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Physicochemical soil quality in areas under different management systems in the Cerrado

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ABSTRACT

This study aimed to quantify the physical and chemical properties of the soil, as well as carbon stocks, under different management systems. A completely randomized design was adopted, evaluating four systems: (1) Agroforestry System (AFS), (2) Sugarcane cultivation (sugarcane), (3) Pasture, and (4) Native Forest, with five replicates each. Disturbed and undisturbed soil samples were collected during the rainy season at depths of 0.0–0.10, 0.10–0.20, 0.20–0.30, and 0.30–0.40 m to assess chemical attributes, total organic carbon (TOC), soil bulk density (Bd), and carbon stock (Cstock). A sensitivity index (SI) was also calculated for selected attributes. The AFS and native forest areas showed the best chemical soil quality, with higher values of soil organic matter, phosphorus (P), and potassium (K) in the surface layers, as well as higher TOC values at the 0.0–0.10 m depth (12.70 and 47.90 g kg^{-1}) and greater Cstock at the 0.20–0.30 m depth (48.67 and 139.16 g kg^{-1}), respectively. The AFS, established only five years ago, provided higher nutrient contents P (14.47 mg dm^{-3}), K (1.12 $mmol_c$ dm^{-3}), Ca (23.07 $mmol_c$ dm^{-3}), and Mg (6.47 $mmol_c$ dm^{-3}) at the 0.0–0.10 m depth, as well as higher TOC and Cstock at all depths, compared to the sugarcane and pasture systems. The high Bd observed in the Sugarcane area indicates soil compaction and restrictions to normal root development. The SI values for TOC and Cstock indicate that all production systems have led to a decline in soil quality due to their conversion to agricultural use.

Keywords: Agroforestry system; Sugarcane; Pasture; Native forest.

Qualidade físico-química do solo em áreas sob diferentes sistemas de manejo no Cerrado

RESUMO

Neste estudo objetivou-se quantificar os atributos físico-químicos e o estoque do carbono do solo das áreas com diferentes sistemas de manejo. O delineamento utilizado foi o inteiramente casualizado, sendo avaliados quatro sistemas de manejo: 1 - Sistema agroflorestal (SAF); 2 - Área cultivada com cana-de-açúcar (Cana); 3 - Pastagem (PA) e; 4 - Mata Nativa (MN), com cinco repetições. Foram coletadas amostras deformadas e indeformadas do solo durante o período chuvoso nas profundidades de 0,0-0,10; 0,10-0,20; 0,20-0,30 e 0,30-0,40 m, para avaliação dos atributos químicos, carbono orgânico total (COT), densidade do solo (Ds) e estoque de carbono (EstC). Também foi calculado o índice de sensibilidade (Is) para alguns atributos avaliados. Observou-se que as áreas de SAF e MN apresentaram a melhor qualidade química do solo, com maiores valores de matéria orgânica do solo, P e K nas camadas mais superficiais, assim como maiores valores de COT na profundidade 0,0 a 0,10 m (12,70 e 47,90 g kg^{-1}) e de EstC na profundidade de 0,20 a 0,30 m (48,67 e 139,16 g kg^{-1}), respectivamente; O SAF com apenas cinco anos de implantação, proporcionou maiores teores dos nutrientes P (14,47 mg dm^{-3}), K (1,12 $mmol_c$ dm^{-3}), Ca (23,07 $mmol_c$ dm^{-3}) e Mg (6,47 $mmol_c$ dm^{-3}) na profundidade de 0,0 a 0,10 m, de COT e EstC em todas as profundidade, em comparação aos sistemas com Cana e PA. A elevada Ds na área de Cana indica que o solo está compactado e com restrição ao desenvolvimento radicular normal das plantas. O Is para o COT e EstC mostra que todos os sistemas perderam qualidade do solo aos entrar no processo de produção de alimentos.

Palavras-chave: Sistema agroflorestal; Cana-de-açúcar; Pastagem; Mata nativa.

1. Introduction

The conversion of natural ecosystems into cultivated areas can disrupt the dynamics of soil organic matter (SOM), as the rates of organic matter input in production systems are often lower than the actual losses, potentially compromising the soil physical, chemical and biological quality (Ferreira et al., 2020). This imbalance is primarily due to the intensity of SOM decomposition processes, nutrient loss through leaching, and carbon emissions to the atmosphere, all of which contribute to reducing the amount of carbon stored in the soil (Loss et al., 2015).

The decline or accumulation of SOM within the same edaphic environment depends on factors such as vegetation cover, precipitation, temperature, and, most importantly, the management system adopted. When maintained over a long period, the SOM content tends to stabilize at a new equilibrium, directly influencing soil carbon stock (Cstock). This is because the main processes responsible for carbon sequestration are humification, aggregation, and sedimentation, whereas erosion, decomposition, volatilization, and leaching account for the primary pathways of carbon loss (Rufino et al., 2022).

The intensive tillage practices associated with conventional farming systems reduce soil carbon concentration, primarily within the first 10 years after converting forests and native pastures into croplands (Assunção et al., 2019). In contrast, regenerative agriculture can lead to increased carbon concentrations, as the management systems promote the accumulation of organic material in the surface and subsurface horizons of the soil (Nijmeijer et al., 2019).

