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Impact of different use systems on total and mineralizable organic carbon in a sandy soil

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ABSTRACT

This study aimed to evaluate the impact of different land use systems on total organic carbon (TOC) contents and stocks and the daily and total evolution of mineralizable carbon (C-CO_2) in a sandy-textured Argissolo Vermelho Amarelo. The study was carried out in Eldorado, MS, in a reference area of Native Forest (NF) and three managed areas: Permanent Pasture (PP), Direct Sowing b(DS), and an area of Private Natural Heritage Reserve (PNHR) in the process of natural regeneration. Soil samples from the 0.0-0.05, 0.05-0.10, and 0.10-0.20 m layers were collected to assess soil density (Sd), TOC contents, with subsequent calculations of the stratification index (SI), carbon stock (StockC), and variation of the total organic carbon stock (ΔStockC), in addition to the determination of daily emission and calculation of total C-CO_2 accumulation. The NF area had the highest levels and stocks of TOC, reaching 16.42 g kg^{-1} and 20.90 Mg ha^{-1}, respectively. On the other hand, the PP and PNHR areas had the lowest content and StockC. The areas of PP, DS, PNHR, and NF presented SI values of 1.08, 1.13, 1.32, and 1.61, respectively. The NF area showed higher peaks and a higher total accumulation of C-CO_2, inferring the highest biological activity in this area. By multivariate analysis, none of the managed areas was close to the NF in quality. The worst results considering the evaluated attributes were observed in the areas of PP and PNHR due to the stage of degradation of these areas as a result of exploration and land use history.

Keywords: Soil organic matter, Private Natural Heritage Reserve (PNHR), Conservation unit.

Impacto de diferentes sistemas de uso no carbono orgânico total e mineralizável do solo sob solo arenoso

RESUMO

O objetivo deste trabalho foi avaliar o impacto de diferentes sistemas de uso nos teores e estoques de carbono orgânico total (COT) e a evolução diária e total do carbono mineralizável (C-CO_2) em um Argissolo Vermelho Amarelo de textura arenosa. O estudo foi realizado no município de Eldorado, MS, em uma área de referência de Mata Nativa (MN), e em três áreas manejadas: pastagem permanente (PP), semeadura direta (SD) e área de Reserva Particular de Patrimônio Natural em processo de regeneração natural (RPPN). Amostras de solo das camadas 0,0-0,05, 0,05-0,10 e 0,10-0,20 m foram coletadas para avaliação de densidade do solo (Ds), teores de COT, com posteriores cálculos do índice de estratificação (IE), estoque de carbono (EstC) e variação do estoque de carbono orgânico total (ΔEstC), além da determinação da emissão diária e cálculo do acúmulo total de C-CO_2. A área de MN apresentou os maiores teores e estoques de COT, chegando a 16,42 g kg^{-1} e 20,90 Mg ha^{-1}, respectivamente. Já as áreas de PP e RPPN os menores teores e EstC. As áreas de PP, SD, RPPN e MN apresentaram valores de IE de 1,08, 1,13, 1,32 e 1,61, respectivamente. A área de MN apresentou maiores picos e maior acúmulo total de C-CO_2. Pela análise multivariada, nenhuma das áreas manejadas se aproximou em qualidade a MN. Os piores resultados nos atributos avaliados são observados nas áreas de PP e RPPN devido ao estágio de degradação destas áreas em função do histórico de exploração e uso do solo.

Palavras-chave: Matéria orgânica do solo, Reserva Particular do Patrimônio Natural (RPPN), Unidade de conservação.

1. Introduction

Soil supplies numerous basic environmental services essential to human well-being, such as food production, nutrient cycling, and carbon sequestration (C) (Parron et al., 2015; Fonseca et al., 2014). Its use for agricultural activities can lead to chemical, physical, and biological attributes changes, and it is necessary to intervene through management that promotes the sustainability of these areas, as well as yield (Rogers et al., 2019). Due to these factors, it is necessary to know the most diverse soil quality indicators (SQ) (Santos et al., 2017a).

Among the various factors that influence the ability of ecosystems to store C, resident species, climate, and soil characteristics, such as density and natural fertility, in addition to the types of land use patterns, which change rapidly by anthropic activities, can be cited (Costa et al., 2020). When soil management is carried out intensively, with frequent revolving, an example of areas with conventional tillage, organic C is released into the atmosphere in the form of carbon dioxide (CO_2) as a result of the increase in mineralization of soil organic matter (SOM) by the action of microorganisms, as well as in poorly managed and degraded areas, with uncovered soils, in which the level of soil loss increases (Falcão et al., 2020) together with SOM by erosion (Ferreira et al., 2020; Franco et al., 2015).

However, QS research in areas with soil removal for clay extraction is scarce in the literature/ studies that assess these areas and that present comparisons with known management systems are essential to assess the impact of this activity. Thus, quantifying C contents and stocks in the soil and other attributes, such as mineralizable carbon (C-CO_2), is essential to identify the most appropriate management systems for each regional reality. It is important to highlight that the intake of plant residues under the soil added to non-mobilization increases the physical protection of intra-aggregate C against microbial attack, delaying the decomposition process, with consequent C accumulation in the edaphic system (Adhikari et al., 2019; Lee et al., 2020).

