18 cm^3 cm^{-3}) presenting a higher concentration of macropores than the silvopastoral system (0.09 cm^3 cm^{-3}), with the 95% confidence interval (Fig. 2). The higher soil macroporosity in the native forest indicates a non-compacted soil, which is already expected

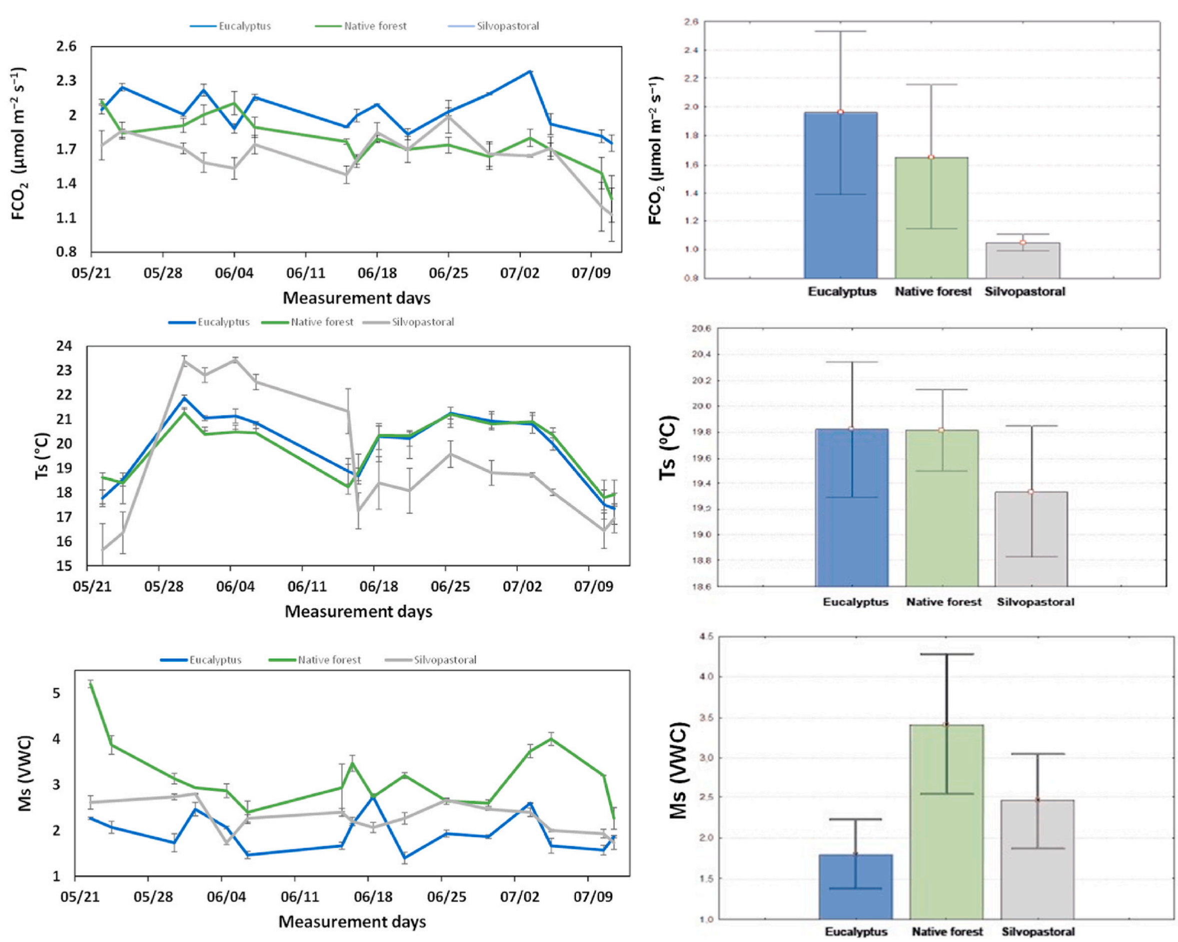

Fig. 1. The line graphs present the daily averages and standard error bars of the mean for each evaluation day, the bar graphs present the accumulated means over the evaluation period with confidence interval bars (95% confidence) of variables: soil CO_2 emission (FCO_2), temperature, (Ts) and soil moisture (Ms) for *Eucalyptus camaldulensis* planted forest, native Cerrado forest and silvopastoral system. N (number of observations) = 240.