Well-managed pastures can also contribute significant amounts of carbon (C) to the soil due to the vigorous growth and constant renewal of the root systems of cultivated grasses (Poaceae), unlike what is observed in overgrazed pastures and under poorly managed conditions (Santos et al., 2019). Souza et al. (2012) emphasize that areas subjected to more intensive grazing tend to accumulate less C in the soil, as there is a greater loss of C and nitrogen (N) from the system, primarily due to microbial respiration and animal grazing. In contrast, areas under moderate grazing intensity or pasture–crop integration systems tend to show increased C and N contents, as the lability of SOM in these areas is similar to that of ungrazed systems, resulting in improved soil quality.

Regarding chemical attributes, management systems that promote SOM accumulation tend to exhibit higher cation exchange capacity and a greater ability to complex toxic elements and make nutrients available to crops grown in succession or rotation (Loss et al., 2009a; Troian et al., 2020).

Soil management systems aimed at food production have evolved in complexity and diversity, with particular emphasis on agroforestry and agroecological systems, which seek to integrate agricultural, livestock, and forestry activities within the same area (Fayad et al., 2016). These systems are based on the premise that different plant species can coexist in the same environment, each fulfilling its role while mutually benefiting one another (Altieri & Nicholls, 2011). Given the wide range of management systems used in the Brazilian Cerrado, there is a growing need to establish qualitative and quantitative parameters to assess the effectiveness of these practices and their influence on SOM content and agricultural productivity (Torres et al., 2021).

In this context, the hypothesis tested in this study is that agroforestry systems promote superior soil chemical quality, higher soil organic matter (SOM) content, and greater soil carbon stock (Cstock) over a shorter period. Therefore, this study aimed to quantify the physicochemical attributes and soil carbon stock in areas under different management systems.

2. Material and Methods

The study was conducted in an experimental area located in the Triângulo Mineiro/Alto Paranaíba mesoregion, accessible between the municipalities of Uberaba and Uberlândia, Minas Gerais (MG), at 19°18’05” S and 48°18’46” W, and 783 meters above sea level. The research activities were carried out between October 2023 and January 2024. The areas evaluated included land-use systems involving sugarcane cultivation, pasture, and an agroforestry system. An adjacent native forest area was used as a reference for natural soil conditions.

The soil in the evaluated areas was classified as *Latossolo Vermelho distrófico* (Santos et al., 2018), with a sandy clay loam texture. In the 0–0.30 m soil layer, particle size distribution was 260, 720, and 20 g kg^{-1} of clay, sand, and silt, respectively. The region climate is classified as an Aw tropical savanna with a dry winter according to the updated Köppen classification system (Beck et al., 2018). It is characterized by a rainy summer and a dry winter, with annual averages of 1,300 mm precipitation, 22 °C temperature, and 68% relative humidity. During the evaluation period, the average temperature and cumulative rainfall are presented in Figure 1.

Regarding the land-use history of the evaluated areas, all were used as pasture for over 70 years under a monoculture system. The area still used as pasture in this study shows signs of degradation, with a stocking rate of less than 1.0 animal units per hectare (AU ha^{-1}), no recent history of liming, and previous use for coffee cultivation.

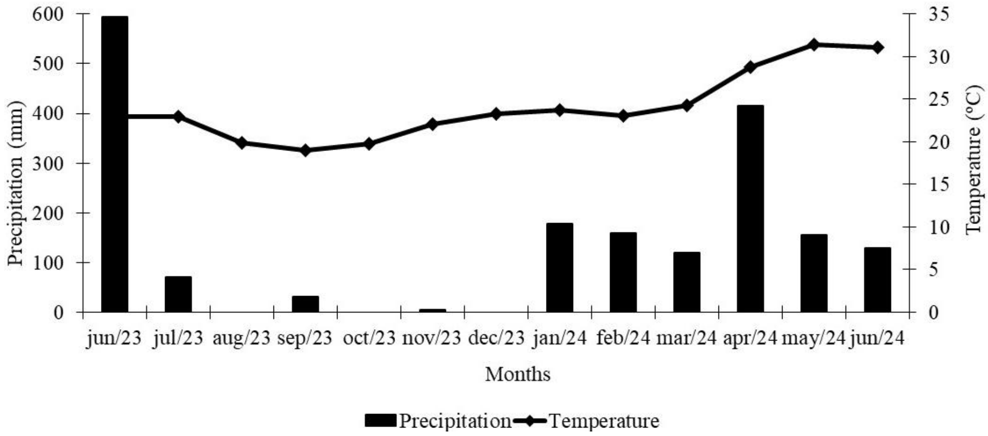

Figure 1. Precipitation and average temperature from October 2023 to June 2024 obtained from the Meteorological Database for Teaching and Research (BDMEP) of INMET (2024).

The agroforestry system (AFS) area has been under management for five years and covers approximately 38 m × 25 m, totaling about 950 m². In July 2022, 2.0 Mg ha^{-1} of lime was applied. The AFS consists of eleven raised bed rows, each approximately 17 meters long, with an inter-row spacing of half a meter. Even-numbered rows are planted with various types of *Citrus*, spaced 1.5 meters apart, and intercropped with large green manure tree species such as *Gliricidia sepium* and *Inga* spp., also spaced at 1.5 meters.

In the odd-numbered rows, several varieties of banana (*Musa* spp.) are grown, intercropped with papaya (*Carica papaya*), also spaced 1.5 meters apart. The remaining spaces and forest strata are occupied by short-cycle crops such as squash (*Cucurbita moschata*), scarlet eggplant (*Solanum aethiopicum*), and fast-growing green manure species like jack bean (*Canavalia ensiformis*) and pigeon pea (*Cajanus cajan*).