With the addition of more labile C sources to the soil, there is stimulation of microbial respiration, resulting from the decomposition and mineralization of SOM, influenced by the quantity and quality of the residue, temperature, and intrinsic factors of the soil, releasing a greater amount of CO_2 into the atmosphere (Sandén et al., 2019). To evaluate these increases in C-CO_2 released by microbial activity, it is possible to quantify mineralizable C by the evolution of C-CO_2 (Haney et al., 2018) from the respiration of aerobic heterotrophic microorganisms during the oxidation of organic compounds (Shi et al., 2020).

The different soil management systems can directly affect soil carbon contents and stocks, in addition to C-CO_2 emission, which can be used as quality indicators (Sandén et al., 2019; Adhikari et al., 2019; Costa et al., 2020; Morais et al., 2020; Morais et al., 2021). The study aimed to evaluate the impact of different land use systems on total organic carbon (TOC) contents and stocks and the daily and total evolution of mineralizable carbon (C-CO_2) in a sandy-textured Argissolo Vermelho Amarelo.

2. Material and Methods

Soil samples were collected in different management systems with known history, located in the Porto Morumbi district in Eldorado, Cone-Sul region of Mato Grosso do Sul, Brazil (Figure 1).

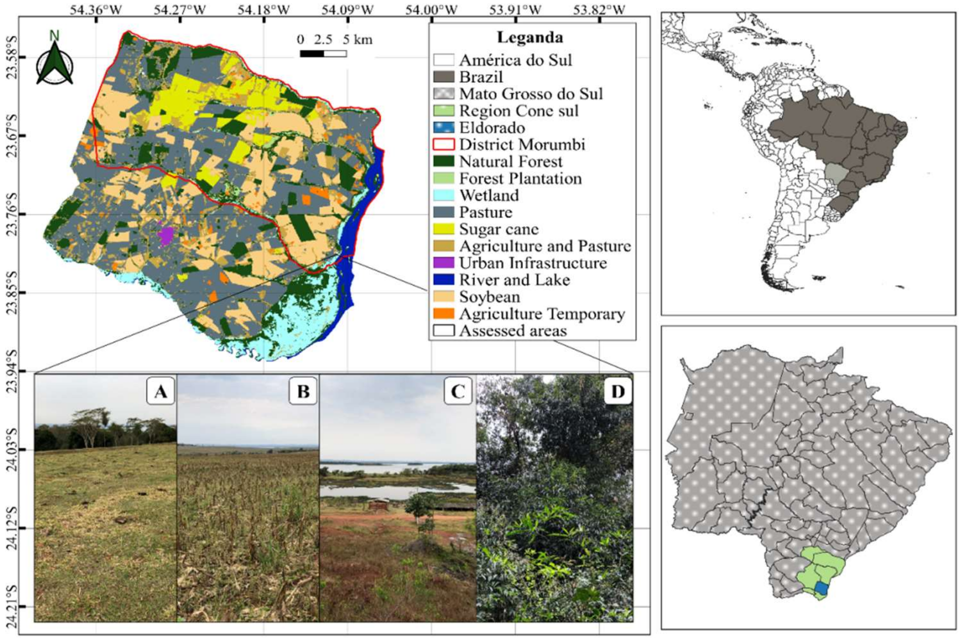

Figure 1. Location map of the experimental area, with land use and occupation data in Eldorado, MS, Brazil. MapBiomas project (2021). QGIS version 3.14 "Pi". (A) Permanent Pasture, (B) Direct Sowing, (C) Private Natural Heritage Reserve, (D) Native Forest.

The study areas are located at coordinates 23º48' S and 54º06' W, with an average altitude of 272 meters, and located within the Environmental Protection Area (APA) of the Islands and Flood plains of the Paraná River (Ilhas e Várzeas do Rio Paraná) (ICMBio, 2019). The climate of the region is subtropical – Cfa, according to the Koppen classification (Peel et al., 2007), with an average temperature of the coldest month between 14 and 15ºC and rainfall ranging from 1,400 to 1,700 mm per year (Semade, 2015).

All four areas studied are on soil classified as Argissolo Vermelho Amarelo distrofico típico (Santos et al., 2018), equivalent Acrisols (Iuss Working Group Wrb, 2015) and Ultisols (Soil Survey Staff, 2014) of sandy texture (Santos et al., 2018), making up four different systems, analyzed in a completely randomized design. The areas of the present study have their respective history of use and management shown in Table 1. In each of the four study areas, disturbed soil samples from the 0-0.2 m layer were collected for soil physical and chemical characterization analyses (Table 2).

For each of the four study areas, composite disturbed soil samples were collected in five replicates in the 0.00-0.05, 0.05-0.10, and 0.10-0.20 m layers, each composite sample being represented by five simple samples for the total organic carbon (TOC) analyses and subsequent calculations of the stratification index (SI), C stock (StockC), and stock variation (ΔStockC). In all areas and layers, undisturbed samples were collected with a volumetric ring with a volume of 100 cm³ with five replicates for soil density analysis (Sd). In addition, immediately after collection, part of the samples of the 0-0.05 m layer was reserved under refrigeration for subsequent soil incubation in the laboratory for mineralizable carbon analysis ($C-CO_2$)

The Sd was determined by the methodology described by Claessen (1997). The TOC content was determined by oxidation of organic matter by potassium dichromate in a sulfuric medium under heating and titrated with ammoniacal ferrous sulfate (Yeomans; Bremner, 1988), with subsequent calculation of the StockC according to the equivalent mass method (Reis et al., 2018; Ozório et al., 2020).