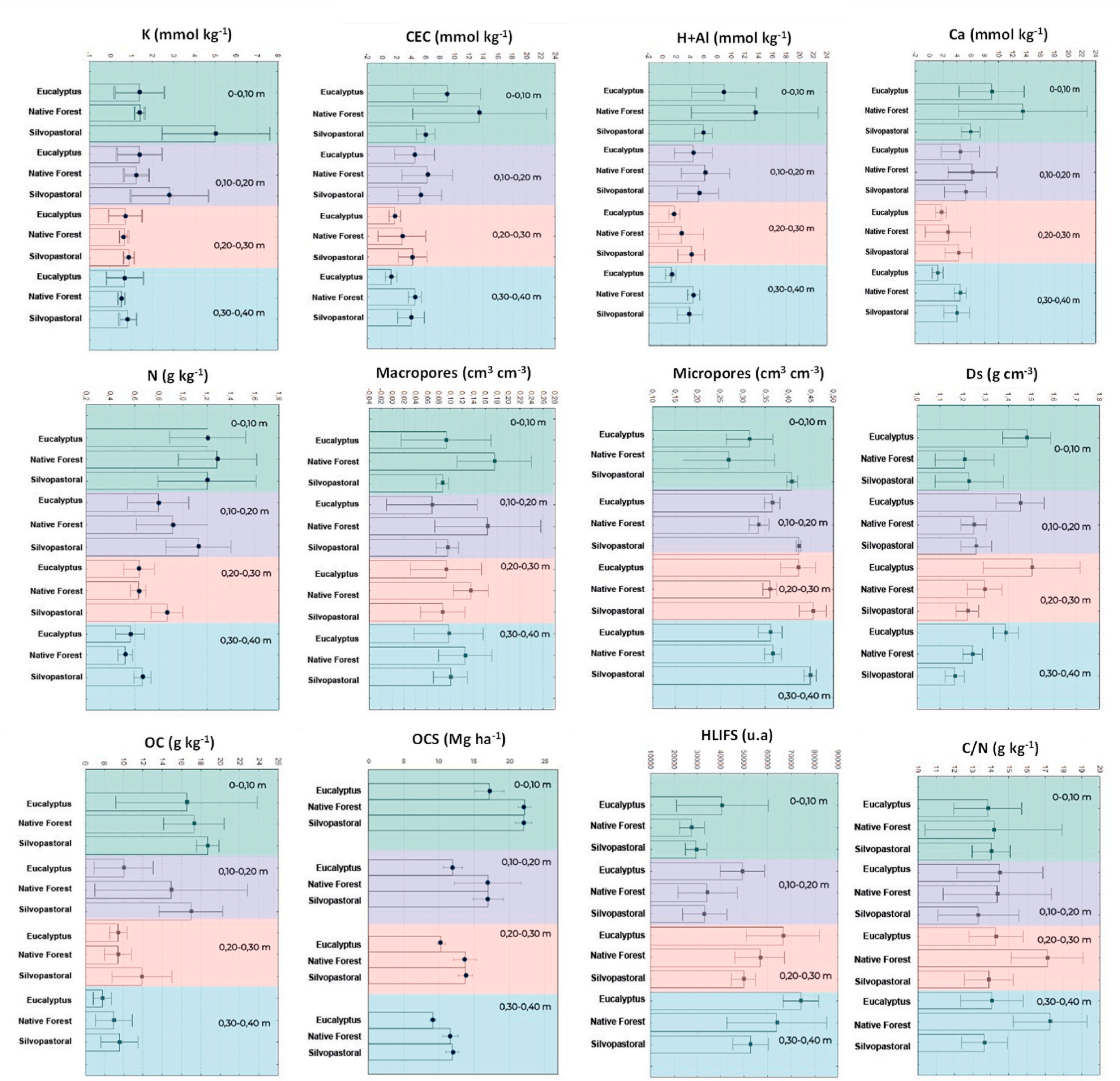

Fig. 2. Means and bars of confidence interval (95% confidence) of soil attributes at depths of 0.00–0.10, 0.10–0.20, 0.20–0.30, and 0.30–0.40 m for the planted forest of *Eucalyptus camaldulensis*, Cerrado native forest, and silvopastoral system. K = potassium content; Ca = calcium content; H + Al = potential acidity; CEC = cation exchange capacity, N = nitrogen; Macropores = soil macroporosity; Micropores = soil microporosity; OC = organic carbon, Ds = soil density; HLIFS = degree of humification of soil organic matter; C/N = carbon-to-nitrogen ratio; OCS = organic carbon stock.

for a natural system.

The soil under the eucalyptus planting system showed higher density (1.48 g cm^{-3}), whereas the soil under native forest (1.21 g cm^{-3}) and silvopastoral systems (1.22 g cm^{-3}) showed similar densities, at the depth of 0.00–0.10 m, but these values following along the profile with little variation in depth (Fig. 2).

