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Carbon storage and physical and chemical properties of a medium-textured soil in agricultural systems in Brazil

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ABSTRACT

The objective of this study was to evaluate the physical and chemical properties and carbon storage in different agricultural production systems in medium-texture soils in the subtropical region of Brazil. Soil samples were collected in three management systems: Pasture (PP), no-till (NT), and no-till + *Urochloa* (NT+*U*), in addition to a native forest area (NF), in four soil layers up to 0.40 m. Chemical and physical soil analyses were performed. Bulk density and penetration resistance results did not indicate soil compaction in the areas managed after 24 years. The PP area had higher total porosity and microporosity values than the NT and NT+*U* areas. The PP area had the highest values of the sum of bases and CEC. NT+*U* and PP areas had the highest TOC contents and carbon storage potential up to the 0-0.40 m layer. The PP area in the 0-0.40 m profile had 52.89%, 72.21%, 79.79%, and 97.08% Mg ha^{-1} more stocks than the NF area in the four soil layers evaluated. In the 0.20-0.40 m stratum, the NT+*U* area had StockC values of 11.21 Mg ha^{-1}, which was 17.62% more than the NT area. These results show the potential of grasslands for carbon storage in medium-texture soils under subtropical climates, mainly due to the characteristics of grasslands that can produce significant amounts of biomass constantly deposited in the soil.

Keywords: Climate change, Soil quality, Carbon sequestration, Corn+*Urochloa ruziziensis* intercrop.

Estoque de carbono e propriedades físicas e químicas de um solo de textura média em sistemas agrícolas no Brasil

RESUMO

O objetivo deste estudo foi avaliar as propriedades físicas e químicas e o armazenamento de carbono em diferentes sistemas de produção agrícola em solos de textura média na região subtropical do Brasil. Foram coletadas amostras de solo em 3 sistemas de manejo: Pastagem (PP), plantio direto (PD) e plantio direto + *Urochloa ruziziensis* (PD+*U*), além de uma área de mata nativa (MN), em 4 camadas até 0,40 m. Foram realizadas análises químicas e físicas do solo. Os resultados de densidade do solo e resistência à penetração não indicaram compactação do solo nas áreas manejadas após 24 anos. A área de PP apresentou maiores valores de porosidade total e microporosidade em relação às áreas PD e PD+*U*. A área PP apresentou os maiores valores de SB e CTC. As áreas PD+*U* e PP apresentaram maiores teores de COT e potencial de estocagem de carbono, até a camada de 0-0,40 m. A área PP no perfil de 0-0,40 m apresentou 52,89%, 72,21%, 79,79% e 97,08% Mg ha^{-1} a mais estoque que a área NF nas 4 camadas avaliadas, respectivamente. Na camada de 0,20-0,40 m, a área PD+*U* apresentou valores de StockC de 11,21 Mg ha^{-1}, o que representou 17,62% a mais que a área PD. Estes resultados mostram o potencial das pastagens para o armazenamento de carbono em solos de textura média sob clima subtropical, principalmente devido às características das pastagens que podem produzir quantidades significativas de biomassa que é constantemente depositada no solo.

Palavras-chave*:* Alterações climáticas, Qualidade do solo, Sequestro de carbono, Cultura consorciada de milho+ *Urochloa ruziziensis.*

1. Introduction

According to the latest report of the Intergovernmental Panel on Climate Change (IPCC, 2021), the planet will warm by 1.5 ºC in the next 20 years. According to this report, these changes will also affect food production across the planet, especially in Brazil, where corn production could decrease by up to 71%, soybean and pasture production by up to 33%, and other crops in the sector if global greenhouse gas emissions are not reduced (IPCC, 2021).

Considering climate change scenarios, the use of sandy soils, especially in Brazil, has been much discussed in building the national agricultural economy (Dionizio et al., 2020; Donagemma et al., 2016). In sandy soils and medium-textured soils in tropical and subtropical climates, the combination of high temperatures, high soil aeration, low organomineral association, and high soil microbial activity throughout the year leads to accelerated organic matter decomposition and greenhouse gas emissions (Cordeiro et al., 2022). In addition to GHG emissions, these soils generally have low field capacity and permanent wilting point, low organic carbon concentration, and low cation exchange capacity, making agriculture on these soils more costly (Huang; Hartemink, 2020; Gmach et al., 2018).

However, the different management and production systems in Brazil have the potential to contribute to the reduction of GHG emissions from sandy, medium-heavy, and clayey soils (Cordeiro et al., 2022; Ramos et al., 2018; Donagemma et al., 2016; Bayer et al., 2006). The best-known of these systems are pasture and no-till systems (Oliveira et al., 2020; Ribeiro et al., 2020; Santos et al., 2019a; Sithole et al., 2019). Some studies have also shown that integrated production systems, such as crop-livestock integration (CLI) and crop-livestock-forest integration (CLFI), can be alternatives to enhance carbon storage (C).

Another valuable tool for agriculture that has a positive impact on soil quality parameters, especially on medium-heavy and sandy soils, is the use of *Urochloa ruziziensis* intercropped with corn in the second crop, without using cattle (Salton et al., 2008). This model of agricultural production aims to increase land cover through organic matter (SOM) production (Mateus et al., 2020), reduce soil and water loss through water erosion (Martini, et al., 2021), and promote increases in carbon stocks (StockC) (Salton et al., 2008).

In addition to reducing carbon dioxide (CO_2) emissions, the accumulation of C in soil in conservation systems promotes improvements in physical and chemical properties compared to conventional management systems (Cherubin et al., 2021; Falcão et al., 2020). These improvements allow the reduction of soil bulk density and penetration resistance, better pore distribution, higher cation exchange capacity, and better nutrient availability (Lorenz et al., 2019). These factors favor productivity and reduce the impact of climatic factors, especially drought, by reducing solar radiation on the soil and extending the period of higher soil moisture (Gomes et al., 2018).