To verify trends of accumulation or loss of TOC compared with the reference system (Native Forest), the ΔStockC was calculated by the difference between the mean values of StockC in this system (reference) and each of the others. The obtained value was divided by the thickness (cm) of each layer. In addition, with the results of the TOC content, SI was also calculated, which represented the ratio between the TOC contents of the 0.00-0.05 m layer and the TOC content of the 0.10-0.20 m layer as proposed by Franzluebbers (2002).

Table 1. History and description of the change in management systems of the different study areas

Area	Area/hectare	Management history
PP	5 hectares	Cultivated with *Brachiaria brizantha* Hochst Stapf cv. MG4 permanently for ten years. Used for grazing beef animals with a stocking of 1.2 animal units (AU) ha^{-1} with visible signs of degradation. The area was initially deforested in 1970 and was cultivated for 39 years in a conventional tillage system.
DS	50 hectares	Agricultural production in direct sowing with a succession of soybean (summer) and corn (second harvest) crops, this type of system being carried out in the area in the last ten years. It was previously cultivated in a conventional tillage system for 39 years.
PNHR	15 hectares	Private Natural Heritage Reserve: it was previously used with the removal of soil for the production of ceramics for 41 years, being converted into a conservation unit and isolated in the last two years.
NF	20 hectares	The native vegetation of the Atlantic Forest - Semideciduous Seasonal Forest. This area represented the original condition of the soil without anthropic action.

PP: Permanent Pasture, DS: Direct Sowing, PNHR: Private Natural Heritage Reserve, NF: Native Forest

Table 2. Physical and chemical soil attributes of the 0-0.2 m layer of the four areas studied in the Porto Morumbi district, Eldorado, MS.

Área	Sand	Silt	Clay	pH	OM	P	K	Ca	Mg	Al	H+Al	SB	CEC	V
	--------g kg^{-1}--------			$CaCl_2$	g dm^{-3}	mg dm^{-3}	---------------------$cmol_c dm^{-3}$--------------------							%
PP	860	43	97	4.59	14.76	6.79	0.04	0.80	0.60	0.13	1.40	1.44	2.84	50.70
DS	794	59	147	4.07	20.77	13.88	0.17	1.10	0.80	0.39	2.80	2.07	4.87	42.50
PNHR	894	26	80	4.13	13.39	10.44	0.05	0.60	0.30	0.30	1.80	0.95	2.75	34.50
NF	832	44	124	4.69	26.78	12.01	0.15	3.00	1.10	0.10	2.40	4.25	6.65	63.90

Granulometry: pipette method. Chemical characterization – Calcium Chloride (pH); Mehlich (P and K); KCl 1N (Ca, Mg and Al); Calcium Acetate pH 7 (H + Al); OM: Organic matter; SB: Sum of bases; CEC: Cationic exchange capacity; V: Base Saturation.

The determinations of C-CO_2 emission in the laboratory were performed according to a method proposed by Mendonça & Matos (2005), in which 50 g of soil were placed in plastic containers of 3000 cm^3, sealed hermetically, together with a flask containing NaOH solution 0.5 mol L^{-1} for the capture of C-CO_2 and another flask with water to maintain moisture. The containers were arranged in the laboratory in a completely randomized design. C-CO_2 emission evaluations were performed at 24-hour intervals in the first seven days, 48-hour intervals between the 8th and 17th days, and 96-hour intervals until the 49^{th} day. The calculation of the evolved C-CO_2 was presented in mg of C-CO_2/kg of soil during the sample monitoring interval. For the total accumulation, the sum of all readings performed was calculated.

The results were analyzed in a completely randomized design, subjected to variance analysis employing the F-test. The mean values were compared to each other by the Tukey test at 5% probability with the aid of the R Core Team program (2019). All tests were performed using the ExpDes.pt (Ferreira et al., 2018). A complementary analysis was also performed, using the multivariate technique of principal component analysis - PCA, to analyze interrelationships involving all variables and explain them in terms of their inherent dimensions (Silva et al., 2020).

3. Results and Discussion

The area cultivated under DS had higher soil density (Sd) in the 0-0.05 and 0.05-0.1 m layers, with values of 1.52 and 1.54 Mg m^{-3}, respectively, differing only from the native forest (NF) area (Figure 2). Regarding the 0.10-0.20 m layer, there was no difference in Sd between all areas evaluated. In this last treatment, this result can be explained between the soil areas, and the individual pedogenetic characteristic can be explained as it is sandy soil (Lima et al., 2018).

According to Reinert et al. (2008), higher Sd values in DS areas can be observed due to the cultivation in a crop succession system, unlike areas with greater floristic heterogeneity, where crop rotation is practiced. Moreover, since the crop rotation system is not adopted, improvements in soil physical attributes in SD take longer to occur (Rosset et al., 2014). Lower SD values in MN (Figure 4) are due to the absence of anthropic actions added to the higher levels of total organic carbon (TOC) (Figure 4) due to the organic material added continuously by the native vegetation.