Sugarcane has been cultivated in the area for approximately 13 years. One production cycle comprising six harvests was initially completed, after which lime was applied to the soil. The area was then planted with one cycle of soybean, followed by the re-establishment of sugarcane. Harvesting is fully mechanized, and all crop management practices, such as spraying and fertilization, are performed directly over the sugarcane residues left on the soil surface.

Before establishing the agroforestry system (AFS) and at the end of the first sugarcane cycle, lime was applied at rates of 1.5 and 2.0 Mg ha^{-1}, respectively. The lime used contained 36.4% calcium oxide, 44.0% magnesium oxide, a neutralizing value (NV) of 99.87%, and a relative neutralizing power (RNP) of 90.28%, aiming to raise base saturation to approximately 70%.

Downstream from all three areas lies a native forest area composed of the same vegetation that existed before deforestation for pasture establishment. This vegetation is classified as a Semideciduous Riparian Seasonal Forest, functioning as a receiving zone for surface runoff and sediments transported from higher areas in the landscape.

A completely randomized design (CRD) was used, in which four areas under different management systems were evaluated as treatments: (1) Agroforestry system (AFS), (2) Sugarcane cultivation (Sugarcane) (*Saccharum officinarum* L.), (3) Brachiaria pasture (PA) (*Urochloa brizantha* cv. Marandu), and (4) Native forest (NF). All sampling and analyses were conducted with five replications for each soil layer: 0.00–0.10 m, 0.10–0.20 m, 0.20–0.30 m, and 0.30–0.40 m.

Undisturbed soil samples were collected using volumetric rings measuring 48 mm in diameter and 53 mm in height, with a Uhland sampler, at the soil layers of 0.00–0.10, 0.10–0.20, 0.20–0.30, and 0.30–0.40 m for the determination of bulk density (Bd). These samples were oven-dried in a forced-air circulation oven at 105 °C until reaching a constant dry mass. Bulk density was then calculated as the ratio between the dry mass and the ring volume (Teixeira et al., 2017).

In each area, ten mini-pits measuring 0.50 × 0.50 m at the surface and 0.50 m deep were excavated, and soil samples were collected at the soil layers of 0–0.10, 0.10–0.20, 0.20–0.30, and 0.30–0.40 m. The samples were then homogenized to obtain five replications for each layer across the different areas at the beginning of the rainy season in the region.

The homogenized samples were air-dried to obtain air-dried fine earth (ADFE) to determine pH values and the concentrations of Ca^{2+}, Mg^{2+}, Al^{3+}, K^+, P, and potential acidity (H^+Al). Soil pH in $CaCl_2$ was determined using a 1:2.5 soil-to-solution ratio after 10 minutes of shaking and 30 minutes of settling, with readings taken using a benchtop pH meter. Exchangeable Ca^{2+}, Mg^{2+}, and $Al^{3+}$and potential acidity (H^+Al) were extracted with a 1 mol L^{-1} KCl solution and titration; sulfur (S) was analyzed by turbidimetry. Phosphorus (P) and potassium (K^+) were extracted using a double-acid solution (0.05 mol L^{-1} HCl + 0.0125 mol L^{-1} H_2SO_4) following the Mehlich-1 method and analyzed by colorimetry (P) and flame photometry (K^+), respectively, according to the methodology of Teixeira et al. (2017).

For total organic carbon (TOC), at the same sampling soil layers (0–0.10, 0.10–0.20, 0.20–0.30, and 0.30–0.40 m), quantification was performed using the modified Walkley-Black method (Tedesco et al., 1995). A 0.5 g portion of air-dried fine earth was weighed, ground in a porcelain mortar, and sieved through a 60-mesh screen. The material was placed in a 250 mL Erlenmeyer flask, adding 5 mL of potassium dichromate ($K_2Cr_2O_7$, 0.167 mol L^{-1}) and 7.5 mL of sulfuric acid (H_2SO_4). The mixture was then heated in a digestion block at 170 °C for 30 minutes, followed by the addition of 80 mL of distilled water and 0.3 mL of indicator solution (phenanthroline), and finally titrated with 0.2 mol L^{-1} ammonium ferrous sulfate solution.

For the calculation of carbon stock (Cstock), the method described by Fernandes and Fernandes (2013) was used, as determined by Equation 1.

CStock (Mg ha^{-1}) = [(C x Bd x e) / 10] Equation 1

Where C is the total organic carbon (TOC) content in the soil layer (g kg^{-1}); Bd is the soil bulk density (Mg m^{-3}); and e is the thickness of the soil layer under analysis (cm).

To compare the values of bulk density (Bd), total organic carbon (TOC), and carbon stock (Cstock) across the different management systems, using the native forest as a reference, the sensitivity index (SI) proposed by Bolinder et al. (1999) was used. This index estimates the extent of changes in soil physical and chemical attributes due to the land cover types. The index was calculated using Equation 2:

SI = as / ac Equation 2

SI is the sensitivity index, as is the value of the variable (Bd, TOC, or Cstock) in the area under the evaluated management system, and ac is the value of the same variable in the native forest area (reference). The closer the SI is to one, the smaller the change observed in the evaluated soil attributes.

The results were analyzed for normality and homogeneity using the Lilliefors and Cochran-Bartlett tests. Subsequently, the data were subjected to analysis of variance (ANOVA), applying the F-test for significance, and the means were grouped using the Scott-Knott test ($p < 0.05$), with the aid of the AgroEstat software developed by Barbosa and Maldonado Junior (2009).

