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Cropping and soil management systems effects on soil organic matter fractions in diversified agricultural fields in the Cerrado

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ABSTRACT: Soil organic matter (SOM) dynamics can be significantly influenced by various cultivation practices, particularly under environmental and edaphic conditions that enhance and accelerate the transformations of organic materials such as straw, root biomass, and organic fertilizers. This study aimed to evaluate the impact of different cultivation and soil management systems on SOM fractions in agricultural areas of the Cerrado Goiano region. The research was conducted across three areas with diverse production systems: 1) BV area, including soybean monoculture (SM01), integrated crop-livestock-forest (ICLF01), pasture (PA01), and Cerrado vegetation (NV01); 2) ML area, featured soybean-corn monoculture succession (SMS02), agroforestry (AF02), pasture (PA02), and native Cerrado vegetation (NV02); and 3) IF area, comprised soybean-corn succession (SMS03), integrated livestock-forest (ILF03), pasture (PA03), and native Cerrado vegetation (NV03). Disturbed and undisturbed soil samples were collected from two layers: 0.00-0.05 and 0.05-0.10 m. Samples were analyzed for total organic carbon, carbon storage, and SOM physical (granulometric and densimetric) and chemical (fulvic acid, humic acid, and humin) fractionations of soil organic matter (SOM). Additionally, water-floatable light organic matter (LOM), the carbon management index, and its components were determined. Soil organic matter fractions were similarly influenced by the characteristics of cultivation and management systems. However, there were more pronounced differences between systems in the BV area compared to the ML and IF areas. Among the parameters studied, LOM proved to be the most efficient and effective in distinguishing SOM input across different cultivation and soil management systems, particularly in pasture systems.

Keywords: organic carbon, forms of land use, soil conservation practices, organic fractions.

INTRODUCTION

Cerrado is the second largest Brazilian biome, surpassed only by the Amazon. It spans approximately 200 million hectares, accounting for about 25 % of the Brazil's territory (IBGE, 2004). Currently, the Cerrado is among the largest cultivated areas in the world, primarily producing grain crops such as corn, beans, soybeans, and sunflower (IBGE, 2010). Located in central Brazil, Cerrado covers roughly 97.0 % of the state of Goiás (IBGE, 2004). Numerous studies have been conducted in this region, focusing on the dynamics of chemical properties like carbon and nitrogen levels across various land use and management systems, as well as in the original Cerrado vegetation (Fontana et al., 2006; Rangel et al., 2007; Siqueira Neto et al., 2009; Rossi et al., 2012; Guareschi et al., 2012; Loss et al., 2016; Nanzer et al., 2019; Pinto et al., 2022; Oliveira et al., 2023).

Cerrado lands were typically used as extensive pastures until the 1970's (Loss et al., 2012; 2013a) and were subsequently converted into annual crops using the soil conventional preparation system, which involves plowing and harrowing. Soil conservation techniques augmented the no-tillage system to replace conventional soil preparation system. More recently, the no-tillage system has been combined with integrated production systems such as the integrated crop-livestock-forest (ICLF) system.

Conservation agriculture is a production system mostly centered on minimal soil disturbance, maintenance of the soil permanent vegetation cover with live plants or their residues, and crop diversification (Bayer and Dieckow, 2023), but also includes terraces and contour lines, road adjustments, and drainage channels. No-tillage system is largely defined by these three pillars, which enhance production sustainability, soil biodiversity, natural biological processes, and the efficient use of water and nutrients (FAO and ITPS, 2020). In this context, the ICLF, crop-livestock (ICL), and livestock-forest (ILF) systems are closely associated with conservation agriculture.

We also have agroforestry (AF) systems, a combination of forest species with agricultural crops, related or not to livestock farming. Agroforestry systems, associated with arboreal forest components and large biodiversity, offer constant deposition of plant residues, maintaining soil organic matter (SOM) and enhancing physical, chemical, and biological soil properties (Iwata et al., 2012).

