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Physicochemical characterization of oxisol subjected to succession culture[1]

Atributos físico-químicos de um latossolo vermelho distroférrico submetido a sucessões de culturas

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HIGHLIGHTS:

Pearl millet proved to be efficient in K cycling.
The higher organic matter concentration in the 0-5 cm layer promoted better soil physicochemical conditions.
Congo grass stood out for its ability to increase the Mg concentration in the 0-5 cm soil layer.

ABSTRACT: No-till farming is the practice closest to the concept of sustainable agriculture. The minimum soil movement and continuous contribution of crop residues to the farming system reduce erosion, mitigate the greenhouse effect, increase the organic matter content, and improve the physical and chemical quality of the soil. This study aimed to assess the effect of five-year succession cropping on the physical and chemical attributes of oxisol. The crops were sown for five consecutive years in the same plots, using a randomized block design in split plots with four replicates. The plots were crops grown in succession to soybean, namely Congo grass (*Urochloa ruziziensis* syn. *Brachiaria ruziziensis*), Congo grass intercropped with maize (*Zea mays* L.), pearl millet (*Pennisetum glaucum*), sorghum (*Sorghum bicolor* L.), maize, and slender leaf rattlebox (*Crotalaria ochroleuca*). The subplots were the following sampled soil layers: 0-5, 5-10, and 10-20 cm. The physicochemical attributes of these three soil layers were evaluated. Pearl millet cycled K efficiently, providing the soil with K concentrations equivalent to those of the K fertilization treatments. No single crop or intercrop increased the soil P concentration. Congo grass stood out for its ability to increase the Mg concentration. The 0-5 cm soil layer had the best physicochemical attributes based on the accumulated organic matter.

Key words: double cropping, soil physicochemical properties, soil quality

RESUMO: O sistema plantio direto é o sistema que mais se aproxima do conceito de agricultura sustentável. A movimentação mínima do solo e o aporte contínuo de palhada ao sistema, reduz a erosão, contribui para a atenuação do efeito estufa, aumenta o teor de matéria orgânica e melhora a qualidade física e química do solo. Objetivou-se com este estudo avaliar o efeito de cinco anos de sucessão de culturas sobre os atributos físicos e químicos de latossolo vermelho distroférrico. As culturas foram semeadas por cinco anos consecutivos nas mesmas parcelas, utilizando o delineamento em blocos casualizados, em parcelas subdivididas, com quatro repetições. As parcelas foram cultivadas em sucessão à soja, sendo elas: braquiária solteira (*Urocloa ruziziensis* syn *Brachiaria ruziziensis*), braquiária consorciada com milho (*Zea mays* L.), milheto (*Pennisetum glaucum*), sorgo (*Sorghum bicolor* L.), milho e crotálaria (*Crotalaria ochroleuca*). Já as subparcelas, foram representadas pelas camadas de solo amostradas: 0-5, 5-10 e 10-20 cm. Foram avaliados os atributos químicos e físicos do solo, nas três camadas mencionadas. O milheto é eficiente na ciclagem de K, proporcionando níveis deste elemento no solo equivalentes aos tratamentos que receberam adubação potássica. Nenhuma cultura isolada ou em consórcio elevou a concentração de P no solo. A braquiária destaca-se pela sua capacidade de elevar as concentrações de Mg. A camada do solo de 0-5 cm possui as melhores condições físico-químicas em função da matéria orgânica acumulada.

Palavras-chave: culturas de segunda safra, atributos físico-químicos do solo, qualidade do solo

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Introduction

The adoption of conservation systems, such as no-till farming (NTF), is an alternative to ensuring the sustainability of intensive land use (Silva et al., 2021). This viable system requires the use of cover crops that enable farmers to produce and maintain a high amount of crop residue on the ground (Laconski et al., 2022).

Well-managed NTF enhances soil chemical attributes by increasing organic matter (OM) content, macro- and micronutrient availability, and cation exchange capacity (CEC), decreasing soil acidity, adding nitrogen to the system through biological nitrogen fixation (BNF), and promoting Al^{3+}-OM and Mn^{2+}-OM complexation when these elements reach toxic concentrations in the soil (Silva et al., 2022).