In this way, using management systems such as crop-livestock integration, no-till, and pasture, combined with conservation measures, can contribute to developing profitable agriculture with low GHG emissions on tropical sandy soils. However, even in the search for alternatives to solve the problem of carbon loss from sandy soils in combination with higher productivity and rational use of fertilizers through conservation systems and practices, several studies show that there are still several obstacles to overcome (Cordeiro et al., 2022; Firmino et al., 2022; Dionizio et al., 2020; Gmach et al., 2018; Donagemma et al., 2016).

Studies that evaluate the effects of different management systems on soil properties and carbon storage capacity of low clay soils are extremely important, especially in the search for mitigation strategies and measures aimed at more cost-effective production with a reduction of carbon emissions to the atmosphere. This study tested the hypothesis that conservation systems such as well-managed pastures and crop-livestock integration systems can provide high levels of organic carbon and improve the chemical and physical properties of sandy soils. With this in mind, the objective of this study was to evaluate the physical and chemical properties and carbon storage in different agricultural production systems in medium-texture soils in the subtropical region of Brazil.

2. Material and Methods

Soil samples were collected in Terra Roxa, in the western region of Paraná, in Brazil, in farming systems with a known history of cultivation (Figure 1). The climate of the region is subtropical (Cfa), according to Köppen (Caviglione et al., 2000). The soils in the study area were classified as Argissolo Vermelho-Amarelo Distroférrico, with medium texture, presenting 666, 147, and 187 g kg^{-1} of sand, silt, and clay, respectively, in the 0-0.40 m layer (Santos et al., 2018).

The classification corresponded to the Paleudalfs in the Soil Taxonomy of the USA (Soil Survey Staff, 2014) or the Rhodic Acrisols in the FAO classification system (Iuss Working Group WRB-FAO, 2015). Four different areas were evaluated in a completely randomized design (CRD) with the same characteristics, such as soil type and texture, relief, and climate, all within a 600 m^2 radius.

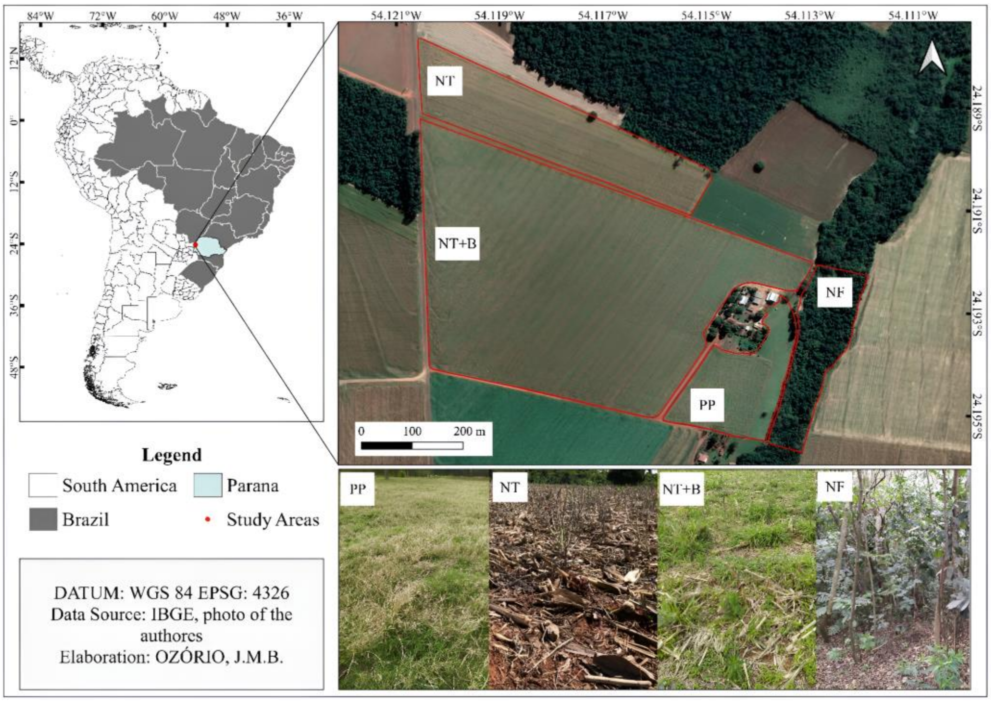

Figure 1. Map of the experimental location in Terra Roxa, Paraná, Brazil (Source: QGIS, version 3.14 “Pi”).

One of them is an area of pasture (PP) of 4.1 ha (24º11´37 "S, 54º06´49 "W, and 307 m of elevation). The area consists of pasture with Coast Cross species (*Cynodon dactylon* (L.) Pers), which is considered resistant to low temperatures and with a high leaf/stem ratio. Dairy cows have continuously grazed the area for 44 years, with a livestock stocking rate of two units/animal per hectare, with periodic reforms approximately every 15 years and the application of 2.1 Mg ha^{-1} of limestone.

The second is an area under no-till system (NT) of 11 ha (24º11´27 "S, 54º06´52 "W, and 325 m of elevation) cultivated successively with soybeans (*Glycine* max) (summer) and corn (*Zea mays*) (second crop). Historically, this area consisted of native forests of the Atlantic Forest biome, which were cleared in the 1970’s. It was later managed with conventional tillage in a soybean/corn succession for 20 years and no-till for the last 24 years. Dolomitic limestone (1.2 Mg ha^{-1}) is applied to the area every three to four years. In addition, agricultural gypsum is applied during the same period when limestone is applied, which is recommended due to the presence of exchangeable aluminum. In general, 200 kg ha^{-1} of the NPK formulation 04-30-10 is applied to the area when soybeans are grown, and 200 kg ha^{-1} of the NPK formulation 10-15-15 is applied when corn is grown.