The analysis of soil chemical attributes showed that N decreased along the profile. The shallowest depths (0.00–0.10 and 0.10–0.20 m) presented no differences between systems, but the depths 0.20–0.30 and 0.30–0.40 m under the silvopastoral system had a higher concentration of this nutrient than the Cerrado native forest. K^+ concentrations remained stable in the native forest and eucalyptus system, but a drastic depletion of this nutrient was observed in depth in the silvopastoral system when comparing the shallowest three depths. Ca^{2+}, H^++Al^3, and CEC showed higher values in the surface soil layer (0.00–0.10) of the native forest and eucalyptus system, with depletion in the subsequent depths. However, the silvopastoral system showed little variability in their concentrations along the soil profile (Fig. 2). For example, in the silvopastoral system, Ca^{2+} varied from 6.00; 5.25; 4.25 and 4.00 mmol kg^{-1} across the evaluated depths (0,00-0,10m; 0,10-0,20m; 0,20-0,30m and 0,30-0,40m), respectively.

Organic carbon (OC) decreased along the profile and the degree of humification of organic matter (HLIFS) increased, which impacted the carbon stocks of the systems (Fig. 2). OC in the eucalyptus system decreased considerably from the first (16.53 g kg^{-1}) to the second (10.01 g kg^{-1}) depth and then stabilized. Moreover, OC concentration in the native forest (17.60 g kg^{-1}) and the silvopastoral system (18.7 g kg^{-1}) remained at similar values in the first two depths, with a reduction from the third depth: 9.43 g kg^{-1} native forest and, 11.89 g kg^{-1} to silvopastoral.

Carbon stability needs to be estimated to determine soil quality indicators and evaluate soil carbon content and stock. Stability was estimated by calculating the decay constant (k) and soil carbon half-life ($t_{1/2}$) or the time required for 50% of the C–CO_2 to be decomposed. The eucalyptus system and the native forest also showed similar behavior relative to the k constant and the half-life time of labile soil carbon. However, the soil under the silvopastoral system stood out, as the k constant values indicated that the carbon evaluated along the profile of the soil managed in the silvopastoral system was decomposed more slowly than the carbon of the eucalyptus system and native forest. Consequently, carbon half-life, that is, the permanence time of labile carbon, was longer in the silvopastoral system, indicating higher carbon stability in this system.

Soil C/N ratio showed no differences between systems at the different depths due to its low variation. However, the native forest showed an increase in the C/N ratio at the depths 0.20–0.30 and 0.30–0.40 m. Overall, the mean values of these soil physical and chemical attributes show that some of them presented different behaviors depending on depth and management, especially those more associated with SOM degradation and gas emissions. Thus, a principal component analysis was performed to establish interdependence relationships between these attributes and FCO_2 to explain the dependence structure in the original set of variables and observe certain characteristics that enable the identification of natural correlations and multiple influences of the effect of converting natural areas to agricultural systems on the dynamics of CO_2 emissions.

The first and second principal components, when evaluated at different depths, explained between 65 and 75% of the total variation in the original data (Fig. 3). The overlap of the confidence ellipses (95% confidence) of the first depth showed that the silvopastoral and eucalyptus systems do not differ from the native forest, indicating that they present characteristics that make them similar to the natural forest environment at that depth. In contrast, the behavior of the point dispersion and confidence ellipses between the two conservationist systems (silvopastoral and eucalyptus systems) shows the formation of distinct groups (systems) due to the non-overlapping of ellipses. In summary, the conservationist systems do not differ from the native forest, but they differ from each other (Fig. 3). This behavior changes from the depth of 0.10–0.20 m, in which the silvopastoral system stands out, differing from both the eucalyptus system and the native forest, and this behavior is maintained at the following depths (0.20–0.30 and 0.30–0.40 m).

The projections of the attributes associated with the characteristics responsible for this behavior show that the soil under the silvopastoral system has a higher percentage of micropores, CEC, H^++Al^3, and K^+ in the first layer (0.00–0.10 m), in addition to sharing other characteristics more associated with the soil of the native forest, such as the highest organic carbon stock (OCS) and C/N ratio, which possibly contributes to the non-distinction of the silvopastoral system from the native forest. The other end of the chart at the same depth shows that the other attributes Ds, HLIFS, N, and macro (PC2) and FCO_2, temperature, and Ca (PC1) are associated with the eucalyptus system and native forest.