Similarly, NTF also enhances soil physical properties, especially when its OM content increases significantly. An increase in OM increases aggregate stability, soil macro- and microporosity, moisture retention, and thermal efficiency and decreases soil and particle densities (Costa et al., 2020).

Considering the aforementioned benefits, the type of crop that should be used in each region must be identified based on its adaptation to local edaphoclimatic conditions, with a focus on crop rotation and/or succession, to take full advantage of the positive characteristics of each soil (Silva et al., 2021).

Considering that avoiding tillage and continuously providing crop residues are essential to the effective management of NTF, the aim of this study was to assess the effect of succession cropping on the physicochemical properties of oxisol.

Material and Methods

This experiment was conducted at the Experimental Farm of the Federal University of Jataí, located at the geographic coordinates 17° 55' 29" S, 51° 42' 36" W at an altitude of 696 m above the mean sea level in the municipality of Jataí, state of Goiás, Brazil, during the 2020/2021 crop year. The soil of the experimental area is a Dystroferric Red Latosol with a clayey texture (EMBRAPA, 2018) that corresponds with an oxisol soil (United States, 2014).

According to the Köppen climate classification, this region has an Aw or tropical savanna climate, with a rainy summer and dry winter, an annual average temperature of 22.9 °C, and an average annual rainfall of 1443 mm (INMET, 2021).

Before starting the experiment, the area had already been cultivated for approximately 12 years under NTF in a successive cropping system, with soybean in the summer and maize/sorghum as a double crop. The experiment started after the 2014/2015 harvest, and the same crops were grown in the same plots until the end of the study.

The experimental design consisted of randomized blocks in split plots with four replicates. In February 2015, the crops succeeding soybean, namely Congo grass (*Urochloa ruziziensis* syn *Brachiaria ruziziensis*), Congo grass intercropped with maize (*Zea mays* L.), pearl millet (*Pennisetum glaucum*), sorghum (*Sorghum bicolor* L.), maize, and slender leaf rattlebox (*Crotalaria ochroleuca*), were sown in individual plots, with each plot consisting of 10 m rows, 45 cm apart. The subplots were the following sampled soil layers: 0-5, 5-10, and 10-20 cm.

The soybean sowing density was 18 seeds m^{-1}, as recommended for this crop, whereas the double crops were sown at a density of 5 kg ha^{-1} for *Brachiaria ruziziensis* seeds, 15 kg ha^{-1} for sorghum seeds, 15 kg ha^{-1} for pearl millet seeds, and 8 kg ha^{-1} for slender leaf rattlebox seeds, as recommended by Torres et al. (2015).

The dry masses of the succession crops were determined in two seasons. In the first harvest, sorghum, Congo grass, pearl millet, maize intercropped with Congo grass, maize, and slender leaf rattlebox yielded 14.35, 9.50, 9.25, 6.43, 5.00, and 4.75 Mg ha^{-1} of dry mass, respectively. Conversely, in the second collection, the dry mass still present in the area was 9.50, 10.70, 3.97, 8.66, 3.77, and 6.66 Mg ha^{-1}, respectively.

Intercropped and monocropped maize crops were fertilized with 100 kg ha^{-1} P_2O_5, 60 kg ha^{-1} K_2O, and 150 kg ha^{-1} N. Sorghum and pearl millet were fertilized with half the dose recommended for maize. Congo grass and slender leaf rattlebox were not fertilized. This method was used from the start of the experiment to the fifth year of the study based on practices commonly adopted by farmers in the region for growing each crop or intercrop with soybean.

In the fifth year of this study, the succession crops were sown in the first week of March 2020, and the soybean of the following harvest was sown on October 31, 2020. The soybean variety used was Vigor CG7370 RR, which was fertilized with 300 kg ha^{-1} 02-20-18, as recommended by Sousa & Lobato (2004).