The other is an area under no-till system with soybean (summer) and corn intercropped with *Urochloa ruziziensis* (second crop) (NT+*U*) of 28 ha. (24º11´31 "S, 54º06´52 "W, and 323 m of elevation). Historically, this area consisted of native forest of the Atlantic Forest biome, which was cleared in the 1970s and later managed for 20 years with conventional tillage under soybean/corn succession. In the last 20 years, the area has also been managed under the no-till system with soybeans and corn, and in the last four years, *Urochloa ruziziensis* intercropped with corn was adopted in the second crop. Limestone (2 Mg ha^{-1}) is applied to the area every four years to correct soil acidity.

An average of 200 kg ha^{-1} of the NPK formulation 15-15-15 in addition to KCl in topdressing is applied for soybean cultivation. For corn (second crop), 240 kg ha^{-1} of the NPK formulation 15-15-15 and ammonium sulfate in topdressing are applied. The soybean and corn crops are inoculated before sowing. For last, the native forest area (NF) of the Atlantic Forest biome with the phytophysiognomy of a deciduous seasonal forest of 28 ha (24º11´31 "S, 24º06´52 "W and 307 m elevation) - NF comprises a permanent protected area, isolated, without access of animals, without anthropic modification. Five 400 m^2 plots were delineated in each study area where the soil samples were collected.

Each plot represented a replicate, and each composite sample consisted of ten samples within the studied systems in the 0-0.05, 0.05-0.10, 0.10-0.20, and 0.20-0.40 m soil layers. In addition, undisturbed samples were collected using a volumetric ring with a volume of 100 cm^3 in all systems and layers studied for analyses of soil bulk density, porosity, and penetration resistance. The bulk density (Bd), particle density (Pd), and Water-dispersible clay (WDC) with subsequent calculations of flocculation degree (FD), total porosity (Tp), macroporosity (Ma), and microporosity (Mi) were performed according to the methodology of Almeida et al. (2017).

Based on the Tp results, the macropores/total pore volume ratio (Ma/TPV) was calculated according to Taylor and Ashcroft (1972). Soil penetration resistance (PR) was determined under field capacity conditions using a benchtop penetrometer model MA-933. Soil pH was determined in $CaCl_2$ solution (soil ratio: 1:2.5 solution); Al^{3+}, Ca^{2+}, and Mg^{2+} were extracted with KCl 1 mol L^{-1}, with Al^{3+} determined by titration with NaOH 0.015 mol L^{-1} and Ca^{2+} and Mg^{2+} determined by atomic absorption spectroscopy (AAS); P and K^{+} extracted with Mehlich solution, where P was determined by colorimetry and K^{+} by flame photometry, and potential acidity (H+Al) extracted with calcium acetate solution 0.5 mol L^{-1} buffered at pH 7.0, determined by titration with NaOH 0.1 mol L^{-1} (Teixeira et al., 2017).

Total organic carbon (TOC) was determined by oxidation of organic material (Yeomans; Bremner, 1988). From the results obtained, the total organic carbon stock (StockC) was calculated using the equivalent mass method (Reis et al., 2018). The results were tested for normality and variance homogeneity using the Shapiro-Wilk and Bartlett's tests. Then, the results were subjected to analysis of variance with the application of the F-test, and the means were compared by Tukey's test (p=0.05) using R Core Team software (R Core Team, 2019). All tests were performed using the ExpDes.pt package (Ferreira et al., 2018). Multivariate analysis was performed through principal components analysis – PCA (Silva et al., 2020) as a complementary technique. The correlations between the soil's physical and chemical attributes were evaluated by Pearson correlation, using p=0.05 as the significance criterion.

3. Results and Discussion

The physical properties of the soil changed depending on the management system applied, as shown in Table 1. Water-dispersible clay (WDC) results ranged from 12.71 g kg^{-1} to 65.30 g kg^{-1} in all soil layers. The highest WDC values were observed in the areas with pasture (PP) and no-till + Urochloa ruziziensis (NT+U) in the first two layers. In the layers 0.10-0.20 m and 0.20-0.40 m depth, the lowest values were observed in the area with NT (Table 1).

Table 1. Values of water-dispersible clay (WDC), flocculation degree (FD), particle density (Pd), bulk density (Bd), Macropores (Ma), Micropores (Mi) and total porosity (Tp macropore ratio/total pore volume (Ma/TPV), soil penetration resistance (PR), saturated soil moisture content (θ) and field capacity (θ24), in the different management systems in the Western region of Paraná**.**