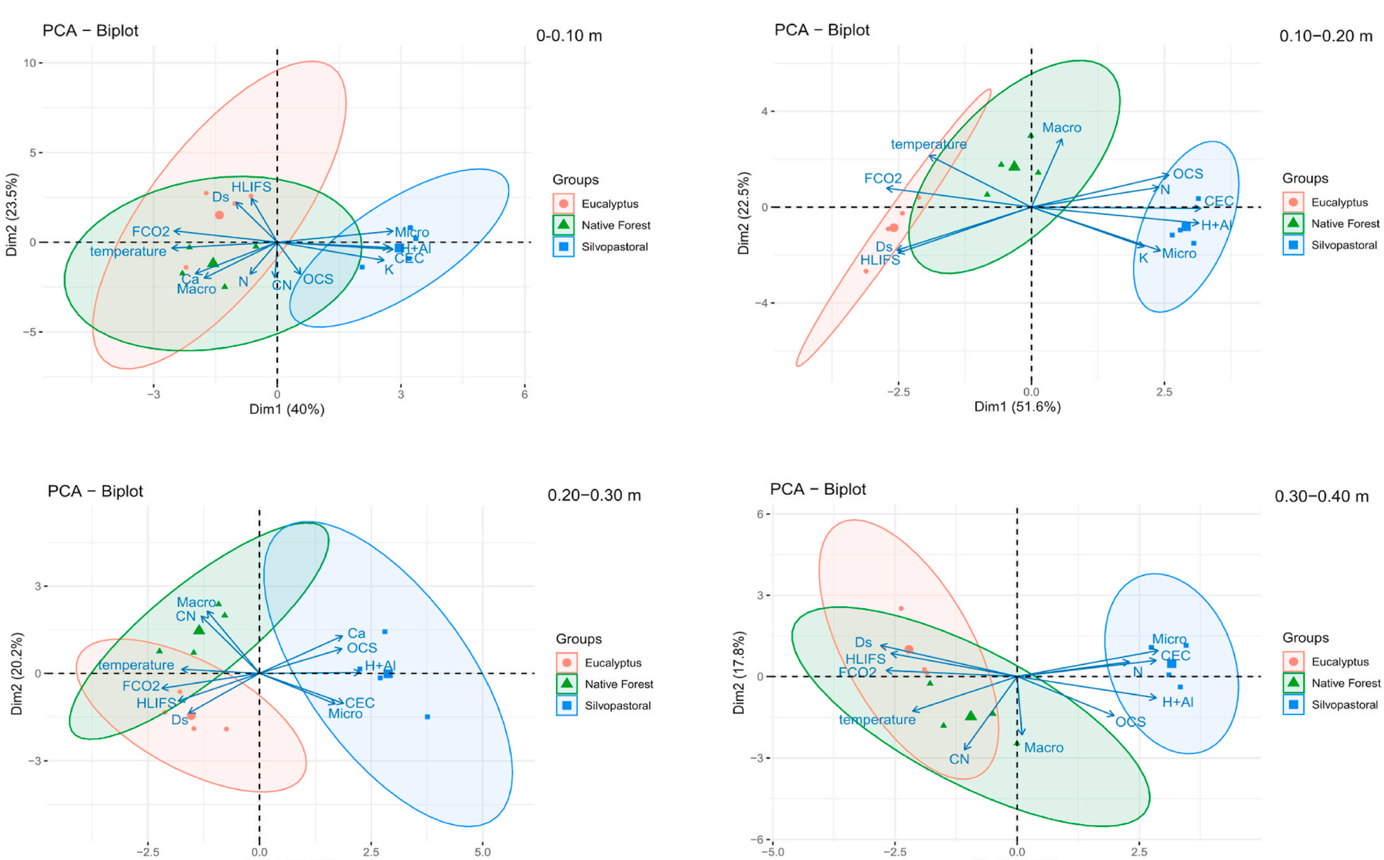

Fig. 3. Biplots with soil attributes, study areas, and confidence ellipses (95% confidence), correlation tables between soil attributes, and the first two principal components (PC1 and PC2) for depths of 0.00–0.10, 0.10–0.20, 0.20–0.30, and 0.30–0.40 m FCO_2 = soil CO_2 emission, Temperature = soil temperature, K = potassium, Ca = calcium, H^++Al^3 = potential acidity, CEC = cation exchange capacity; Macro = macropores; Micro = micropores; D = soil density; OCS = organic carbon stock; N = nitrogen; C/N = carbon-to-nitrogen ratio; HLIFS = degree of humification of soil organic matter.

The depth of 0.10–0.20 m showed that the highest contents of organic carbon and N are no longer associated with the native forest but with the silvopastoral system and this characteristic is maintained at the other depths (Fig. 3). The eucalyptus system presents characteristics similar to the native forest from this depth, and higher HLIFS associated with higher temperatures are possibly favoring higher FCO_2 in these two systems, that is, the dynamics of microorganism metabolism is more intense and soil respiration is higher, which possibly affected the organic carbon content in depth when multivariately evaluated in association with other soil attributes.