The TOC contents of the different areas in the 0-0.05 m layer ranged from 7.28 g kg^{-1} to 16.42 g kg^{-1}, with higher content in the NF area (Figure 3). This higher content of TOC in the NF in the surface layer is due to the continuous deposition of plant material from litter (branches, leaves, flowers, fruits, and tree bark) on the soil surface , in addition to lower losses by erosive processes (Barros et al. 2013), as well as the absence of anthropic activity in this location, as observed by Rosset et al. (2014; 2016; 2019), Assunção et al. (2019) and Ferreira et al. (2020) comparing managed areas and native vegetation of Atlantic Forest in Guaíra, PR, by Ozório et al. (2019; 2020) in Terra Roxa, PR and Martins et al. (2020) and Troian et al. (2020) in Iguatemi, MS.

It is also noteworthy that even though the DS area was managed with intensive soil revolving under CPS after deforestation from 1970 to 2009, the TOC contents were higher than in the areas of PP and PNHR in all layers evaluated, similar to the NF in the 0.10-0.20 m layer, reaching 11.46 g kg^{-1} in the 0-0.05 m layer. (Figure 3).

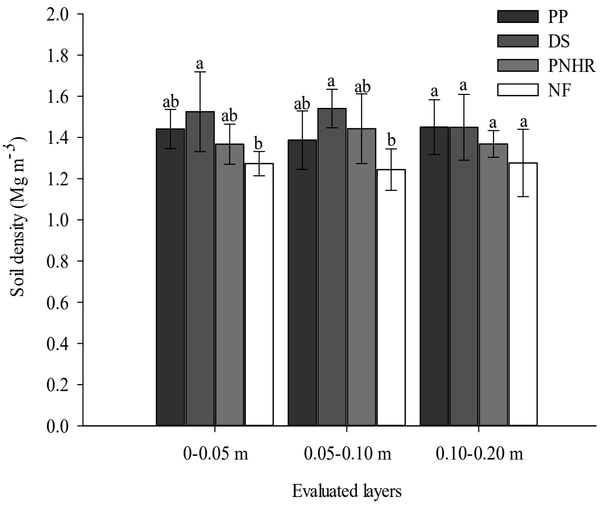

Figure 2. Soil density (Sd) for the different areas evaluated. For each layer, means followed by equal letters do not differ from each other by the Tukey test at 5% probability. PP: Permanente Pasture, DS: Direct Sowing, PNHR: Private Natural Heritage Reserve, NF: Native Forest.

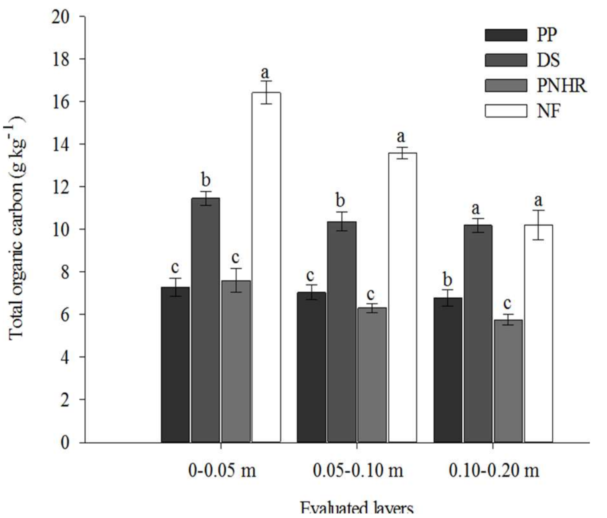

Figure 3. Total organic carbon (TOC) in the different areas. For each layer, means followed by equal letters do not differ from each other by the Tukey test at 5% probability. PP: Permanente Pasture, DS: Direct Sowing, PNHR: Private Natural Heritage Reserve, NF: Native Forest.

That is because of the ten years of adoption of the DS even in the soybean/corn succession system, reflecting the importance of this management system for carbon accumulation (C) in the soil. Higher TOC contents in the most superficial layer in DS with soybean/corn succession were also found by Moura et al. (2021) and Alves et al. (2020). The lowest TOC contents in all layers evaluated were observed in the areas of PP and PNHR, ranging from 6.79 to 7.28 g kg^{-1} and 5.75 to 7.61 g kg^{-1}, respectively (Figure 3), showing no potential for TOC accumulation. In the PP area, the low TOC content is due to the advanced stage of degradation of the area, derived from poor soil management (low percentage of soil cover, presence of weeds in total area, and laminar erosion), in addition to overgrazing due to animal overcrowding. Similar results were found by Oliveira et al. (2021), Damian et al. (2021), and Cezimbra et al. (2021).

In the area of PNHR, the low levels of TOC (Figure 3) is a result of the high level of degradation of the area due to the exploration of the soil for clay extraction that occurred for decades before the isolation of the area in 2017, when the PNHR was created. The area is in the process of natural regeneration. It is likely that over time, the TOC contents in the PNHR area tend to increase due to the isolation of the area and consequent suspension of exploratory anthropic activities, as well as the process of natural regeneration (Onofre et al., 2010). The increase in TOC contents is fundamental for the recovery of degraded areas, given the direct association with the improvement of edaphic quality (Lal, 2018) resulting from the improvement in chemical (Macintosh et al., 2019), physical (Santos et al., 2019) and biological attributes of the soil (Yada et al., 2015).