These systems have advantages such as: a) improved physical, chemical, and biological soil conditions; b) increased cycling and efficient nutrient use by plants due to grass, legume, and forest species rotation or intercropping; c) increased competitiveness of rural enterprises due to regular fodder, grain, and wood supply; and d) income diversification and stabilization in rural properties, letting the recovery of degraded areas with pastures (Gazolla et al., 2015; Bernardi et al., 2023). These systems significantly improve soil quality by increasing crop productivity, improving the quality of forage for animals, and providing ecosystem services such as carbon sequestration and groundwater recharge (Salton et al., 2011; Beutler et al., 2016; Vilela et al., 2016; Loss et al., 2016; Bernardi et al., 2023).

Soil quality is measured by parameters indicating the state of ecosystem environmental or sustainability condition. The SOM is a central indicator of soil quality and health (FAO and ITPS, 2020; Bernardi et al., 2023). It regulates water and air content in the soil, influencing its temperature and it is actively involved in ion exchange reactions that determine the level of soil fertility (Blum et al., 2018). Effects of different management systems become more evident if we consider SOM quality. The SOM fragmentation into granulometric, densimetric, or chemical fractions, among others, helps control the effect of management, the degree of transformation, and SOM cycling and lability (Cerli et al., 2012).

Different organic carbon fractions in the soil have distinctive chemical, physical, and morphological features, with their distribution indicating SOM quality (Canellas et al., 2003). These fractions can be used to evaluate land use changes resulting from management, leading to more accurate recommendations. These fractions include carbon from SOM humic fractions (Castro et al., 2016; Loss et al., 2013a), oxidizable carbon use (Loss et al., 2013b), carbon from granulometric SOM fractions (Loss et al., 2012; Rossi et al., 2012), and carbon from water-floatable light organic matter (LOM) (Loss et al., 2011, 2012; Guareschi et al., 2012). This study aimed to evaluate the impact of different cultivation and soil management systems on SOM fractions in agricultural areas in the Cerrado Goiano biome region.

MATERIALS AND METHODS

The study was conducted in three different areas of the Cerrado biome in the state of Goiás, in central-western Brazil (Figure 1). The region has, according to Köppen classification system, an Aw tropical wet-dry climate with two well-defined seasons: dry winter (May–September) and rainy summer (October–April). Average annual precipitation is 1,700 mm yr^{-1}, and the annual average temperature is 24.2 °C (Ribeiro et al., 2023). The principal soil class in the study area is *Latossolos Vermelho-Amarelo Distróficos* with clay content above 500 g kg^{-1} (Santos et al., 2018), which corresponds to Oxisol, according to the USA Soil Taxonomy class (Soil Survey Staff, 2014), or Ferralsol in the FAO classification system (IUSS Working Group WRB, 2015).

The three study areas were in the following properties: i) Boa Vereda farm, in Inaciolândia (BV area); ii) Mata do Lobo farm, in Rio Verde (ML area); and iii) Instituto Federal Goiano, *campus* of Morrinhos, in Morrinhos (IF area), all in the state of Goiás, Brazil. The areas have the same relief, climate, and soil class; and agricultural activities are conducted using diversified production systems (Figure 1).