3. Results and Discussion

Overall, the sugarcane and native forest areas showed the highest potential hydrogen (pH) values, ranging from 5.15 to 5.65, which is close to the ideal range (around 5.3) for plant development, where calcium and magnesium contents tend to be higher. However, the same pattern was not observed in the agroforestry system (AFS) and pasture (PA) areas, where the soil exhibited acidic pH values ranging from 4.3 to 5.0, indicating the need for liming. Among the managed areas, the pasture system showed the lowest surface soil pH values, reflecting a more acidic condition under this management system. Nonetheless, the AFS and native forest areas exhibited the best soil fertility based on chemical analyses, which is associated with their higher SOM content (Table 1).

The AFS and native forest areas showed similar results at all soil layers ($p < 0.05$) for phosphorus (P), with values higher than those observed in the sugarcane and pasture areas. For potassium (K) and SOM contents, the native forest area stood out with the highest contents, followed by the AFS area, which presented higher values at all soil layers, except for SOM at the 30–40 cm layer compared to the sugarcane and pasture areas (Table 1). These results indicate that the AFS area, due to its greater plant diversity, including tree species and green manures, promotes increased SOM, leading to higher contents of P and K.

The higher nutrient contents in the native forest area are due to the absence of anthropogenic interference, combined with its position in the landscape as a receiving zone for surface runoff and sediments transported from higher elevations. This contributes to the enrichment of the forest soil with SOM and enhances nutrient cycling.

The similar Ca and Mg values found in the sugarcane and AFS areas are attributed to the application of lime in the soil, which is not applied in the pasture area, resulting in the lowest Mg contents (Table 1). However, no significant differences were observed in Ca content among the PA, sugarcane, and AFS areas, likely due to the efficient calcium cycling carried out by the root system of the grasses, specifically *Urochloa brizantha*.

When comparing pH values between the AFS and pasture areas, higher values were observed in the surface soil layer of the AFS. These differences are due to the lime applied when the AFS was established, as the area was previously under pasture. Additionally, given the greater plant diversity in the AFS, its pH is expected to remain higher than that of the pasture area over time. In their study, Iwata et al. (2012) also reported an increase in pH following the establishment of an AFS in areas with only six years of implementation and stated that this value tends to rise over time, as evidenced by a higher pH in another AFS established 13 years prior on the same soil. Similarly, Loss et al. (2009b) reported higher pH values in pasture areas compared to an AFS, attributing the lower acidity in the pasture to the periodic application of lime during pasture renovation.

Table 1. Potential hydrogen (pH), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), aluminum (Al), sulfur (S), and organic matter (OM) contents under agroforestry, sugarcane, pasture, and native forest management systems in Uberaba, Minas Gerais, Brazil (2024).

Layer	pH	P	K	Ca	Mg	Al	S	OM
m	$CaCl_2$	mg dm^{-3}	----.$mmol_c$ dm^{-3} ----			-- mg dm^{-3} --		g kg^{-1}
				Agroforestry system				
0.00-0.10	5.00 aB	14.47 aA	1.12 aB	23.07 aB	6.47 aB	0.20 bB	0.62 bB	21.89 aB
0.10-0.20	4.77 aB	11.37 bA	0.92 bB	16.30 bB	4.52 bB	1.95 aB	0.82 bB	16.24 bB
0.20-0.30	4.67 aB	10.32 bA	0.87 bB	12.90 bB	5.02 bB	2.27 aB	1.80 aB	17.58 bB
0.30-0.40	4.52 aB	7.17 cA	0.75 bB	9.77 cC	3.47 cB	2.30 aB	2.07 aC	12.27 bB
				Sugarcane				
0.00-0.10	5.50 aA	4.92 aB	0.67 aC	29.27 aB	4.62 aC	0.01 aC	2.00 cA	10.55 aC
0.10-0.20	5.65 aA	4.85 aB	0.50 aC	27.40 aB	5.50 aB	0.01 aC	2.17 cA	9.22 aC
0.20-0.30	5.52 aA	4.42 aC	0.40 aC	15.87 bB	5.37 aB	0.01 aC	3.72 bA	8.28 aC
0.30-0.40	5.15 aA	3.37 aC	0.40 aC	9.90 cC	3.90 bB	1.10 bC	11.27 aA	7.50 aB
				Pasture				
0.00-0.10	4.42 aC	6.42 aB	0.41aD	28.40 aB	2.47 aD	2.30 dA	0.57 bB	11.93 aC
0.10-0.20	4.37 aB	6.22 aB	0.30 bC	26.07 aB	1.17 bC	3.00 cA	0.82 bB	9.34 aC
0.20-0.30	4.27 aB	6.50 aB	0.22 bC	23.60 aB	1.22 bC	3.42 bA	1.27 bB	8.57 aC
0.30-0.40	4.27 aB	5.97 aB	0.12 cD	20.30 aB	0.70 cC	4.00 aA	2.72 aB	8.05 aB
				Native forest				
0.00-0.10	5.72 aA	13.97 aA	2.20 aA	323.47 aA	16.02 aA	0.01 aB	0.87 bB	82.58 aA
0.10-0.20	5.60 aA	10.65 bA	2.00 aA	284.42 bA	14.32 aA	0.01 aC	1.05 bB	73.27 bA
0.20-0.30	5.57 aA	10.30 bA	1.72 bA	209.97 cA	12.57 bA	0.01 aC	1.80 aB	58.82 cA
0.30-0.40	5.47 aA	8.27 cA	1.32 cA	168.07 dA	10.12 cA	0.01 aD	1.72 aC	45.03 dA
F-test	46.17**	121.15**	261.85**	104.42**	244.18**	423.31**	160.56**	42.21**
CV%	6.95	14.65	19.38	17.74	21.21	22.15	24.62	11.53

Means followed by the same lowercase letter in the column for the soil layers in the same management system and uppercase letters for the management systems at the same soil layer belong to the same group by the Scott-Knott test ($p < 0.05$). CV% = Coefficient of variation.