Considering only the managed areas, it was observed that the areas of PP, DS, and PNHR presented SI values of 1.08, 1.13, and 1.32, respectively. The PP and DS were similar, and the PNHR area had an intermediate value. The NF area presented the highest SI, 1.61 (Figure 4). This is due to the continuous deposition of litter, indicating a greater accumulation of C in the soil surface layer (Ozório et al., 2019), corroborating the highest levels of TOC in the 0.00-0.05 m layer in this respective area (Figure 4).

The lower value of SI in the PP area is due to the lack of practices that assist the proper development of grasses, along with overgrazing by cattle in this area, which causes changes in soil structure, decreased plant development and dry matter intake, and consequently, TOC (Santos et al., 2017b) over time, as can be observed with the finding of low TOC contents in this area (Figure 3). On the other hand, the low SI in the DS area is due to the non-adoption of a crop rotation system, in which there is potential for faster C accumulation in the soil over the years of cultivation concerning the crop succession system (Boddey et al., 2010). Lower values of SI for areas under DS and PP concerning native vegetation of Atlantic Forest were also observed by Ozório et al. (2019) in the municipality of Terra Roxa, PR.

The NF area presented the highest C stocks (StockC) concerning the other areas evaluated in the layers 0-0.05 and 0.05-0.10 m, and in the sum of the layers, that is, in the section 0-0.20 m. For the 0.10-0.20 m layer, the StockC in the DS was similar to the NF (Figure 5). The PP area presented StockC of 9.26; 8.76 Mg ha^{-1} in the 0.00-0.05 and 0.05-0.10 m layers, similar to the values observed for PNHR, 9.68; 7.86 Mg ha^{-1}. However, for the 0.10-0.20 m layer, the PP area presented higher StockC (8.66 Mg ha^{-1}) than the PNHR (7.34 Mg ha^{-1}).

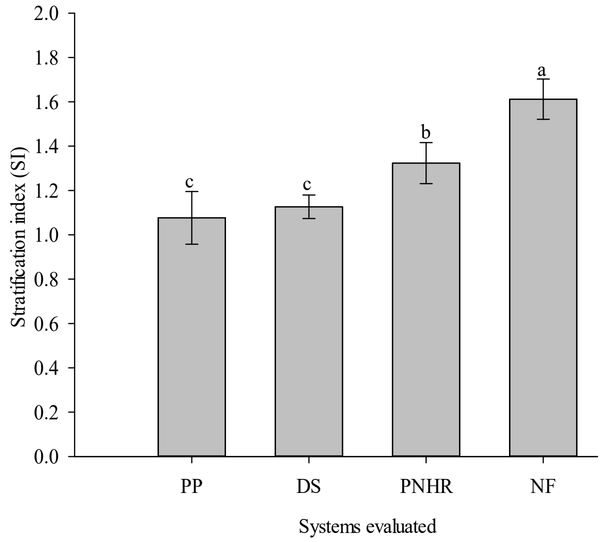

Figure 4. Carbon stratification index (SI) for the different areas evaluated. Means followed by equal letters do not differ from each other by the Tukey test at 5% probability. PP: Permanente Pasture, DS: Direct Sowing, PNHR: Private Natural Heritage Reserve, NF: Native Forest.

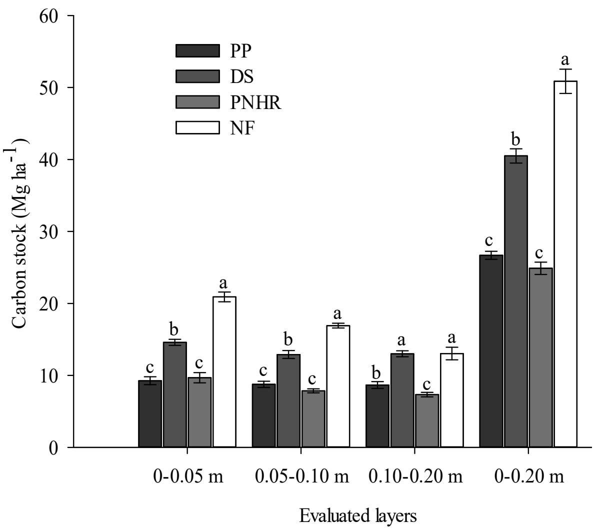

Figure 5. Total organic carbon stock (StockC) in the 0-0.05; 0.05-0.1; 0.1-0.2 m layers and in the 0-0.2 m section for the different areas evaluated. For each layer, means followed by equal letters do not differ from each other by the Tukey test at 5% probability. PP: Permanente Pasture, DS: Direct Sowing, PNHR: Private Natural Heritage Reserve, NF: Native Forest.

The direct contribution of C can explain higher StockC in the area of DS concerning PP and PNHR through soil cover and minimum revolving, essential requirements for the maintenance of StockC (Rogers et al., 2019). The lowest StockC in the areas of PP and PNHR is a consequence of the inadequate management carried out in these areas in recent years/decades, as highlighted by the history of land use and occupation of these areas. In a study of pastures in Brazil, Oliveira et al. (2022) found that losses of up to 0.25 Mg C ha^{-1} year^{-1} occur in degraded pastures, and simple management adoptions for pasture improvement can ensure a rapid recovery of carbon stocks, contributing map increase carbon sequestration.