Before sowing soybean, the succession crops were dried on October 30, 2020, requiring a second application of glyphosate (3 L ha^{-1}) and clethodim (800 mL ha^{-1}) after soybean emergence on November 18, 2020. Cucurbit beetle (*Diabrotica speciosa*) control on soybean was performed on December 08, 2020, using the insecticide Mustang (200 mL ha^{-1}). On December 20, 2020, and January 06, 2021, fungicides (Penncozeb WDG (1 kg ha^{-1}) and Aproach (300 mL ha^{-1})) and insecticides (Expedition (300 mL ha^{-1}) and Wetcit (200 mL ha^{-1})) were applied.

Soil physicochemical quality was evaluated in the 2020/2021 crop year, that is, following the fifth consecutive season after starting the treatments.

The physicochemical tests were performed at the Federal University of Jataí (UFJ) soil laboratory, following the method proposed by Silva (2009) and Teixeira et al. (2017).

For soil chemical analysis, three simple samples were collected from each plot and pooled into a composite sample in October 2020. The samples were collected from the 0-5, 5-10, and 10-20 cm layers using a Dutch auger. The samples were placed in appropriate containers, dried in a forced ventilation oven at 65 °C for 24 hours, and subsequently sent to the UFJ soil laboratory for analysis according to the method described by Silva (2009) to determine the pH, base saturation (V%), cation exchange capacity (CEC), macro- and micronutrients, and organic matter (OM).

Soil physical properties were evaluated using 117.75 cm^3 volumetric rings. Three samples per plot were collected between soybean rows from the 0-5, 5-10, and 10-20 cm soil layers immediately after soybean harvest in February 2021. The soil (volumetric ring) and particle (volumetric flask) densities and total porosity were determined using the method described by Teixeira et al. (2017).

The data were subjected to analysis of variance, and the means were clustered using the Scott-Knott test ($p \leq 0.05$). All data were analyzed using the software Rbio (Bhering, 2017).

Results and Discussion

Tables 1, 2, and 3 summarize the analysis of variance (F values) of the soil's chemical properties. The interaction between sources of variation in plots (succession crops) and subplots (soil layers) only interacted with potassium content.

Individual evaluations of the sources of variation in the plots showed that the succession crops significantly affected potential acidity (H+Al), magnesium, and phosphorus. This was related to the NTF, which enhances soil chemical attributes by increasing surface OM and nutrient cycling (Fernandes et al., 2019). In contrast, the other variables, such as pH, the sum of bases (SB), CEC, base saturation (V%), aluminum, calcium, OM, copper, iron, manganese, and zinc, were not affected by succession crops (Tables 1, 2, and 3).

The lack of interaction between succession crops and soil layers for the other variables (Tables 1, 2, and 3) may be related to the period when NTF was established in this area because, as suggested by Calegari et al. (2008), this experimental area may be at an initial phase in the development of the NTF system. Therefore, research studies should be continued for a longer time to detect other long-term effects. Additionally, soil type could have an effect, as clay soils need more time to respond to the increase in OM (Borges et al., 2020).

Breaking down the interaction between the sources of variation for soil K concentration (Table 4) showed that the treatments with slender leaf rattlebox and Congo grass were in the same group and had the lowest K values in the 0-5 and 5-10 cm soil layers. Furthermore, in the 5-10 cm soil layer, sorghum and maize had the lowest K concentrations. Conversely, the treatments with pearl millet and maize intercropped with Congo grass remained in the groups with the highest K concentrations in all soil layers. Table 4 also shows that the 0-5 cm layer belongs to the group with the highest K concentration in the plots with pearl millet, sorghum, maize, and maize intercropped with Congo grass.

The high K concentration observed in the 0-5 cm layer (Table 4) may be explained by the fertilization performed during sowing in the plots with pearl millet, sorghum, maize, and maize intercropped with Congo grass. Conversely, slender leaf rattlebox and Congo grass were sown without fertilization, following practices commonly used by farmers in the study region.