Evaluating conservation management systems that contribute significant amounts of organic matter to the soil surface, Nascente et al. (2015) observed that such systems promote increases in nutrient content, organic matter, cation exchange capacity, and base saturation as successive crop cycles progress, particularly in the upper soil layers. Regarding phosphorus (P), although the values are considered low to very low (Alvarez et al., 1999), the AFS stood out compared to the P contents observed in the pasture and sugarcane areas.

These results are associated with greater plant diversity, using green manures in the AFS, and nutrient uptake through the deep roots of large tree species, which also helps explain the higher values. The tree component in the AFS promotes greater biomass production, which is later transformed into organic residues, thereby enhancing nutrient cycling within the agroecosystem.

Phosphorus (P) content decreased with increasing depth, showing significant differences ($p < 0.05$) between layers within the AFS and native forest systems. The decrease in P contents with depth was also observed by Souza and Alves (2003), who stated that the absence of soil disturbance, combined with the intense input of organic residues in both systems, contributes to P accumulation in the uppermost soil layer.

Moreover, in these environments, the greater accumulation of plant biomass supports soil microbiota (fungus and bacteria), which in turn enhances P availability through various mechanisms such as the release of organic acids, siderophores, hydroxyl ions, extracellular enzymes, and P released during substrate decomposition (Oliveira-Paiva et al., 2022).

When evaluating the chemical and physical characteristics of soil under forest, AFS, and pasture (PA) in southern Bahia, Barreto et al. (2006) also reported higher P content in the forest and AFS in the 0–0.10 m layer compared to PA. Pereira et al. (2010) emphasize that high SOM contents, particularly the light organic matter fraction, reduce phosphorus adsorption in the soil, a behavior that helps explain the higher P values observed in the AFS and native forest areas. In a natural system, phosphorus availability is closely linked to the organic cycling of nutrients (Santos et al., 2008). According to Vasconcellos and Beltrão (2018), in agroforestry systems (AFS), which aim to simulate trophic chains and biological interactions typical of areas with natural vegetation, biological activity at the soil content is intense, supporting the results observed in this study.

In the AFS, no phosphate fertilizer was applied, yet phosphorus contents at all four soil layers were higher than those found in the sugarcane and pasture areas. These results contrast those reported by Loss et al. (2009a), who observed higher P content in pasture than an AFS. However, the difference is attributed to the fertilization applied in the pasture area in the study by Loss et al. (2009b), which was not carried out in the present study, suggesting greater sustainability of agroecosystems based on agroecological principles.

As stated by Martin and Isaac (2018), AFS is a system in which the application of inorganic phosphate fertilizers derived from finite sources and associated with increased production costs for farmers is unnecessary.

Exchangeable potassium (K) contents decreased with increasing depth in the AFS and native forest treatments. According to Alvarez et al. (1999), K contents observed across all four systems are considered low, with the highest values recorded in the native forest area at all sampled layers. This is attributed to greater nutrient cycling within that system. Similarly, Ribeiro et al. (2019), when evaluating soil fertility in different AFSs, also observed a decline in K, Ca, Mg, and S contents with depth results consistent with those found in the present study.

The pasture area showed the lowest K contents, which is consistent with the findings of Ferreira et al. (2011), who reported that grazing intensity did not contribute to increased K cycling, a pattern also observed in the present study, considering that the area is only lightly used for cattle grazing. Klug et al. (2020) also confirmed this behavior regarding K contents, noting a decrease in Ca and Mg contents with increasing depth. In the present study, Mg contents did not vary with depth in the AFS, sugarcane, and pasture systems; this trend was observed only in the native forest area (Table 1).

According to Alvarez et al. (1999), Ca and Mg contents in the AFS, NF, and sugarcane systems were within adequate ranges. Given that the highest Mg contents were observed in the native forest area, it can be inferred that these values are directly related to the greater presence of organic residues deposited through litterfall. No significant differences ($p < 0.05$) were found between the AFS and sugarcane systems, indicating that the direct planting of commercial crops over crop residues has a similar effect in both areas. The lowest SOM contents were observed in the sugarcane and pasture systems results that differ from those reported by Souza and Alves (2003), who found that under no-tillage (NT) and minimum tillage systems in *Latossolo Vermelho distrófico*, there was a significant increase in SOM, maintaining contents similar to those found in areas with natural vegetation in the Cerrado.

Regarding micronutrients, soil analysis showed that the native forest area stood out for its contents of iron (Fe), zinc (Zn), manganese (Mn), and boron (B) (Table 2). This is explained by the high amount of organic residues from various plants, which, as they decompose, recycle both macro and micronutrients back into the soil, as highlighted by Cunha et al. (2012).