The exploratory analysis of data with confidence intervals (Fig. 1) showed no significant differences in the mean soil temperature accumulated over the evaluation period for the different systems (Fig. 1). However, the multivariate analysis showed that soil temperature and FCO_2 are directly related at all depths (Fig. 3). Fig. 3 shows the principal component analysis for the depth of 0.10–0.20 m. The two-dimensional plane generated with the first two principal components PC1 and PC2 accounts for 79.1% (56.6% in PC1 and 22.2% in PC2) of the variability contained in the set of original variables. The attributes that constitute PC1 are CEC (−0.93), $H^{+}+Al^{3}$ (−0.92), FCO_2 (0.79), Ts (0.76), OCS (−0.75), HLIFS (0.74), Ds (0.73), micropores (−0.71), N (−0.70), and K^{+} (−0.62). PC2 consists only of macropores (−0.83) (Supplementary Material 1). According to the factorial loadings and projections in the biplot, CEC, $H^{+}+Al^{3}$, OCS, N, K^{+}, and micropores are related to each other, but inversely associated with FCO_2, soil temperature, HLIFS, and soil density. Again, CEC, $H^{+}+Al^{3}$, K^{+}, OCS, and micropores are more representative in the area with the silvopastoral system, and soil nitrogen is also strongly associated with this system at this depth (0.10–0.20 m). It reaffirms the relationship between the attributes K^{+}, $H^{+}+Al^{3}$, CEC, and organic carbon, influencing the activities of soil microorganisms, as these attributes regulate organic matter.

The multivariate analysis of principal components for the depth of 0.20–0.30 m showed that the first two components together explained 64.9% of the total variation in the original data. The first principal component (PC1) accounted for 46.4% of this total variation, while the second principal component (CP2) accounted for 18.5% (Fig. 3). Ten out of the 12 soil attributes selected by the analysis were retained in PC1, namely: N (0.87), FCO_2 (−0.82), $H^{+}+Al^{3}$ (0.80), OCS (0.72), HLIFS (−0.70), Ca (0.68), CEC (0.66), micropores (0.66), soil temperature (−0.61), and Ds (−0.60). In contrast, PC2 retained macropores (−0.80) and C/N ratio (−0.73) (Supplementary Material 1). FCO_2, the degree of humification of organic matter, soil temperature, and soil density are directly related to each other at the depth of 0.20–0.30 m and inversely related to nitrogen, potential acidity, organic carbon, calcium, cation exchange capacity, and micropores.

The highest CEC, $H^{+}+Al^{3}$, N, OCS, and Ca values were associated with the silvopastoral system. The C/N ratio and macropores were more significant in the soil under the native forest. FCO_2, HLIFS, temperature, and soil density were similar in the native forest and eucalyptus system. Nine out of the 11 attributes selected by the principal component analysis for the depth of 0.30–0.40 m were retained in PC1. The attributes that contributed most to this component, in order of relevance, were micropores (0.90), $H^{+}+Al^{3}$ (0.89), soil density (0.88), FCO_2 (−0.84), HLIFS (−0.81), N (0.72), soil temperature (−0.67), and OCS (0.62), while the C/N ratio (−0.85) and macropores (−0.67) were retained in PC2. FCO_2, HLIFS, and soil temperature were directly related to each other at this depth (0.30–0.40 m) and inversely related to micropores, $H^{+}+Al^{3}$, CEC, Ds, N, and OCS. Furthermore, OCS, $H^{+}+Al^{3}$, CEC, and nitrogen were strongly related to the silvopastoral system. The silvopastoral system contributed to soil carbon accumulation over consecutive years, as the soil under this system also has a higher CEC and adequate $H^{+}+Al^{3}$.

4. Discussion

4.1. Dynamics of FCO_2, soil temperature, and soil moisture as a function of agricultural systems

The lower FCO_2 values found in the silvopastoral system may be related to the higher deposition of remaining straw from trees and *Brachiaria* pasture, which not only maintains the water content in the soil (Ussiri and Lal, 2009; Corradi et al., 2013) but also provides material at different levels of decomposition and complexity of plant residues, resulting in lower soil respiration rates, as this system's characteristic influences the selective action of microorganisms that decompose quickly the most labile substances, followed by those with higher stability to decomposition, influencing the speed of production and release of CO_2, which starts to be reduced over time (Pulrolnik, 2009). Other authors also have found lower FCO_2 in agroforests (Bailey et al., 2009) due to the carbon balance (Lovell, 2010; Netter et al., 2022). On the other hand, the loss of the tree component and forest degradation contribute to approximately 20% of annual greenhouse gas emissions worldwide (FAO, 2020).

The Eucalyptus system was also efficient in terms of low CO_2 emissions, with values similar to the native forest. Reversing current trends in the degradation of agricultural areas, acting decisively to restore degraded ecosystems, is one of the crucial environmental challenges of this century (Metzger et al., 2017). Reforestation programs were implemented in Brazil to direct actions that contribute to overcoming these challenges of reducing environmental impacts, and eucalyptus is the main forest species used in soils with low fertility and water deficit and is frequently used in the Brazilian Cerrado (Gama-Rodrigues et al., 2005), representing around 70% of the total area of planted forests in Brazil (ABRAF, 2012).