The high K concentration in the 5-10 cm layer in the plots with pearl millet (Table 4) may be related to its high dry mass accumulation (9.25 Mg ha^{-1}) in the first season, which markedly decreased to 3.97 Mg ha^{-1} in the second season; as a result, this nutrient became readily available to the soil. Conversely, the high K concentration observed in the treatment with maize intercropped with Congo grass may be explained by fertilization at sowing. According to Torres & Pereira (2008), Congo grass and pearl millet accumulate large K quantities due to their high absorption capacity and deep root system.

Table 2. Summary of the analysis of variance (F values) for the sources of variation, succession crops (plots) and soil layers (subplots) and their interaction, for K, P, Ca, Mg, and organic matter (OM)

Sources of variation	K^+	P	Ca^{2+}	Mg^{2+}	OM
Block	0.70^{ns}	2.01^{ns}	7.47^{**}	5.67^{**}	0.17^{ns}
Succession crops (SC)	13.14^{**}	4.66^{**}	0.98^{ns}	6.36^{**}	1.24^{ns}
Soil layers (SL)	10.42^{**}	11.85^{**}	11.74^{**}	11.22^{**}	6.82^{**}
SC × SL	2.28^{**}	1.99^{ns}	1.11^{ns}	0.94^{ns}	0.83^{ns}
CV (%) (SC)	32.61	57.57	17.55	33.68	15.23
CV (%) (SL)	52.94	93.17	26.48	41.98	17.56

Ns - Non-significant; ** and * - Significant at $p \leq 0.01$ and $p \leq 0.05$ by F test, respectively

Table 3. Summary of the analysis of variance (F values) for the sources of variation, succession crops (plots) and soil layers (subplots) and their interaction, for Cu, Fe, Mn, and Zn

Sources of variation	Cu^{2+}	Fe^{2+}	Mn^{2+}	Zn^{2+}
Block	2.49^{ns}	1.53^{ns}	0.05^{*}	0.72^{ns}
Succession crops (SC)	2.05^{ns}	0.86^{ns}	1.59^{ns}	1.97^{ns}
Soil layers (SL)	4.89^{*}	0.54^{**}	13.11^{**}	8.79^{**}
SC × SL	0.71^{ns}	2.64^{ns}	0.67^{ns}	0.56^{ns}
CV (%) (SC)	13.30	14.97	11.73	33.99
CV (%) (SL)	16.77	11.13	19.72	52.13

ns - Non-significant; ** and * - Significant at $p \leq 0.01$ and $p \leq 0.05$ by F test, respectively

Table 4. Soil K concentration in mg dm^3 as a function of succession crops and soil layers

Succession crops	Soil layers (cm)		
	0-5	5-10	10-20
Millet	0.50 aA	0.30 bA	0.16 bA
Sorghum	0.38 aA	0.15 bB	0.13 bA
Maize	0.36 aA	0.18 bB	0.14 bA
Slender leaf rattlebox	0.14 aB	0.11 aB	0.20 aA
Congo grass	0.09 aB	0.11 aB	0.13 aA
Maize with Congo grass	0.32 aA	0.30 aA	0.15 aA

Means followed by the same lowercase letter in rows and uppercase letters in columns belong to the same group at $p \leq 0.05$ by the Scott-Knott test

Table 1. Summary of the analysis of variance (F values) for the sources of variation, succession crops (plots) and soil layers (subplots) and their interaction, for pH, the sum of bases (SB), cation exchange capacity (CEC), base saturation (V%), potential acidity (H+Al), and aluminum (Al)