The availability of Mn in tropical soils tends to be reduced by liming, especially when applied to the surface without incorporation (Alvarez et al., 1999). This condition was partially observed in the AFS area between 0.10 and 0.40 m depth, where lime had been incorporated into the soil before system establishment. In the sugarcane area, where soil correction was performed, and in the native forest area, where no lime was applied, the highest pH values were recorded (ranging from 5.15 to 5.65 in the sugarcane area and from 5.47 to 5.72 in the native forest area). In contrast, the highest Mn contents were observed in the pasture area, where the soil was more acidic (between 4.27 and 4.42) (Table 2). This may be explained by the high organic matter inputs in all the systems evaluated (AFS, sugarcane, PA, and NF) through surface plant residues or remnants of root systems in the subsurface.

According to Oliveira Junior et al. (2000), Mn availability depends on factors such as soil acidity, SOM content, and the balance with other elements. However, pH is one of the most important factors, as higher pH contents reduce Mn availability due to oxidation processes, which tend to occur more extensively in areas with higher SOM content.

Regarding boron (B), the highest contents were observed in the native forest area, ranging from 0.10 to 0.20 mg dm^{-3}, where soil organic matter (OM) content is significantly higher compared to the other systems, as OM is the primary source of B in the soil. Quantitatively, these values fall within the range of 0.10 to 0.30 mg dm^{-3}, which is considered medium, according to Malavolta et al. (1997), sufficient to meet plant requirements. In contrast, B contents in the AFS, sugarcane, and pasture areas ranged from 0.02 to 0.07 mg dm^{-3}, remaining below the medium threshold.

The significantly higher B contents ($p < 0.05$) in the native forest area can be readily explained, as this area is located downstream from the other systems and acts as a receiving zone for surface water runoff and sedimentation. According to Mattielo et al. (2009), B deficiency is a common characteristic of Cerrado soils and may also occur during prolonged periods of water deficit, typical of the Brazilian Cerrado.

The AFS presented the highest copper (Cu) contents among the evaluated areas ($p < 0.05$); however, these values are still considered low and unlikely to pose risks to crops (Alvarez et al., 1999). Wastowski et al. (2010) associated higher Cu contents with repeated animal manure (from cattle, swine, or poultry) in a study evaluating chemical element contents in soils under different land use and management systems. Across all systems, no significant differences were observed among soil layers. In the AFS, Cu contents slightly increased to a depth of 0.30 m, and in the native forest area, up to 0.40 m. The opposite pattern was observed in the pasture and sugarcane areas.

Table 2. Soil contents of manganese (Mn), boron (B), copper (Cu), iron (Fe), and zinc (Zn) under agroforestry system, sugarcane, pasture, and native forest management systems in Uberaba, Minas Gerais, Brazil (2024).

Layer.	Mn	B	Cu	Fe	Zn
m			................................mg dm^{-3}................................		
			Agroforestry system		
0.00-0.10	3.77 aB	0.07 aB	0.62 aA	115.20 aB	1.80 aB
0.10-0.20	1.95 bC	0.07 aB	0.65 aA	62.92 bB	1.62 aB
0.20-0.30	1.72 bB	0.07 aB	0.67 aA	51.60 bB	0.72 bB
0.30-0.40	1.40 bC	0.07 aA	0.55 aA	30.22 cB	0.52 cB
			Sugarcane		
0.00-0.10	4.12 aB	0.05 aB	0.40 aB	18.60 aC	1.97 aB
0.10-0.20	4.32 aB	0.05 aB	0.32 aB	15.12 aC	1.12 bC
0.20-0.30	2.27 bB	0.05 aB	0.30 aB	10.07 aC	0.62 cB
0.30-0.40	1.30 cC	0.05 aA	0.32 aB	9.72 aC	0.55 cB
			Pasture		
0.00-0.10	3.45 aB	0.07 aB	0.45 aB	18.20 aC	0.40 aC
0.10-0.20	2.50 bC	0.05 aB	0.42 aB	12.62 aC	0.32 aD
0.20-0.30	2.25 bB	0.05 aB	0.37 aB	13.40 aC	0.30 aC
0.30-0.40	2.27 bB	0.02 aA	0.35 aB	9.12 aC	0.30 aC
			Native forest		
0.00-0.10	5.50 bA	0.20 aA	0.35 aB	156.52 cA	2.72 aA
0.10-0.20	8.67 aA	0.20 aA	0.37 aB	266.37 aA	2.22 bA
0.20-0.30	4.32 cA	0.20 aA	0.40 aB	222.27 bA	1.80 cA
0.30-0.40	4.05 cA	0.10 bA	0.42 aB	211.12 bA	1.12 dA
F-test	121.69**	25.90**	35.89**	1125.15**	450.65**
CV %	16.65	23.45	19.52	14.81	11.13

Means followed by the same lowercase letter in the column for the soil layers in the same management system and uppercase letters for the management systems at the same soil layer belong to the same group by the Scott-Knott test ($p < 0.05$). CV% = Coefficient of variation.

The native forest and AFS areas showed the highest Fe contents, ranging from 156.52 to 266.37 mg dm^{-3} and 30.22 to 115.20 mg dm^{-3}, respectively, while the sugarcane and pasture areas ranged from 9.12 to 18.60 mg dm^{-3} (Table 2). These elevated Fe values are associated with the predominant soil type in the area (*Latossolo Vermelho distrófico*) and the presence of organic substances, which, according to Barbosa Filho et al. (1994), tend to increase Fe solubility through biogeochemical cycles. Cunha et al. (2012) also link these high Fe contents to the quality and biological activity induced by surface-deposited organic matter, a common condition in native forest environments.