Negative variation of the StockC (ΔStockC) was observed in all managed areas in the three layers evaluated, except for the DS area in the 0.10-0.20 m layer. This negative variation is more evident in the 0-0.05 m layer, being more evident in the PP area, followed by the PNHR and DS areas (Figure 6). This marked reduction of StockC in the most superficial layer of the soil indicates greater susceptibility of TOC to oxidation in this layer, especially under conditions of inefficient management systems in accumulating C in the soil profile (Koven et al., 2017), as observed by Santos et al. (2021).

The low deposition of organic matter due to overgrazing in the PP area and clay extraction in surface layers in the PNHR area greatly influence these results. The assessment of ΔStockC in soils under different soil use conditions can help in the choice of conservation soil use and management patterns (Lal, 2018; Shahbaz et al., 2017; Falcão et al., 2020), with consequent preservation of soil physical (Sales et al., 2018) chemical (Falcão et al., 2020; Santos et al., 2021) and biological quality (Rosset et al., 2019; Ferreira et al., 2020).

Regarding the 0-0.20 m layer, negative ΔStockC was noted in all managed areas, being more evident for the PNHR area, followed by the PP and DS areas (Figure 6). In agricultural systems, StockC is influenced, among several factors, by the management adopted because with the differentiated addition of residues to the soil; it is possible to identify different patterns of ΔStockC (Falcão et al., 2020); since these systems, when poorly handled, have reduced capacity to add high amounts of plant residues, directly compromising the accumulation of C in the soil (Mascarenhas et al., 2017).

Ozório et al. (2019) also observed negative ΔStockC in DS areas concerning Atlantic Forest vegetation in Terra Roxa, PR and in PP areas compared to native Cerrado vegetation in Aquidauana and Anastácio, MS. Higher peaks of C-CO_2 emission were observed in NF in 6 of the 20 readings performed, reaching 121.8 and 114.6 mg of C-CO_2 kg of soil-1 on the 5th and 41st days of evaluation, respectively. (Figure 7A). These higher C-CO_2 emission peaks corroborate the highest levels of TOC observed in this area, 16.95 g kg-1 in the 0-0.05 m layer (Figure 4). Similar results were obtained by Borges et al. (2015) in the Region of Triângulo Mineiro, Cerrado biome.

For the Atlantic Forest Biome, Rosset et al. (2019) in Guaíra, PR, and Ozório et al. (2020) in Terra Roxa, PR also observed higher C-CO2 emission peaks in a native vegetation area of Atlantic Forest concerning areas managed under DS with soybean/corn succession and permanent pasture. In the three studies, the authors attributed the highest emission peaks in the native vegetation area to the higher content of TOC due to the better conservation stage, which allows greater microbial activity. It is important to highlight that the differences in vegetation cover reflect C-CO2 emission rates (Castellano et al., 2017).

After a gradual increase in C-CO_2 emission peaks until the fifth day of incubation, there was a marked decrease in C-CO_2 emission peaks, followed by a subsequent increase and decrease (Figure 7A). This significant reduction in C-CO_2 emissions on some specific days happens due to the death of a certain amount of microorganisms, favoring the reduction of subsequent emissions. However, the latter peaks occur because dead microorganisms serve as food for the remnants, the action of the "priming" effect (Kuzyakov et al., 2000; Ghosh et al., 2018), a pattern also observed by Rosset et al. (2019) and Ozório et al. (2020).

On the thirty-seventh day of evaluation, there was a stabilization of C-CO_2 emission in PP (Figure 7A). This stabilization is a result of the total consumption of the readily available organic matter in this area, given the low deposition of plant material on the soil surface due to the high animal stocking. This is related to the low TOC content in the 0-0.05 m layer, 8.89 g kg-1 (Figure 3), in addition to the plant residues coming from only one plant species, in this case, the grass implanted ten years ago.

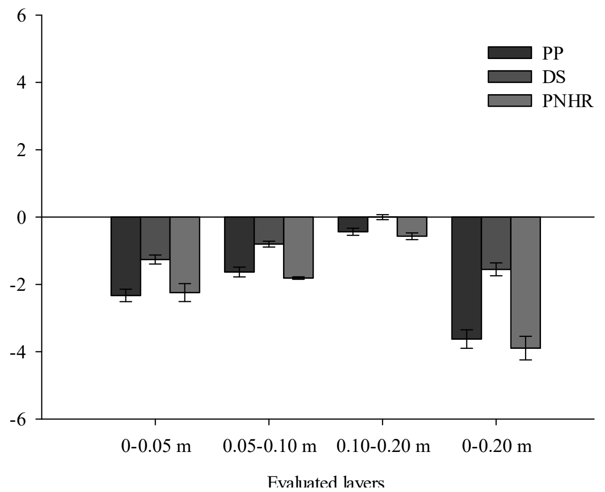

Figure 6. Variation of total organic carbon stock (ΔStockC - Mg ha-1 cm-1) in the layers 0-0.05, 0.05-0.10, and 0.10-0.20 and in the sum of layers (0-0.20 m) for the different management systems concerning the native forest area. PP: Permanente Pasture, DS: Direct Sowing, PNHR: Private Natural Heritage Reserve.