MS	WDC	FD	Pd	Bd	Porosity (m^3 m^{-3})			Relation Ma/TPV	PR (Mpa)	θ (cm^3 cm^{-3})	
	g kg^{-1}	%	g cm^{-3}	(Mg m^{-3})	Ma	Mi	Tp	-	Pr_{24}	UM_S	UM_{24}
0-0.05 m											
PP	41.94a	79.53a	2.52a	1.47ab	0.05b	0.36a	0.41a	0.14b	0.44a	0.41a	0.35a
NT	12.71c	87.41a	2.49ab	1.51ab	0.11a	0.26b	0.37ab	0.30a	0.17b	0.36ab	0.24b
NT+*U*	52.82a	55.63b	2.59a	1.61a	0.08ab	0.22b	0.30c	0.28a	0.38ab	0.30c	0.21b
NF	28.03b	81.66a	2.33b	1.40b	0.11a	0.24b	0.35b	0.32a	0.24ab	0.35b	0.23b
CV(%)	17.81	7.70	3.90	5.30	18.35	10.13	7.51	12.63	13.92	7.97	10.78
0.05-0.10 m											
PP	44.72a	81.90a	2.56a	1.64ab	0.04a	0.31a	0.35a	0.13a	0.60a	0.35a	0.30a
NT	22.17b	83.61a	2.60a	1.68a	0.06a	0.23b	0.29b	0.20a	0.32b	0.27b	0.21b
NT+*U*	51.26a	66.33b	2.55a	1.71a	0.05a	0.23b	0.28b	0.19a	0.40ab	0.27b	0.21b
NF	32.36b	82.58a	2.29b	1.55b	0.06a	0.23b	0.29b	0.20a	0.24b	0.28b	0.22b
CV(%)	14.45	6.42	2.17	3.33	17.90	5.49	6.53	13.74	10.21	6.92	5.91
0.10-0.20 m											
PP	54.45a	80.34a	2.54a	1.59a	0.05a	0.30a	0.35a	0.37a	0.17a	0.35a	0.29a
NT	30.20b	82.16a	2.61a	1.71a	0.06a	0.24ab	0.25b	0.43a	0.11a	0.26b	0.22ab
NT+*U*	46.76a	76.48a	2.53a	1.66a	0.05a	0.23b	0.28b	0.30a	0.18a	0.27b	0.21b
NF	50.93a	70.52a	2.36b	1.67a	0.05a	0.23b	0.28b	0.26a	0.18a	0.27b	0.22b
CV(%)	11.90	9.33	2.40	4.20	12.61	15.09	11.90	19.09	12.95	12.53	16.05
0.20-0.40 m											
PP	65.30a	78.70a	2.56ab	1.62b	0.06a	0.27a	0.33a	0.19a	0.32ab	0.32a	0.25a
NT	35.42b	81.02a	2.60a	1.71a	0.02b	0.23a	0.25b	0.07a	0.39a	0.26b	0.24a
NT+*U*	51.62ab	74.52ab	2.29b	1.66ab	0.04ab	0.24a	0.28ab	0.16a	0.29ab	0.28ab	0.23a
NF	53.94ab	69.24b	2.32ab	1.59b	0.06a	0.23a	0.29ab	0.20a	0.24b	0.28ab	0.22a
CV(%)	14.41	5.15	6.68	2.69	12.65	11.58	7.70	13.96	12.27	8.19	12.32

Means followed by equal letters in the columns in each layer do not differ by the Tukey test ($p \leq 0.05$). CV = Coefficient of variation. MS: Management systems, PP: pasture, NT: No-tillage, NT+U: No-tillage of corn + *Urochloa ruziziensis*, NF: Native forest.

The studied areas had flocculation degree (FD) values above 55.63% in the four studied layers. At 0-0.05 and 0.05-0.10 m, PP, NT, and NF had the highest FD values, with values above 80%. The areas did not differ statistically in the 0.10-0.20 m layer. In the 0.20-0.40 m layer, the lowest FD values were observed in the NT+*U* and NF areas. Variations between 2.29 g cm^{-3} and 2.61 g cm^{-3} were observed in particle density (Pd). The largest differences were observed in the 0.05-0.10 and 0.10-0.20 m layers; the NF area had Pd values lower than the managed areas (Table 1).

In the first two layers evaluated, the areas of PP, NT, and NT+*U* showed no differences in soil bulk density (Bd), which ranged from 1.47 to 1.61 Mg m^{-3} in the 0-0.05 m layer and from 1.64 to 1.71 Mg m^{-3} in the 0.05-0.10 m layer. No differences were observed between the areas in the 0.10-0.20 m layer. In the last layer (0.20-0.40 m layer), the PP, NT+U, and NF areas had the lowest Bd values, 1.62, 1.66, and 1.59 Mg m^{-3}, respectively (Table 1).

The different areas differed concerning macroporosity (Ma) in the 0-0.05 and 0.20-0.40 m layers. In the first layer, the lowest Ma values were observed in PP, 0.05 m^3 m^{-3}, and NT+*U*, 0.08 m^3 m^{-3}. In the 0.20-0.40 m layer, the highest Ma values were observed in PP, NT+*U*, and NF, with 0.06, 0.04, and 0.06 m^3 m^{-3}, respectively. The PP showed the highest microporosity (Mi) in the 0-0.05 and 0.05-0.10 m layers, with 0.36 and 0.31 m^3 m^{-3}, respectively. The lowest values in the 0.10-0.20 m layer were observed in NT, NT+*U*, and NF, ranging from 0.23 to 0.24 m^3 m^{-3}. No differences were observed among the areas in the 0-0.05 m layer (Table 1).

The PP and NT areas showed no differences in total porosity (TP) in the layer 0-0.05 m, with values of 0.42 and 0.37 m^3 m^{-3}, respectively. In the 0.05-0.10, 0.10-0.20, and 0.20-0.40 m layers, the areas NT, NT+*U*, and NF showed no differences, with values lower than in the area PP. The systems evaluated had no differences in macropore ratio and total pore volume (Ma/TPV) in the 0.05-0.10, 0.10-0.20, and 0.20-0.40 m layers. In the 0-0.05 m layer, the PP area had a lower Ma/TPV ratio, unlike the other areas studied. Concerning the analysis of soil penetration resistance (PR), NT, NT+*U*, and NF had a lower PR value in the first two layers, ranging from 0.17 to 0.38 Mpa in the 0-0.05 m layer and from 0.24 to 0.40 Mpa in the 0.05-0.10 m layer. In the 0.20-0.40 m layer, the three managed areas had the highest PR.