Fe contents in the AFS can be considered high, except in the deepest layer (Alvarez et al., 1999), and are associated with the predominance of *Latossolos* in the region, which are rich in Fe oxides, as well as the variability in the distribution of organic residues along the planting rows. Although the AFS outperformed the pasture and sugarcane areas, it still presented lower Fe values than the native forest area ($p < 0.05$). Silva Neto et al. (2008) emphasized that Cerrado soils are rich in iron (Fe) due to the intense weathering of the parent material. The highest zinc (Zn) contents were recorded in the native forest area, followed by the AFS and sugarcane areas. A statistically significant difference ($p < 0.05$) was observed only at the 0.10–0.20 m layer, with the highest value found in the native forest area (Table 2). These contents result from the continuous deposition of organic residues, which is explained by the high presence of organic substances that enhance the solubility of this element (Barbosa Filho et al., 1994).

The soil bulk density (Bd) results indicate that compaction occurred only in the sugarcane area, with values ranging from 1.74 to 1.86 kg dm^{-3} at depths between 0.10 and 0.40 m (Table 3).Considering the critical bulk density (Bd) value for root development is 1.55 kg dm^{-3} for soils with clay content between 200 and 550 g kg^{-1} (Reinert et al., 2008) and 1.65 kg dm^{-3} for sandy soils (Araújo et al., 2004), it can be concluded that root growth restriction is occurring only in the sugarcane area. In contrast, the AFS and pasture areas showed values close to this critical threshold, ranging from 1.48 to 1.65 kg dm^{-3}. In the native forest area, bulk density values ranged from 1.13 to 1.40 kg dm^{-3}, indicating no physical limitation to root system development.

According to Lima et al. (2017), bulk density (Bd) tends to increase with soil depth, likely due to lower organic matter content, reduced aggregation, fewer roots, and compaction caused by the weight of the overlying layers. In the native forest and AFS systems, the lower bulk density values recorded in the 0–0.10 m layer are attributed to the accumulation of organic residues on the surface, high root variability, and higher SOM and TOC contents found in these two areas.

The values obtained for total organic carbon (TOC) and soil carbon stock (Cstock) showed that the native forest area had significantly higher contents than the other areas, ranging from 26.12 to 47.90 g kg^{-1} and 44.39 to 139.16 Mg ha^{-1}, respectively.

Table 3. Soil bulk density (Bd), total organic carbon (TOC), and carbon stock (Cstock) at different soil layers under agroforestry system (AFS), sugarcane (Sugarcane), pasture (PA), and native forest (NF) management systems in Uberaba, Minas Gerais, Brazil (2024).

Soil layer	Bd	TOC	Cstock
m	kg dm^{-3}	g kg^{-1}	Mg ha^{-1}
		Agroforestry system	
0.00-0.10	1.48 bC	12.70 aB	18.80 cB
0.10-0.20	1.63 aB	9.42 bB	29.80 bB
0.20-0.30	1.64 aB	10.20 bB	48.67 aB
0.30-0.40	1.65 aB	7.12 bB	46.46 aB
		Sugarcane	
0.00-0.10	1.86 aA	6.12 aC	11.98 cC
0.10-0.20	1.80 aA	5.35 aC	19.91 bC
0.20-0.30	1.76 bA	4.80 aC	24.95 aC
0.30-0.40	1.74 bA	4.35 aB	32.00 aC
		Pasture	
0.00-0.10	1.61 aB	6.92 aC	10.83 cC
0.10-0.20	1.66 aB	5.42 aC	17.76 bC
0.20-0.30	1.59 aB	4.97 aC	23.69 aC
0.30-0.40	1.59 aB	4.67 aB	29.71 aC
		Native forest	
0.00-0.10	1.13 cC	47.90 aA	44.49 cA
0.10-0.20	1.40 aC	42.50 bA	86.40 bA
0.20-0.30	1.37 aC	34.12 cA	139.16 aA
0.30-0.40	1.24 bD	26.12 dA	80.35 bA
F test	247.85**	66.49**	263.12**
CV %	3.80	14.45	18.67

Means followed by the same lowercase letter in the column for the soil layers in the same management system and uppercase letters for the management systems at the same soil layer belong to the same group by the Scott-Knott test ($p < 0.05$). CV% = Coefficient of variation.

The AFS area followed, with values ranging from 7.12 to 12.70 g kg^{-1} and 18.80 to 48.67 Mg ha^{-1} at the 0–0.40 m soil layer. In the sugarcane and pasture areas, values were similar. Overall, there was a trend of decreasing TOC and increasing Cstock with depth (Table 3). The high TOC values in the native forest area can be attributed to the accumulation of litterfall on the soil surface, a process that also occurs to a lesser extent in the AFS, sugarcane, and pasture areas, which explains the higher values observed in the 0–0.10 m soil layer.

In the native forest and AFS systems, higher Cstock was observed in the 0.20–0.30 m layer, whereas in the sugarcane and pasture areas, the highest values were found at the 0.30–0.40 m depth. In addition to the continuous input of organic residues in both native forest and AFS, the higher root concentration in these layers helps explain the greater carbon storage. A similar pattern was observed in the sugarcane and pasture areas, which is related to the fibrous root system typical of these grasses.