In the last days of the evaluation, there were peaks of C-CO_2 emissions in the areas of DS, PNHR, and NF (Figure 7A). The non-stabilization of C-CO_2 emissions in these three areas is possible due to a greater amount of more labile fractions of C, even in the PNHR area, with lower TOC contents concerning DS and NF (Figure 3). It is worth mentioning that areas with higher levels of labile C in the soil have higher C-CO_2 emissions, in addition to a longer time for emission stabilization, as also observed by Ozório et al. (2020) in areas of Native Forest and DS.

The total C-CO_2 emission of the NF area was 976.4 mg C-CO_2 kg of soil^{-1}, significantly higher than in the areas of PP, DS, and PNHR, with 549.2; 679.2; and 703.2 mg C-CO_2 kg of soil^{-1}, respectively (Figure 7B). This higher total C-CO_2 emission from the NF area is directly related to the highest TOC content (Figure 3) and the highest daily emission peaks presented (Figure 7A). This is a consequence of the continuous litter deposition in the surface layer of said area, in addition to the greater floristic heterogeneity of these residues, circumstances that increase microbial activity, and consequent consumption of labile C, with higher C-CO_2 emission occurrence (Auler et al., 2019).

The areas of PP, DS, and PNHR were similar to each other regarding the total emission of C-CO_2 (Figure 7B), with 56, 70, and 72% of the C-CO_2 emission of the NF area. This low accumulation of C-CO_2 emission is due to the lower levels of TOC in these areas (Figure 3), which can be attributed to the advanced stage of degradation in the PP area; the low diversity of SOM in the DS area due to only having the succession of soybean/corn crops; and the initial process of regeneration in the PNHR area, after a long period of clay extraction, also being an area with a high level of degradation.

Lower total accumulations of C-CO_2 emission in DS areas with a succession of soybean/corn crops compared to native vegetation of the Atlantic Forest were also observed by Rosset et al. (2019) and Ozório et al. (2020), respectively. The multivariate analysis was performed using the data of the attributes Ds, TOC, StockC, SI, and C-CO_2 accumulation, in which the edaphic variables in the 0-0.2 m layer explained 88.1% of the data variation for the two main components (Dim1 and Dim2) (Figure 8).

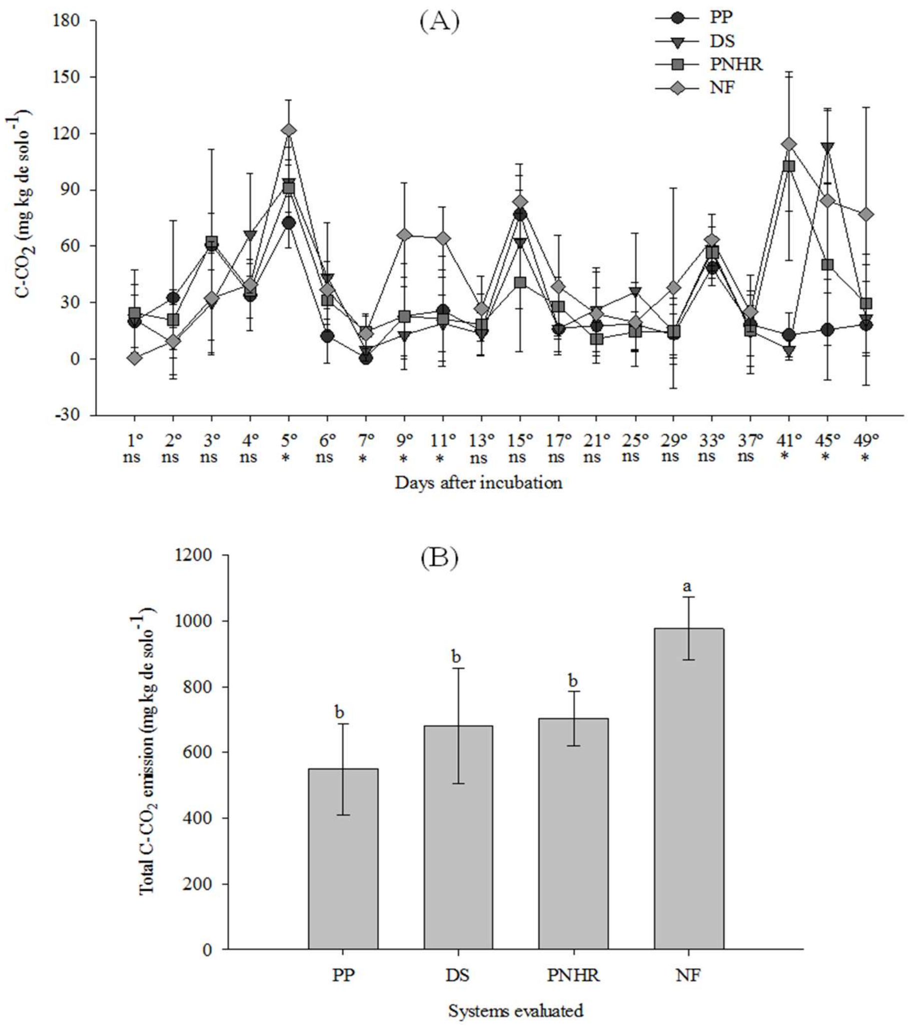

Figure 7. Daily evolution of C-CO_2 in a period of 49 days of evaluation for the different areas. (A) *= significant by the Tukey test at 5%, ns = not significant. Accumulation of C-CO_2 (mg C-CO_2 kg of soil^{-1}) for the different areas evaluated. Means followed by equal letters do not differ from each other by the Tukey test at 5% probability. (B) PP: Permanente Pasture, DS: Direct Sowing, PNHR: Private Natural Heritage Reserve, NF: Native Forest.