The agricultural systems did not change the Bd results up to a depth of 0.10 m. This is the result of the low soil tillage in NT and NT+*U*, as well as the maintenance of the soil covered by the forage species in the area PP throughout the year. It is important to emphasize that the areas did not have Bd values higher than 1.75 Mg m^{-3} in all layers, which would affect the development of roots in soils of medium texture (Reinert et al., 2008). In agreement with the Bd value, the Tp results showed that the managed areas did not cause negative changes in the evaluated profile. The PP area showed superiority for Tp compared to the other areas in the 0.05-0.10 and 0.10-0.20 m layers, possibly related to the effect of root development in successive management years and the high C values and C stock observed by Vasques et al. (2019) and Silva et al. (2019).

Increasing organic matter cover by grasses with the crop-livestock integration and the activity of organisms and decomposition of this cover may contribute to the formation of polysaccharide compounds and bacterial gums, binders of soil particles (Rayne; Aula 2020; Dhaliwal et al., 2019; Bhatia; Shukla, 1982). These binders reduce soil SB, improve soil aggregation, and increase porosity (Bhatia; Shukla, 1982). In the case of grassland, due to management, there is a higher animal stocking rate and consequently higher manure input, which, over time, reduces bulk density and increases overall soil porosity (Dhaliwal et al., 2019; Meng et al., 2019).

The microporosity results were higher in the PP area in the 0-0.05 m layer due to the continuous deposition and stabilization of C that occurs in pastures (Marçal et al., 2021; Scheid et al., 2019). Microporosity is mainly responsible for water retention in the soil profile (Mendes et al., 2022; Bortolini; Albuquerque, 2018). The highest Ma/TPV ratio in the PP area compared to the other areas in the 0-0.05 m layer is due to the decrease in Ma and the increased representativeness of micropores (Table 1). Even without differences from the other areas studied, the PP area's 0.10-0.20 m layer was the only layer with a Ma/TPV value greater than 0.33 m^3 m^{-3}, which is considered ideal for plant development (Torres et al., 2011).

The PR values in the areas studied were lower than those considered a deterrent to root development, established at 2 Mpa in soils of medium texture (Blainski et al., 2008). In agreement with the results of Bd (Table 1), this indicates that soil compaction was not detected even with a long history under the same management. This is justified by the minimal rotation and movement of machinery on the soil in the areas of NT and NT+*U*, and this minimal rotation is one of the factors to avoid a significant increase in soil compaction. (D'acqui et al. 2020; Guimarães Júnnyor et al., 2019).

The different systems resulted in changes in soil chemical properties (Table 2). The lowest pH values were found in the NF area in all the layers evaluated, reaching 4.02 in the 0.20-0.40 m layer. Soil pH in the managed areas ranged from 5.55 to 6.91. The PP area had the highest P levels in the 0-0.05 and 0.05-0.10 m layers, exceeding 80 mg dm^{-3}. In the subsurface layers evaluated, the lowest P contents were found in the NF area (Table 2).

The PP area had higher PR values in the first layers than the other areas, which could be due to animal trampling, which, if not controlled, can lead to soil compaction (Benevenute et al., 2020). Benevenute et al. (2020), who studied soil penetration resistance in pastures, showed that if well managed, pastures can increase livestock resilience without PR increasing to critical levels, but with a tendency for PR to increase slightly. The importance of PR in maintaining soil quality is reflected in the inversely proportional correlation between PR and Ma (Figure 3) because the lower PR, the higher Ma, allowing the flow of water and air in the soil profile (Farhate et al., 2022).

The NF area had the highest H+Al values in all layers, reaching 5.94 cmol$_c$ kg^{-1}, similar to the PP area in the first layer studied. On the other hand, the areas of NT and NT+*U* had the lowest values up to a depth of 0.20 m, not exceeding 1.96 cmol$_c$ kg^{-1}. In the 0-0.05 and 0.05-0.10 m layers, no Al^{3+} contents were detected in the managed areas. In the 0.10-0.20 m layer, 0.16 cmol$_c$ kg^{-1} was detected in the NT area. The PP site had higher Ca and Mg contents in all layers studied, similar to NT at 0-0.05 m for Ca^{2+} and from 0.10 to 0.40 m for Mg^{2+}. There were no differences in K$^+$ contents between the assessed areas in the first assessed layer. In the 0.05-0.10 m layer, the lowest values were observed in the NT+*U* and NF areas.

The PP area had the highest values for the sum of bases (SB) in all evaluated layers, reaching 9.37 cmol$_c$ dm^{-3} in the 0-0.05 m layer. This contrasts the behavior observed in NF with lower SB throughout the soil profile, which did not exceed 3.98 cmol$_c$ dm^{-3}. The PP area had the highest cation exchange capacity (CEC) values up to 0.20 m. The lowest CEC values in the first layers were observed in the areas of NT and NT+*U*. No differences were observed between the evaluated areas in the 0.20-0.40 m layer evaluated.

The highest V% values were observed in the NT to a depth of 0.10 m, followed by the area NT+*U* in the 0-0.05 m layer and the PP and NT+*U* areas in the 0.05-0.10 m layer. NF had the lowest V% values in all layers evaluated. The PP area had the highest TOC contents in the 0-0.05, 0.05-0.10, and 0.10-0.20 m layers, with a content of more than 27.00 g kg^{-1} in the first layer. In the subsurface layer, the highest values were found in PP and NT+*U*, with 11.50 g kg^{-1} and 7.05 g kg^{-1}, respectively.

Table 2. Soil pH, phosphorus content (P), potential acidity (H+Al), aluminum (Al), calcium (Ca), Magnesium (Mg), potassium (K), sum of bases (SB), cation exchange capacity (CEC), base saturation (V%), total organic carbon (TOC), and carbon stock (StockC) of the different management systems under medium texture soil.