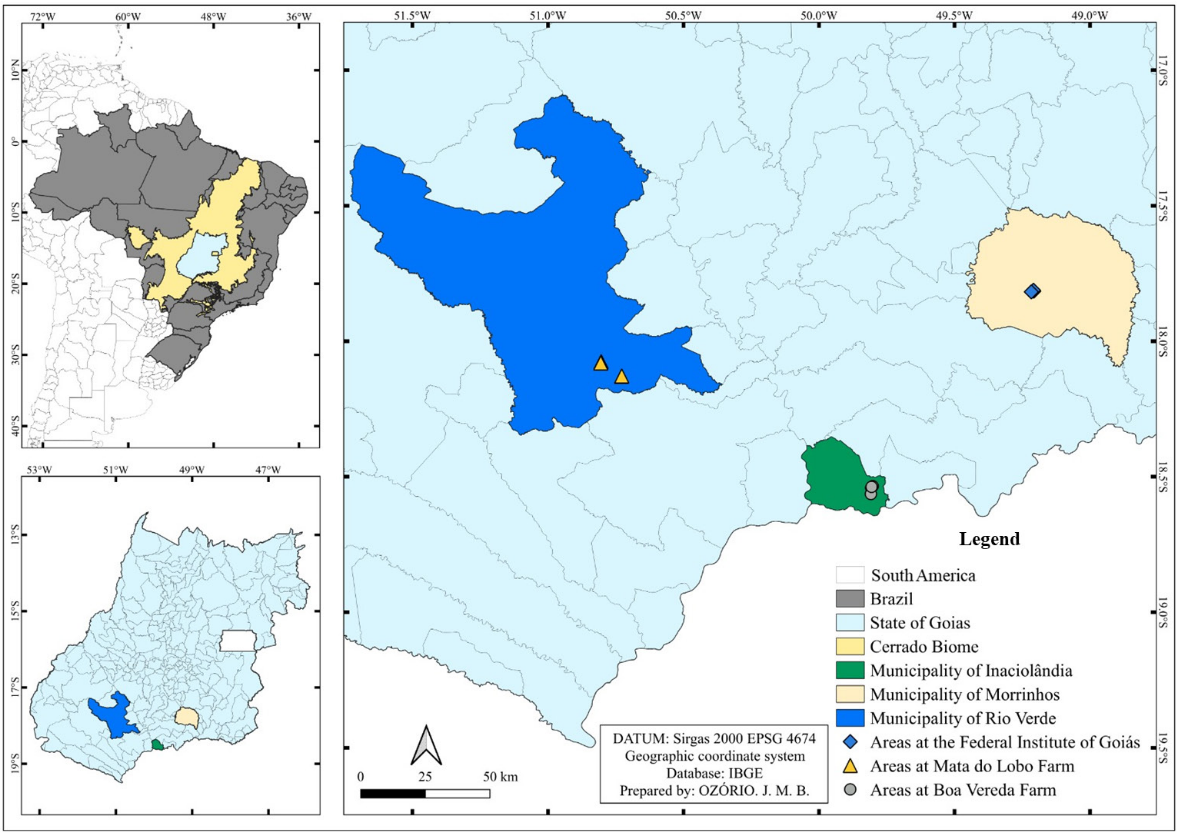

Figure 1. Location of the three study areas (Boa Vereda, Mata do Lobo, and Instituto Federal Goiano) in Goiás, Brazil.

The BV area includes: a) soybean monoculture (SM01); b) integrated crop-livestock-forest (ICLF01) with soybeans, pasture, and eucalyptus trees; c) degraded pasture (PA01); and d) Cerrado vegetation (NV01). The ML area includes: a) sustainably managed soybean-corn succession (SMS02); b) agroforestry (AF02) with coffee as main crop; c) recently fertilized pasture (PA02); and d) Cerrado vegetation (NV02). The IF area includes: a) soybean-corn succession (SMS03); b) integrated livestock-forest (ILF03) with eucalyptus trees combined with sunflower and Piatã grass intercropping; c) pasture (PA03) with lime application; and d) Cerrado vegetation (NV03). Table 1 describes the diversified agricultural production systems used.

A completely randomized experimental design was used for the 12 different forms of land use analyzed, with each of the four 300 m^2 plots representing a pseudoreplication. Disturbed and undisturbed soil samples were collected in November 2022, at 0.00-0.05 and 0.05-0.10 m layers, totaling 96 sampling units (12 forms of land use × 4 pseudoreplications × 2 layers).

Disturbed samples were air-dried, disaggregated, and sieved through a 2.00 mm mesh to obtain the air-dried fine earth (ADFE) fraction used for SOM analyses. Undisturbed samples were collected using a volumetric ring (Kopeck ring) to determine soil bulk density (BD) (Mg m^{-3}), according to Teixeira et al. (2017), and then carbon storage was calculated.

Total organic carbon (TOC) content was determined in the soil by wet oxidation of the SOM with potassium dichromate ($K_2Cr_2O_7$) at a concentration of 0.167 mol L^{-1} in sulfuric medium, and quantified by titration using a ferrous ammonium sulfate solution ($(NH_4)_2Fe(SO_4)_2 \times 6H_2O$) at a concentration of 0.2 mol L^{-1} as titrant, and ferroin as indicator (Yeomans and Bremner, 1988).