Sources of variation	pH (H_2O)	SB	CEC	V%	H+Al	Al
Block	5.07^{*}	7.25^{**}	7.49^{**}	5.48^{**}	3.82^{*}	2.30^{ns}
Succession crops (SC)	2.55^{ns}	1.99^{ns}	0.54^{ns}	2.07^{ns}	3.11^{*}	0.57^{ns}
Soil layers (SL)	3.35^{*}	12.09^{**}	10.07^{**}	13.47^{**}	0.83^{ns}	4.71^{*}
SC × SL	0.62^{ns}	1.10^{ns}	1.36^{ns}	1.03^{ns}	1.18^{ns}	0.47^{ns}
CV (%) (SC)	5.56	20.23	7.60	17.17	16.43	35.32
CV (%) (SL)	4.74	30.34	16.78	16.51	14.26	39.96

ns - Non-significant; ** and * - Significant at $p \leq 0.01$ and $p \leq 0.05$ by F test, respectively

The element K is not associated with any component of the plant tissue structure and does not undergo any change in its ionic form; it is absorbed and made available quickly in the same form, that is, as K^+ (Meneghette et al., 2019). The K provided by crop residues of legumes and grasses accounts for approximately 90 and 80% of the soil K, respectively, highlighting the importance of nutrient cycling in systems with diverse crops (Michelon et al., 2019).

The high K concentration in the 0-5 cm layer (Table 4) may be explained by the OM accumulation on the soil surface in an NTF system, which reduces nutrient leaching (Meneghette et al., 2019).

The soil P concentration was higher in plots with monocropped maize and maize intercropped with Congo grass (Table 5); this can be attributed to the highest fertilization levels (approximately 100 kg ha^{-1} P_2O_5) in these plots.

According to the literature, adopting conservation systems increases the P concentration in topsoil layers, with stronger long-term effects due to OM accumulation, mineralization processes, and the release of organic compounds that compete for P adsorption sites, leaving the nutrient in forms available for plant absorption (Pereira et al., 2019).

For Mg concentrations, two groups were formed because plots with Congo grass had a higher availability of this element. However, for H+Al, the treatments could not be separated into different groups (Table 5).

The higher Mg concentration in plots with Congo grass (Table 5) may be explained by the dry matter of these plots in the last biomass collection, which was 10.70 Mg ha^{-1}. Ribeiro et al. (2020) found similar results when using cover crops and identified Congo grass as one of the crops responsible for increasing soil fertility by increasing OM.

Table 5. Soil P, Mg, and H+Al concentration by succession cropping

Succession crops	P (mg dm^{-3})	Mg^{2+} (cmol$_c$ dm^{-3})	H+Al (cmol$_c$ dm^{-3})
Millet	24.12 b	1.09 b	3.67 a
Sorghum	21.12 b	1.06 b	3.80 a
Maize	35.78 a	0.79 b	4.17 a
Slender leaf rattlebox	13.56 b	1.25 b	3.61 a
Congo grass	15.63 b	1.62 a	3.24 a
Maize with congo grass	28.94 a	1.00 b	3.89 a

Means followed by the same lowercase letter in columns belong to the same group at $p \leq 0.05$ by the Scott-Knott test

Tables 6 and 7 present the different chemical properties of the soil layers studied. The 0-5 cm layer had the highest values for most soil nutrients, but the layers could not be separated based on pH. The highest Al^{3+} levels were found in the 10-20 cm soil layer. Conversely, the highest Cu^{2+} levels were found in the 5-10 and 10-20 cm soil layers. For Mn^{2+} and Zn^{2+}, the highest levels were detected in the 0-5 and 5-10 cm soil layers.

The sources of variation in soil layers did not affect the pH (Table 6). OM influences the pH, as it releases organic compounds, increasing the pH and neutralizing Al^{3+} (Malta et al., 2019), but this was not the case in the present study. Soil pH in the present study varied adequately (ranging from 5.6 to 6.3), and the OM concentration may be classified as good, as described by Sousa & Lobato (2004).

The 0-5 cm soil layer contained higher P, Ca, Mg, K, Mn, and Zn concentrations, SB, CEC, and base saturation owing to its higher OM concentration (Tables 6 and 7). OM reduces the sites of some elements by dissociating functional groups in humic fractions; for instance, phenolic (-OH) and carboxylic (-COOH) groups with an exposed negative charge electrostatically bind to cations released in the solution by crop residues, serving as a reservoir that is subsequently available to meet crop needs (Nanzer et al., 2019).