SM	pH	P	H+Al	Al^{3+}	Ca2+	Mg^{2+}	K$^+$	SB	CEC	V%	TOC	StockC
		mg dm^{-3}		------------------ cmol$_c$ dm^{-3} ----------------					cmol$_c$ dm^{-3}	%	g kg^{-1}	Mg ha^{-1}
0-0.05 m												
PP	5.55c	106.94a	5.64a	0.00b	6.96a	2.18a	0.23a	9.37a	15.01a	62.45c	27.89a	39.05a
NT	6.91a	51.84bc	0.21b	0.00b	5.76a	1.46b	0.16a	7.44b	7.62c	97.63a	17.60b	24.64b
NT+*U*	6.58b	68.38ab	0.95b	0.00b	3.88b	1.38b	0.21a	5.90b	6.86c	85.80b	14.38b	20.14b
NF	4.49d	19.23c	5.64a	0.16a	3.30b	0.54c	0.23a	3.98c	10.35b	38.46d	18.24b	25.54b
CV(%)	2.53	16.99	15.54	11.8	15.33	16.43	19.21	12.90	10.70	4.87	14.62	14.62
0.05-0.10 m												
PP	5.66c	80.18a	3.79b	0.00b	5.68a	1.72a	0.22ab	7.56a	11.36a	66.57b	18.72a	29.19a
NT	6.79b	20.73b	0.28d	0.00b	3.78b	1.56a	0.26a	5.60b	5.88c	95.21a	8.93b	13.92b
NT+*U*	6.23b	33.54b	1.58c	0.00b	2.92b	0.64b	0.16bc	3.90c	5.48c	74.21b	9.94b	15.50b
NF	4.16d	9.80b	5.94a	0.7a	1.26c	0.86b	0.14c	2.19d	8.13b	26.56c	10.87b	16.95b
CV(%)	3.34	5.94	16.62	7.59	15.48	11.78	8.59	17.72	13.89	8.17	20.62	20.62
0.10-0.20 m												
PP	5.93a	44.36a	2.45b	0.00b	4.18a	1.62a	0.64a	6.01a	8.46a	71.09a	12.89a	23.23a
NT	6.13a	40.73a	1.63c	0.16b	2.62b	1.18ab	0.34b	3.96b	5.59c	70.73ab	6.35b	10.67b
NT+*U*	5.91a	41.39a	1.96c	0.00b	2.30b	0.72b	0.19c	3.21b	5.17c	62.10b	7.71b	12.96b
NF	4.08b	4.87b	5.44a	1.04a	0.50c	0.78b	0.13c	1.31c	6.76b	19.34c	7.69b	12.92b
CV(%)	4.13	6.35	15.02	7.43	16.06	19.34	15.14	12.09	9.62	8.62	12.84	12.85
0.20-0.40 m												
PP	6.03a	42.21a	2.26b	0.00b	4.14a	1.70a	0.14a	6.07a	8.33a	72.34a	11.50a	17.58a
NT	5.59a	37.98a	2.67b	0.22b	2.46ab	1.17ab	0.07b	3.77b	6.45a	58.17b	5.99b	9.53b
NT+*U*	5.64a	35.24a	2.60b	0.14b	1.98b	0.78b	0.03bc	2.89bc	5.50a	52.44b	7.05ab	11.21ab
NF	4.02b	3.33b	5.49a	1.24a	0.68b	0.62b	0.02c	1.32c	6.81a	19.46c	5.61b	8.92b
CV(%)	4.62	13.59	16.32	11.23	14.34	11.81	4.15	12.71	21.72	11.41	15.04	15.04

Means followed by equal letters in the column in each layer do not differ by the Tukey test ($p \leq 0.05$). CV = Coefficient of variation. MS: Management systems, PP: Pasture, NT: No-till, NT+U: No-till with corn + *Urochloa ruziziensis*, NF: Native forest.

Up to a depth of 0.20 m, the NT and NT+*U* areas did not differ from the NF area. StockC results showed the same pattern of TOC content (Table 2), with the PP area having higher StockC values up to a depth of 0.20 m, reaching 39.05 Mg ha^{-1} in the 0-0.05 m layer. In the 0.20-0.40 m layer, the NT+U area had StockC values of 11.21 Mg ha^{-1}, 17.62% higher than the NT area. The areas of NT and NT+*U* did not have StockC losses compared to the NF area in the entire profile of 0-0.40 m.

The pH and H+Al results of the NF area follow the same pattern as in the literature for native areas in the same region (Ozório et al., 2020; Rosset et al., 2014). This is the result of a continuous process of natural soil acidification resulting from the decomposition of SOM, which promotes the accumulation of H^{+} ions in the soil and ion exchange between soil colloids and plant roots, a process in which plants uptake Ca^{2+} and Mg^{2+} and release H^{+} (Vries and Breeuwsma, 1987; Helyar and Porter, 1989). The pH and H+Al values observed in the agricultural systems result from the regular soil correction with limestone and gypsum, a common agricultural practice to obtain better crop yields (Fonseca et al., 2022).

The predominance of P content in the PP area is characteristic of the continuous deposition of animal wastes, a result already noted in the first studies on the availability of nutrients in pastures (During; Weeda, 1973). This is mainly reinforced by the fact that it is a reduced pasture area, which significantly limits the space occupied by the animals (Garcia et al., 2021; Assmann et al., 2017; Vadas et al., 2015). On the other hand, the high P contents of the NT and NT+*U* areas, especially in the surface layers, result from the annual phosphate fertilization in the soybean/corn and soybean/corn + *Urochloa ruziziensis*, which favors the availability of P to the plants (Appelhans et al., 2021; Salama et al., 2021).