Soil temperature is one of the main climate factors that influence the vegetation cover decomposition rate, also acting on the speed of chemical reactions as a controlling factor associated with the rapid or slow organic matter degradation (Tullio, 2019). The mean values of soil temperature in the eucalyptus and silvopastoral systems were similar to those observed in the native forest (Fig. 1). The soil in traditional agricultural cultivation systems is totally or partially disturbed, which accelerates organic matter decomposition and alters aggregation, porosity, and density (Toma et al., 2013). In contrast, the non-disturbance in the silvopastoral and eucalyptus systems, associated with the presence of vegetation cover and organic matter, attenuates the thermal amplitude, altering the radiation balance due to the difference in the reflection coefficient and consequent decrease in the soil heating rate, making these systems similar to the native forest area.

In addition, the presence of trees protects and limits the incidence of solar energy (Salton et al., 2014). This characteristic also affects soil moisture, as temperature and moisture can co-vary (Davidson and Janssens, 2006; Savva et al., 2013; Moitinho et al., 2021). In comparison with the native forest, the eucalyptus system has lower soil moisture values (Fig. 1), which possibly occurs due to the characteristic root systems of the species, in which the dynamics of the fine roots to maintain the supporting roots cause a higher rate of renewal of fine roots, directly influencing in the higher requirement for water absorption from the soil (Martins et al., 2004). Replacing trees with crops harms not only soil temperature and moisture but also the temperature of an entire region. In fact, Lapola et al. (2014) discussed that the expansion of agricultural land in the Cerrado biome over native vegetation drastically influences albedo and evapotranspiration, causing an average regional warming of ~1.6 °C, driven mainly by the replacement of this natural vegetation by agricultural land with monoculture pastures, and this sharp increase in albedo is caused by the decrease in the leaf area index.

4.2. Effect of soil depth on the dynamics of attributes associated with FCO_2

Soil physical and chemical properties associated with CO_2 emissions were assessed at different depths to verify a possible effect along the soil profile mediated by the influence of roots. Soil porosity is important for the production and maintenance of water in agricultural soils, also controlling the dynamics of gas exchange within the soil, and any modification in this physical attribute, especially in macropores, contributes to interfering with the flow of water and air, affecting the biological and chemical processes that occur in the soil (Silva et al., 2019). The native forest soil presents higher macroporosity (Fig. 2), a characteristic of a non-compacted area. This proportion of porous spaces in the native forest of the Cerrado biome is also reflected in the lower soil density, the opposite of what was observed in the soil with eucalyptus planting, which presented higher soil density. However, the average density values in the systems vary little with soil depth and no sudden increase in density was observed due to the introduction of eucalyptus in the native area, indicating that the conversion did not negatively affect the soil structure.

Furthermore, no significant difference was observed for the mean values of OC, OCS, and the SOM mineralization stage (HLIFS), which may be related to the more conservationist history of land use in the areas under study and the conversion period. The similarities in values between the agricultural systems and the native forest relative to these important indicators of soil quality, which were repeated throughout the depths, indicate that the conservationist systems compensated for possible initial carbon losses after 32 years of conversion of the areas. Furthermore, there was a stabilization in the dynamics of decomposition and mineralization of soil organic matter over time, possibly due to different residual inputs and constant C/N ratio, i.e., a system that supplies materials to the soil at different levels and stages of decomposition (Totola and Chaer, 2002; Jagadamma, 2009).

Labile C stability was estimated through the decay constant (*k*) and the C half-life. The silvopastoral system stood out in this regard, as carbon was more stable in this management, that is, this system emitted less CO_2 over time although the systems were very similar to the native forest reference in terms of C stock. Therefore, knowing the physical and chemical characteristics of these management systems and how they act to protect this C is important, as C stock (OCS) and stability are good indicators of soil quality and the efficiency of conservationist management. Senescent plant material in these management systems is converted into organic products and can form intimate associations with soil aggregates and minerals through physicochemical and biological transformations (Miller et al., 2019; Kan et al., 2022). Soil aggregates are a vital physical property, as 90% of OCS in topsoil exists in aggregates (Modak et al., 2020). Moreover, not only organic carbon occlusion within soil aggregates but also chemical protection through association with soil minerals determines OCS stability (Chen et al., 2021). Physicochemical protection explains more of the variability in OCS stability compared to soil microbial properties (Chen et al., 2021), although microbial properties are also important, as microbial activity drives OCS mineralization dynamics (Fang et al., 2018).