When evaluating different management systems, Michelon et al. (2019) also found a higher OM concentration in the topsoil layers. The CEC values found in this study are classified as high, the Ca, Mg, and P concentrations are adequate, Cu, Mn, and Zn concentrations are high, and the K concentration is medium-to-high, according to Sousa & Lobato (2004). The soil is an oxisol; that is, it has a high concentration of Fe oxides (EMBRAPA, 2018), which explains the findings regarding Fe in this study.

Crop succession increased the OM concentration on the soil surface (Table 6). Calegari et al. (2008) evaluated a 19-year crop rotation system and showed that all cover crops increased the soil organic carbon and surface OM compared with fallow, and that NTF was the closest system to non-anthropic forest conditions.

Unlike most other elements, Al^{3+} and Cu^{2+} concentrations were higher in deeper soil layers (Tables 6 and 7). The increased soil surface OM concentration may explain this variation, given the formation of stable organo-mineral complexes, such as chelates, which reduce the availability of micronutrients, especially Cu, in the first years of NTF (Diniz et al., 2021).

Table 6. Mean pH, and P, Al, Ca, Mg, K, and organic matter (OM) concentrations in the 0-5, 5-10, and 10-20 cm soil layers

Soil layers (cm)	pH H_2O	P (mg dm^{-3})	Al^{3+}	Ca^{2+}	Mg^{2+}	K^+	OM (g kg^{-1})
			(cmol$_c$ dm^{-3})				
0-5	6.28 a	39.97 a	0.00 b	3.85 a	1.50 a	0.36 a	38.69 a
5-10	6.18 a	19.22 b	0.00 b	3.31 b	1.04 b	0.17 b	34.24 b
10-20	6.06 a	10.39 b	0.02 a	2.64 c	0.87 b	0.12 c	32.28 b

Means followed by the same lowercase letter in columns belong to the same group at $p \leq 0.05$ by the Scott-Knott test

Table 7. Mean of sum of bases (SB), cation exchange capacity (CEC), base saturation (V%), and micronutrients (Cu, Fe, Mn, and Zn) in the 0-5, 5-10, and 10-20 cm soil layers

Soil lavers (cm)	SB	CEC	V (%)	Cu^{2+}	Mn^{2+}	Fe^{3+}	Zn^{2+}
	cmol$_c$ dm^{-3}			(mg dm^{-3})			
0-5	5.65 a	9.27 a	60.41 a	4.72 b	63.22 a	40.60 a	4.15 a
5-10	4.55 b	8.34 b	54.25 b	5.39 a	63.42 a	39.42 a	3.53 a
10-20	3.66 c	7.45 c	47.08 c	5.40 a	48.57 b	36.98 b	2.13 b

Means followed by the same lowercase letter in columns belong to the same group at $p \leq 0.05$ by the Scott-Knott test

Table 8. Summary of the analysis of variance (F values) for the sources of variation, succession crops and soil layers and their interaction, for soil (Ds) and particle (Dp) densities and total porosity (Pt)

Sources of variation	Ds	Dp	Pt
Block	2.00^{ns}	2.41^{ns}	1.29^{ns}
Succession crops (SC)	1.41^{ns}	2.10^{ns}	1.20^{ns}
Soil layers (SL)	35.03^{**}	3.79^{*}	53.05^{**}
SC × SL	0.51^{ns}	0.60^{ns}	0.27^{ns}
CV (%) (SC)	3.39	3.34	4.06
CV (%) (SL)	2.94	4.46	3.20

Ns - Non-significant; ** and * - Significant at $p \leq 0.01$ and $p \leq 0.05$ by the F test, respectively

Table 8 presents a summary of the analysis of variance (F values) of the attributes as a function of sources of variation: succession crops (plots) and soil layers (subplots). No interaction occurred between the sources of variation, plots and subplots. No significant effect was observed for sources of variation; plots for succession crops were evaluated individually. The sources of variation for soil layers significantly affected all mineral variables, soil and particle densities, and total porosity.