Similar results were reported by Rufino et al. (2022), who evaluated soil carbon stocks in agroecosystems and secondary vegetation. They observed that carbon content varies with depth, particularly in samples collected from the surface layer (0–0.20 m). The authors noted an increase in carbon stock in the 0.20–0.40 m and 0.40–0.60 m layers due to the accumulation of organic matter in these layers regardless of the type of environment studied. When comparing TOC contents in conventional tillage systems and agroecological no-tillage systems, Loss et al. (2015) reported higher carbon content in the surface soil layer, particularly under no-tillage, due to the input of plant residues on the soil surface and the absence of soil disturbance. It is well established that SOM directly influences soil quality, resulting in lower bulk density (Bd) and greater aggregate stability (Loss et al., 2009a; b). In the present study, the AFS and native forest systems were the only ones that showed lower Bd values in the surface layer, which is associated with higher TOC (Table 3) and SOM (Table 2) contents. Land-use systems with higher SOM and lower bulk density provide better physical soil conditions, including improved aggregation and porosity (Loss et al., 2015).

It was found that the AFS had the highest Cstock among the areas under land use, although still significantly lower than that of the native forest area. Nevertheless, it was the managed system with the highest recorded value. This result was achieved after only five years of adopting agroecological management practices, during which the amount of stored carbon increased compared to the sugarcane and pasture systems the previous land used before the AFS implementation (Table 3). The continuous input of organic material on the soil surface along the planting rows in the AFS, the preservation of soil structure due to the absence of machinery traffic, and the reduced use of highly soluble inorganic fertilizers when compared to the sugarcane area create favorable conditions for maintaining the diversity of soil organisms.

These are factors highlighted in other studies that demonstrate improvements in soil quality under this system, ranking just below the native forest area (Loss et al., 2009a; 2012; Barbosa et al., 2020).

Considering the native forest area as the original soil condition without anthropogenic interference (SI = 1.0), SI values greater than 1.0 were observed in the AFS, sugarcane, and pasture areas, indicating an increase in bulk density. This suggests a decline in soil physical quality as some compaction occurs, reducing soil porosity (Table 4). Generally, areas with native vegetation and balanced ecosystems exhibit high soil carbon stock (Cstock) values, which can be considered effective strategies for increasing soil carbon in the short term. This was observed in the AFS evaluated in this study, as it is the area with the shortest time since system implementation. This finding is also supported by Iwata et al. (2012), who highlighted the potential of such systems to sequester and accumulate carbon in the soil.

Table 4. Sensitivity index (SI) values for soil bulk density (Bd), total organic carbon (TOC), and carbon stock (Cstock) under agroforestry, sugarcane, and pasture management systems, using native forest as the reference for the original soil condition in Uberaba, Minas Gerais, Brazil (2025).

Soil layer	Bd	TOC	Cstock
m		Agroforestry system	
0.00-0.10	1.31	0.27	0.42
0.10-0.20	1.16	0.22	0.34
0.20-0.30	1.20	0.30	0.35
0.30-0.40	1.33	0.27	0.58
		Sugarcane	
0.00-0.10	1.65	0.13	0.27
0.10-0.20	1.29	0.13	0.23
0.20-0.30	1.28	0.14	0.18
0.30-0.40	1.40	0.17	0.40
		Pasture	
0.00-0.10	1.42	0.14	0.24
0.10-0.20	1.19	0.13	0.21
0.20-0.30	1.16	0.15	0.17
0.30-0.40	1.28	0.18	0.37

According to Torres et al. (2015), the increase in bulk density is related to the rearrangement of soil particles shortly after the soil is disturbed for crop planting or due to compaction, likely occurring in this study. However, with increasing TOC contents in the soil, a reduction in bulk density may occur, increasing soil porosity.

The SI values calculated for TOC and Cstock in the AFS, sugarcane, and pasture areas showed a marked decrease in both parameters, indicating a decline in quality compared to the native forest area. This pattern is consistent with the findings reported by Araújo et al. (2007), who observed that areas under more intensive land use induce greater alterations in soil structure, resulting in higher bulk density values and lower TOC and Cstock contents.

4. Conclusions

It was observed that the agroforestry system and native forest areas exhibited the best chemical soil quality, with higher contents of soil organic matter, phosphorus (P), and potassium (K) in the surface layers, as well as higher total organic carbon (TOC) at the 0.00–0.10 m layer (12.70 and 47.90 g kg^{-1}) and greater carbon stock (Cstock) at the 0.20–0.30 m layer (48.67 and 139.16 g kg^{-1}), respectively.

The AFS, with only five years since implementation, provided higher nutrient contents of P (14.47 mg dm^{-3}), K (1.12 $mmol_c$ dm^{-3}), Ca (23.07 $mmol_c$ dm^{-3}), and Mg (6.47 $mmol_c$ dm^{-3}) at the 0.00–0.10 m soil layer, as well as higher TOC and Cstock at all layers when compared to the sugarcane and pasture systems.

The high bulk density in the sugarcane area indicates that the soil is compacted and restricts normal root development. The sensitivity index (SI) for TOC and Cstock shows that all systems experienced a decline in soil quality upon entering food production systems.

Authors' Contribution

João Vitor Sicari Martins and José Luiz Rodrigues Torres conceived the study, submitted it as part of a Master's thesis project, participated in all stages of its development, and prepared the initial draft of the manuscript. Álisson Borges Leal and Daiane Oliveira Teixeira contributed to sample collection and processing in the soil physics laboratory. Valdeci Orioli Júnior and

Daniel Pena Pereira critically reviewed and revised the entire manuscript. Arcângelo Loss and Dinamar Márcia da Silva Vieira were responsible for the statistical analyses, supported data tabulation and interpretation, and formatted the manuscript in accordance with the journal's guidelines.

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