The superiority of PP in terms of Ca^{2+}, Mg^{2+}, and K^{+} content arises from nutrient cycling, as the area has high C contents and a long management history that allows gradual degradation of SOM with constant mineralization of these nutrients (Lakshmi et al., 2020; Flanagan; Cleve, 1983). In the NT and NT+*U* areas, despite nutrient cycling and frequent fertilization, there is a strong export of nutrients via harvest that do not return to the soil in the form of organic matter (Esper Neto et al., 2021; Ahmed et al., 2020), which justifies the lower levels of Ca^{2+}, Mg^{2+}, and K^{+} in the NT and NT+*U* areas compared to PP.

The TOC content and StockC values observed in the PP area significantly influenced the SB and CEC results, as evidenced by the significant correlation between the variables (Figure 3) and the association of these variables with the PP area (see Figure 2B). This influence is because organic matter, especially in its stable form, contributes to raising the surface of charge exchange in the soil, resulting in increased CEC in tropical and subtropical soils (Ramos et al., 2018).

In medium and sandy texture soils, the contribution of SOM to CEC can be as high as 80% (Manrique et al., 1991; Echeverri et al., 2018), which plays a key role in maintaining soil quality and agricultural productivity (Costa et al., 2020). The cultivated areas had V% values above 50%, called fertile soils. This is the result of the constant soil correction (Fonseca et al., 2022), which is added to the fertilizations for the cultivation of crops mainly found in the NT and NT+*U* areas.

The TOC levels observed in the PP area confirm the potential of pastures to contribute to the function of the soil as an atmospheric C sink when well managed and with a long history of establishment (Oliveira et al., 2020), mainly due to their ability to retain plant material in the soil in large quantities (Oliveira et al., 2018) and to allow the gradual decomposition of SOM (Ramos et al., 2018), allowing its stabilization over the years (Rosset et al., 2016).

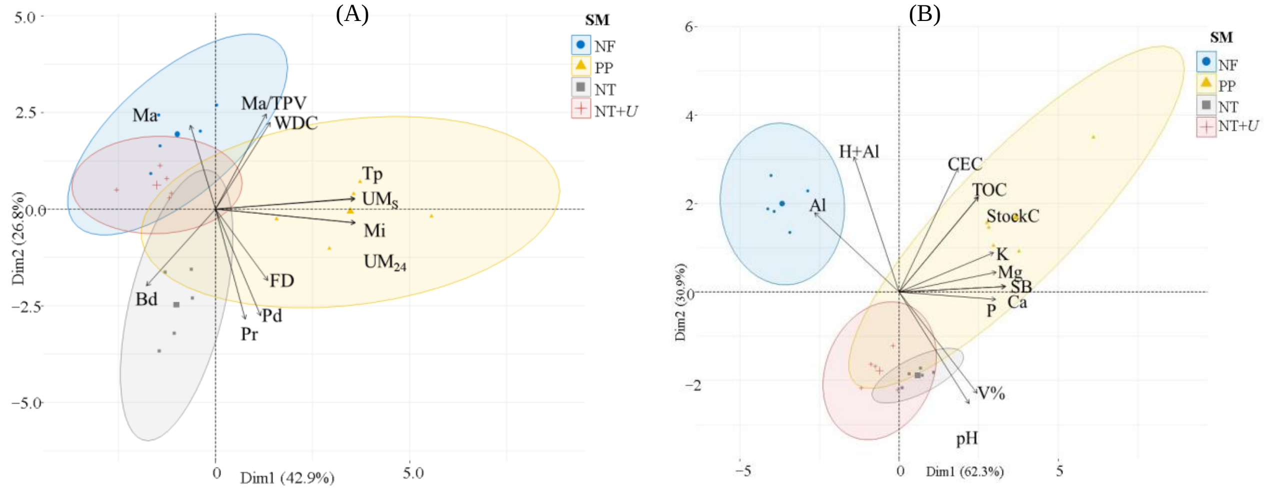

Figure 2. Principal component analysis of soil physical (A) and chemical (B) attributes in different management systems under medium texture soil. MS: Management systems, PP: Pasture, NT: No-till, NT+U: No-till with corn + *Urochloa ruziziensis*, NF: Native forest.

Another factor contributing to the uptake of C in areas of PP is the physical protection that organic material receives through the formation of stable aggregates due to the production of roots that support the aggregation process (Sithole et al., 2019; Mccarthy et al., 2008); C in humified fractions consequently has a cementing effect in the formation of aggregates (Tisdall; Oades, 1982; 1979). In principal component analysis (PCA) of physical variables, the two principal components explained 69.7% of the data variation. The NT+*U* and NF areas showed a stronger association, moving away from the PP and NT areas.

The PP area was more strongly associated with Tp, θ, θ_{24}, Mi, FD, Pd, and PR. The NF area had a higher correlation with Ma/TPV, WDC, and Ma. In particular, Bd had a higher correlation with the NT area (Figure 2A). In the PCA of chemical attributes, the first two components explained 93.2% of the variations in the data, differentiating cultivated areas concerning the NF area. The Al^{3+} and H+Al variables were more closely related to the NF area, and the pH and V% variables were close to the NT and NT+*U* areas. The other chemical variables (CEC, TOC, StockC, K^{+}, Mg^{2+}, SB, and Ca^{2+}) were associated with the area of PP (Figure 2B).

Regarding the Pearson correlation between all variables, it is possible to highlight positive correlations between carbon variables (TOC and StockC) with CEC, Mi, Tp, θ, θ_{24}, and P, K^{+}, Ca^{2+}, and Mg^{2+} contents. It is also important to highlight the inversely proportional correlation between Ma and Bd and PR, where the higher the Ma, the lower the Bd and the PR (Figure 3). These higher C contents and stocks in the PP area favor the maintenance of soil quality, as evidenced by the correlation of TOC and StockC contents with physical and chemical attributes (Figure 3) and by the association of the PP area with the highest values of Tp, Mi, FD, Pd, CEC, K, Mg, SB, Ca, and P in the principal components analysis (Figures 2A and B). Weber et al. (2020) also observed these relationships in a study with Argissolo in northeastern Brazil.