Rocha et al. (2020) did not observe differences between the effects of succession crops on mean soil density (Ds), particle density (Dp), or total porosity (Pt) when studying different succession crops in the same type of soil present in the experimental area of this study, albeit using a direct sowing system in the second year, proving the need for longer periods of evaluation to detect changes in soil physical properties in this conservation system.

In an experiment conducted in a clayey oxisol at Selvíria (MS, Brazil), Silva et al. (2017) found a significant interaction between cover crops and sampling soil depth for Ds, macroporosity, and Pt under a furrow irrigation system and fertilization in an area previously used in an NTF system for 10 years, reinforcing the long-term benefits of this system.

The lack of a significant effect of the succession crops can be partly explained by the type of soil in the study area, an oxisol with a clayey texture. Clayey soils require more time for increases in OM to change soil physical properties compared with sandy soils, where small increases in OM result in fast changes (Borges et al., 2020).

Serpa et al. (2020) observed that management and cover crops produced significant differences in soil physical quality, with the plants that yielded the highest amount of crop residues positively affecting soil physical properties, especially in the topsoil layers.

The Ds, Dp, and Pt values were better in the topsoil layers, between 0 and 5 cm for Ds, Dp, and Pt and between 5 and 10 cm for Dp, demonstrating the benefits of using succession crops for OM production in these layers (Table 9).

Succession crops decrease topsoil Ds due to the higher OM concentration and microbial activity, among other factors (Silva et al., 2017). The Ds values tended to increase in the deeper soil layers due to the decrease in OM concentration with depth and the pressure of the topsoil layers on the lower layers (Table 9).

According to Collares et al. (2011), the soil density suitable for agricultural crops is below 1.4 g cm^{-3}. In this study, the Ds values ranged from 1.19 g cm^{-3} in the 0-5 cm soil layer to

Table 9. Mean soil (Ds) and particle (Dp) densities and total porosity (Pt) of the soil layers

Soil layers (cm)	Ds	Dp	Pt
		(g cm^{-3})	
0-5	1.19 c	2.74 b	0.53 a
5-10	1.25 b	2.83 b	0.50 b
10-20	1.27 a	2.84 a	0.48 c

Means followed by the same lowercase letter in columns belong to the same group at $p \leq 0.05$ by the Scott-Knott test

1.27 g cm^{-3} in the 10-20 cm layer (Table 9), which were within the recommended limits for agricultural crops.

OM directly affects Ds because its Dp is approximately 1.2 g cm^{-3}, in contrast to most mineral soils, which have a higher Dp, ranging from 2.6 to 2.7 g cm^{-3} (Balin et al., 2017).

When analyzing different cropping systems, Monteiro et al. (2019) observed that the OM concentration is related to the type of soil management. A soil management system such as NTF increases the OM concentration, thereby improving soil structure, water retention, and physical properties (Sousa et al., 2020).

Soil Pt was correlated with Ds. As Ds increases, Pt tends to decrease, interfering with water infiltration and soil aeration processes. However, the presence of OM improves soil stability, biopore formation by dead roots, and microbial activity, increasing Pt and decreasing Ds on the soil surface (Balin et al., 2017). The Pt values ranged from 0.53 to 0.48, and the 0-5 cm layer had the best Pt and Ds results, given the higher OM concentration on the soil surface (Table 9).

Conclusions

1. Pearl millet cycled K efficiently, increasing the levels of this element in the soil.

2. Monocropped maize and maize intercropped with Congo grass enhanced the potential to increase the soil P concentration.

3. Congo grass stood out for its capacity to increase Mg concentration in the soil layers analyzed in this study.

4. The use of crop successions promoted an increase in OM concentration on the soil surface.

5. The 0-5 cm soil layer had the best physicochemical conditions based on the accumulated OM, P, Ca^{2+}, Mg^{2+}, K, Mn^{2+}, Fe^{3+}, and Zn^{2+}.

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