Another important fact is that the silvopastoral system showed no decrease in CEC along the depths when compared to the eucalyptus system and the native forest (Fig. 2), in which CEC values decreased considerably from the first to the last studied depths. This fact is interesting for this study, as CEC characterizes the soil's ability to release various nutrients (Ca^{2+}, K^+, and Mg^{2+}), contributing to the long-term maintenance of SOM and soil fertility (Ronquim, 2010). The fact that there was no decrease in CEC along the depths in the silvopastoral system, indicates that this system has greater potential to release nutrients in deeper layers of the soil when compared to the eucalyptus system, possibly an effect of rooting depth. Also, the lower variability of CEC throughout the soil profile can positively favor C stock in most subsurface soil layers.

The biplot with the relationships between attributes and management systems at a depth of 0.00–0.10 m shows similarities between the native forest group and the silvopastoral system, as the confidence ellipses (95% confidence) overlap. The direct relationship between $H^+ + Al^3$, CEC, and K^+ observed in the soil under the silvopastoral system is understood since the CEC of soil represents the total amount of cations ($Ca^{2+} + Mg^{2+} + K^+ + H^+ + Al^3$) that remain on its surface under exchange conditions. Most of the CEC in fertile soil is occupied by essential cations, that is, alkalis ($Ca^{2+} + Mg^{2+} + K^+$), which is due to the direct relationship between CEC and $H^+ + Al^3$ (Ronquim, 2010; Moitinho et al., 2015; Teixeira et al., 2017).

The silvopastoral system can increase productivity and reduce the risk of degradation, as the grass root system that spreads across the upper part of the soil is constantly renewed. Dead roots and old leaves that fall to the soil surface are easily decomposed by microorganisms, cycling this plant material, and adding nutrients to the soil (Cerri et al., 2017). This characteristic of the silvopastoral system at a depth of 0.00–0.10 m favored the increase in micropores, $H^+ + Al^3$, CEC, and K^+ (Fig. 3). These attributes are SOM regulators and actively influence soil organic matter, also acting on the FCO_2 dynamics, regulating the CO_2 production rate, which is basically a biochemical process related to root respiration and the microbial community dynamics, the latter being affected by soil temperature, soil moisture, and the nutritional status of the soil (Lal, 2009). In this sense, La Scala et al. (2000) and Moitinho et al. (2015) found a positive influence of soil CEC relative to reductions in CO_2 emissions from soil to the atmosphere.

Similarities were observed between the N content in the native forest and the eucalyptus system at the depth of 0.00–0.10 m. However, higher amounts of this element at other depths are associated with the silvopastoral system (Fig. 3), an interesting fact, as soil N stocks are constantly used as a reference for crop sustainability (Cerri et al., 2017). The fact that the C/N ratio is more associated with the eucalyptus system and the native forest and there is a higher N content in the soil under the silvopastoral system, which has a lower C/N ratio in depth (Figs. 2 and 3), can help to understand this relationship. In fact, the C/N ratio allows the evaluation of the degree of evolution of soil organic matter and estimating the capacity to produce assimilable nitrogen forms (Cui et al., 2022). The higher the C/N ratio, the slower the SOM decomposition rate, and the nitrogen will be immobilized by microorganisms. Conversely, the lower the C/N ratio, the easier the SOM decomposition and, consequently, nitrogen will be released (Braga, 2015). Thus, the quantity and maintenance of soil N are controlled especially by the chemical composition of plant tissues and decomposition, biomass, and microbial activity (Carvalho et al., 2014).

In addition, the C/N ratio when playing a crucial role in the decomposition of crop residues has implications for soil health and nutrient cycling, the C/N ratio of cover crops or service crops is essential, some cover crops fix nitrogen (low C/N), while others contribute organic matter (higher C/N) (Cosentino et al., 2017), understand this dynamic, is very important for planning rotations, crop use and assess the service crops in agricultural systems.

The higher C and N values associated with the silvopastoral system demonstrate its benefits to soil quality over consecutive years in addition to maintaining soil carbon and nitrogen stocks. It would explain the higher percentage of micropores, higher nutrient allowance from the decomposition of organic residues, and, consequently, more benefits for soil fertility (Cerri et al., 2017). These benefits come from the increase in carbon in the soil in depth and the reduction in FCO_2, that is, the lower metabolic dynamics of microorganisms in this system favor higher stability of this carbon in the soil.

The silvopastoral system formed a separate group from the native forest and the eucalyptus system at other depths (0.10–0.20, 0.20–0.30, and 0.30–0.40 m) and maintained the same physical and chemical characteristics observed at the depth of 0.00–0.10. The soil under this system presented higher carbon stock along the profile. This stronger relationship with the carbon stock was possibly an important characteristic for this distinction of the silvopastoral system from the other groups formed by the native forest and the eucalyptus system (Fig. 3). According to Albrecht and Kandji (2003), agricultural lands are important potential carbon sinks capable of absorbing large quantities of this element, especially in systems with trees reintroduced with crops and/or carefully managed animals. In addition, agroforestry has been widely practiced throughout the ages as a means of achieving agricultural sustainability and slowing down the negative effects of agriculture, such as soil degradation and desertification. Still according to the authors, the C sequestration potential of agroforestry systems is estimated between 12 and 228 Mg ha^{-1}, with a median value of 95 Mg ha^{-1}.