The results also showed that the NT and NT+*U* areas did not promote the reduction of TOC content concerning the NF area, although they were areas with medium soil texture, which is a limiting factor for the maintenance of soil TOC content (Bossio et al., 2020; Mitchard, 2018). This demonstrates the efficiency of the no-till system in promoting the maintenance of C content over the years of cultivation (Santos et al., 2019a), characterizing these areas as low-C farming areas (Yadav et al., 2018; Sithole et al., 2019).

StockC levels showed the same pattern as TOC levels. It is important to highlight the ability of PP to store C in the 0-0.40 m profile, which had 52.89%, 72.21%, 79.79%, and 97.08% Mg ha^{-1} more than the NF area stocks in the 0-0.05, 0.05-0.10, 0.10-0.20, and 0.20-0.40 m layers, respectively. This potential has been highlighted by authors conducting long-term research in the Atlantic forest biome (Rosset et al., 2014; Santos et al., 2019b; Oliveira et al., 2018; 2020).

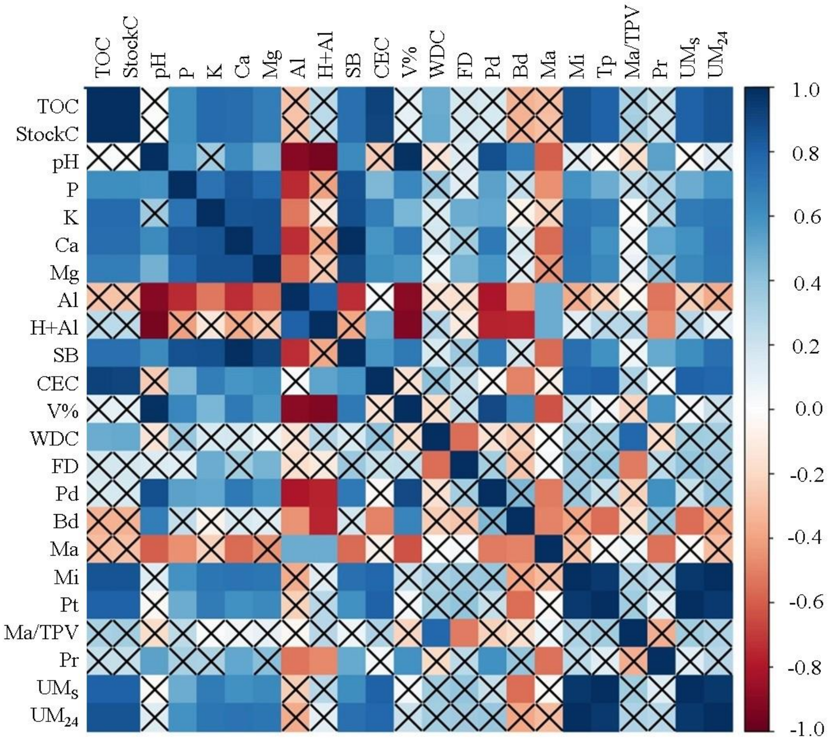

Figure 3. Pearson correlation (r) between the chemical and physical attributes of the soil. Indications with (X) are non-significant correlations ($p \leq 0.05$).

Melo et al. (2006), who evaluated the potential of different land use changes in the Atlantic Forest biome, found that the C sequestration potential in well-managed pastures is 2.71 Mg ha^{-1} year^{-1}, with an estimated C storage potential of 73.88 Tg year^{-1}. Santos et al. (2019a) studied the change in soil StockC following the change from native vegetation to pasture in the Atlantic Forest of Brazil and observed an increase of 20 Mg ha^{-1} after 15 years of land use change.

The introduction of *Urochloa ruziziensis* promoted an increase in soil C content and stocks at NT+*U* compared to NT, which was noticeable from the 0.05-0.10 m layer. For the same variables, NT+*U* in the 0.20-0.40 m layer was similar to PP, with the highest C contents and stocks. In the last layer, this increase was 0.42 Mg ha^{-1} year^{-1} after sowing the corn+ *Urochloa ruziziensis* intercropping. This effect arises from the action of roots, which have a great potential to store C in underground layers (Oliveira et al., 2021; Santos et al., 2019a), which is desirable because it makes this C inaccessible to the action of management (Oliveira et al., 2020), in addition to the action of decomposers that can promote the emission of this C in the form of greenhouse gasses (Ramos et al., 2018).

4. Conclusions

The studied areas showed no signs of compaction or changes in soil pore classes. The areas with permanent grassland and no-till showed better soil fertility, as indicated by the high phosphorus content and base saturation. The pasture area showed potential for carbon sequestration in medium-texture soils. The corn + *Urochloa ruziziensis* intercropping in the second crop tended to increase carbon stocks in the subsoil even after four years. The highest carbon contents and stocks improved porosity, exchangeable bases, and cation exchange capacity in medium-texture soils.

Authors' Contribution

Jefferson Matheus Barros Ozório wrote the project, conducted analyses, and drafted the manuscript. Jean Sérgio Rosset reviewed the project and the manuscript. Laércio Alves de Carvalho reviewed the project and the manuscript. Naelmo de Souza Oliveira conducted laboratory analyses and reviewed the manuscript. Felipe das Neves Monteiro was responsible for sample collection and laboratory analyses. Jolimar Antonio Schiavo reviewed the project and the manuscript. Elói Panachuki reviewed the project and the manuscript.

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