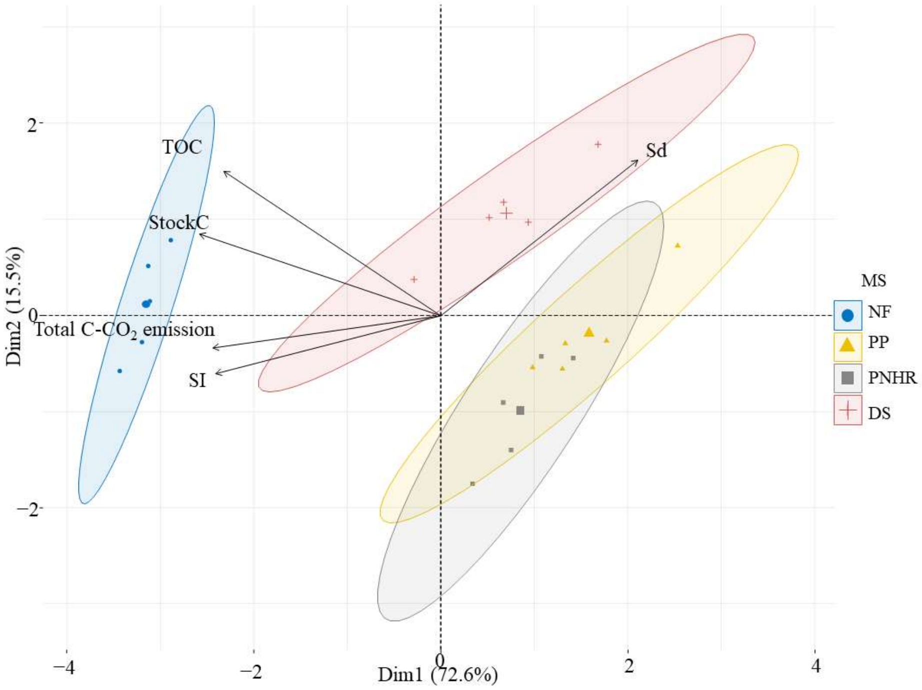

Figure 8. Multivariate Principal component analysis - PCA for the different management systems (MS). PP: Permanente Pasture, DS: Direct Sowing, PNHR: Private Natural Heritage Reserve, NF: Native Forest.

The first component (Dim1) explains 72.6 % of the total variance. The second component explains 15.5 % of the total variance. The variables TOC, StockC, SI, and C-CO_2 accumulation were more influential in the NF and the Sd indicative for the other areas. Considering the NF as the equilibrium system, the DS area is the closest to it, followed by PNHR and PP, but in different positions within the quadrants.

The analysis allowed us to infer from the layout of the groups that the management systems in question did not effectively contribute to the improvement of the edaphic quality within the parameters evaluated due to the lack of proximity of the characteristics presented by the NF, which is the reference system of soil quality. The area closest to the NF in the distribution within the quadrants was the DS. Similar results were found by Martins et al. (2020) and Troian et al. (2020), demonstrating that, according to the management system adopted, changes in soil attributes may happen due to systems that do not prioritize the use of conservation practices.

4. Conclusions

The area under direct sowing presents higher soil density concerning the area with the original condition of native vegetation. The managed areas have lower content and stocks of total organic carbon and stratification index, with a negative alteration of carbon stock concerning the natural condition of the soil in the native forest area. The removal of the original vegetation cover along with the inadequate use of the soil cause a reduction in soil carbon stocks, and the recovery process is slow, as seen in the area of Private Natural Heritage Reserve, even after two years of isolation and beginning of the natural regeneration process, is still with the quantitative carbon reduced.

Among the managed areas, the direct sowing stands out with higher content and total organic carbon stocks, demonstrating that even in succession, the system contributes to the quantitative improvement of the soil organic fraction over the adoption time. The managed areas have lower daily emission peaks and lower total mineralizable carbon emissions, indicating lower microbial activity in these areas. The historically adopted forms of management, especially in the areas of permanent pasture and the Private Natural Heritage Reserve, do not benefit the improvement of the quality of edaphic attributes of the evaluated parameters because none of the areas was close to the reference characteristics of the native forest area.

Authors' Contribution

All the authors participated in the elaboration of the project, Giovana Giovana Tetsuya Lopes, Ozielly Maiane Mendes da Silva, Wesley Vieira dos Santos, José Victor Hugo dos Santos, and Andrea dos Santos Gonçalves, actively participated in the analysis and writing of the paper, Jean Sérgio Rosset, Jefferson Matheus Barros Ozório, and Leandro Marciano Marra participated in the interpretation of the data and revision of the text. All authors provided critical feedback on the manuscript

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