Unlike what was observed in Fig. 1, soil temperature showed a direct relationship with FCO_2 in the eucalyptus management and the native forest when evaluated together with other soil physical and chemical attributes (Fig. 3). Panosso et al. (2011) also observed similar behavior between soil temperature and FCO_2 when comparing emissions in sugarcane areas under raw and burned sugarcane harvesting. The relationship observed between soil temperature, FCO_2, and HLIFS in the eucalyptus system and the native forest at all depths (Fig. 3) may be related to the activity of microorganisms in the decomposition of soil litter, as an increase in nutrient cycling leads to higher emissions, humic acid contents, and humification (Lal, 2009). Inkotte et al. (2015) evaluated litter in eucalyptus reforestation and native forests in the Planalto and West regions of the State of Santa Catarina, Brazil, and observed that forest covers behaved differently in terms of decomposition and microbial activity, which was quantified through mineralizable carbon in the CO_2 evolution. According to the authors, *Sapindus saponaria* litter presented a higher decomposition rate and, consequently, higher accumulated amounts of CO_2 compared to other forest covers.

The results indicated how complex the study of FCO_2 in systems under different vegetation covers is, as respiration in this ecosystem is autotrophic and heterotrophic. Respiration in soils without vegetation cover is exclusively heterotrophic, that is, it occurs through the metabolism of various organisms associated with substrates and organic compounds easily measured in the soil. However, the variability of CO_2 fluxes in soils with different vegetation covers is even higher because respiration is the result of litter decomposition, root respiration, dead root decomposition, fungal respiration, and microbial respiration, controlled by edaphoclimatic conditions, which makes it very difficult to separate the different CO_2 sources (Kuzyakov, 2006). However, the FCO_2 values of the eucalyptus and silvopastoral systems after 32 years of conversion are very close to that of the soil of the native forest, which indicates that both of them can be considered conservationist systems capable of storing carbon and mitigating CO_2 emissions although the silvopastoral system has presented the lowest accumulated value.

We emphasize that, although organic matter, the soil carbon cycle and sequestration are very important topics in the analysis of climate change for mitigation concerns and even more so if the analysis is focused on the assessment of gas emissions, such as CO_2, there are still implications very serious in relation to changes in land cover from native forest to other production systems, also related to climate change and conservation, for example, soil biodiversity and support for wildlife conservation and these changes are significant, especially in the Cerrado biome. According to data from the World Wildlife Fund (WWF, 2022), most species have lost between 25% and 65% of their original distribution area. The Brazilian agricultural sector already has good examples of how to expand production, without deforesting, recovering, and reforesting degraded areas.

5. Conclusions

The lowest values of soil CO_2 emissions are related to the silvopastoral management system, with a 36% reduction in soil CO_2 emissions when compared to the conversion of the native forest to the silvopastoral system and a 19% increase when converting the native forest to the eucalyptus system. Soil temperature, the degree of humification of organic matter, carbon stock and stability, and the carbon-to-nitrogen ratio most contributed to characterizing the soil CO_2 emission process in conservationist systems in the Cerrado.

In conservationist terms, the lower CO_2 emission values for silvopastoral areas and the similarity of carbon and carbon stock with the native forest, in addition to the lower decay constant and consequent longer half-life of labile carbon under this system, allow us to infer that the area with the silvopastoral system is a balanced ecosystem, which has great potential both to stabilize carbon in the soil and to reduce the contribution of agriculture to greenhouse gas emissions, mainly CO_2.

CRediT authorship contribution statement

Bruna de Oliveira Silva: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Formal analysis, Data curation, Conceptualization. **Mara Regina Moitinho:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Alan Rodrigo Panosso:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Formal analysis, Data curation, Conceptualization. **Dener Marcio da Silva Oliveira:** Writing – review & editing, Writing – original draft, Visualization, Validation, Investigation, Conceptualization, Resources, Project administration, Methodology, Formal analysis, Data curation, Conceptualization. **Rafael Montanari:** Writing – review & editing, Writing – original draft, Visualization, Conceptualization. **Mario Luiz Teixeira de Moraes:** Writing – review & editing, Writing – original draft, Visualization, Conceptualization. **Débora Marcondes Bastos Pereira Milori:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Data curation, Conceptualization. **Elton da Silva Bicalho:** Writing – review & editing, Writing – original draft, Visualization, Conceptualization. **Newton La Scala:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Data curation, Conceptualization.

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.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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