The BD (Mg m^{-3}) was quantified by the Kopeck ring method (Teixeira et al., 2017). Total organic carbon and BD values were used to calculate carbon storage (CSt) by the equivalent layer method (Veldkamp, 1994; Carvalho et al., 2009). This study considered soil layers equivalent to the Cerrado biome as a reference for storage calculations using the equivalent layer method, representing the original soil condition. The CSt was calculated for each soil layer using equation 1, proposed by Fernandes and Fernandes (2013):

$$\text{CSt} = \frac{\text{TOC} \times \text{SD} \times \left(\frac{\text{SDref}}{\text{SD}} \times t\right)}{10} \quad \text{Eq. 1}$$

in which: CSt is the organic carbon storage in a given layer (Mg ha^{-1}); TOC is the total organic carbon at the sampled layer (g kg^{-1}); SD is soil bulk density at the sampled layer (Mg m^{-3}); SDref is the soil density at the sampled layer in the reference area (Mg m^{-3}); and *t* is the thickness of the considered layer (cm).

Physical granulometric fractionation was conducted using 20 g of ADFE added with 60 mL of sodium hexametaphosphate solution $(NaPO_3)_n$ 5 g L^{-1}, which was homogenized for 15 h in a horizontal shaker (Cambardella and Elliot, 1992). Then, the suspension was sieved through a 53 µm mesh using a water jet to remove the silt and clay fractions. The material retained on the sieve, which consists of particulate organic matter (POM) with the sand fraction, was dried in an oven at 60 °C, and subsequently weighted, crushed in a porcelain mortar, and analyzed for carbon content in the POM fraction (C content of the POM), according to Yeomans and Bremner (1988).

The material that passed through the 53 µm mesh sieve consists of mineral-associated organic matter (MAOM), which includes the organic matter associated with the silt and clay fractions. This MAOM content is calculated as the difference between TOC and C content of the POM, with adjustments made as necessary. After analyzing the C content of the POM, a calculation was made using the percentage of material retained on the 53 µm sieve (POC), as shown in equation 2. After correction, the C content of the MAOM (MAOC) was calculated using the difference between the TOC and POC contents. Carbon management index (CMI) and the management index of its respective components were calculated according to the original proposal by Blair et al. (1995), as shown in equations 3, 4, 5, and 6.

$$POC = \frac{C\ of\ the\ POM \times POM}{1000}$$ Eq. 2

in which: POC is the particulate organic carbon content corrected according to the mass of the sand retained on the 53 μm sieve (g kg^{-1}); C of the POM is the organic carbon content in the particulate fraction (g kg^{-1}); and POM is the particulate organic matter mass in the ADFE sample (g kg^{-1}).

$$CSI = \frac{TOC\ treat}{TOC\ ref}$$ Eq. 3

$$Lab = \frac{POC}{MAOC}$$ Eq. 4

$$LabI = \frac{Lab\ treat}{Lab\ ref}$$ Eq. 5

$$CMI = CSI \times LabI \times 100$$ Eq. 6

Table 1. Location of the studied areas and cultivation and soil management systems implemented in the Cerrado region of Goiás, Brazil

Areas	City	Cultivation and soil management systems
Boa Vereda (BV) Farm	Inaciolândia	Soybean monoculture (SM01): The system used to be a degraded pasture, and since 2020, soybeans have been grown using a conventional tillage system, turning the soil before sowing. During this turning, 2 Mg of lime were incorporated. When the soybeans were sown, a base fertilizer of 350 kg of 08-28-16 was used. Integrated crop-livestock-forest (ICLF01): The system has been grazing for many years, without any investment in fertilization. The area was initially sowed soybeans by desiccating the pasture and correcting it with 2 Mg of lime. Soybean crop was fertilized with 350 kg of 08-28-16. When the soybean crop was harvested, eucalyptus was planted. In the next harvest, the soybean crop was planted between the eucalyptus rows, with subsequent sowing of piatã fodder. The system has continued for four years with intercropping of eucalyptus and forage. Pasture (PA01): System with old pasture without any history of fertilization or investment. There are high signs of degradation and compaction in the system. Cerrado vegetation (NV01): Forest fragment with no human intervention. Considered a "Cerrado típico".
Mata do Lobo (ML) Farm	Rio Verde	Soybean-corn succession (SMS02): System with soybeans and corn grown in a semi-organic system (only the herbicide and mineral fertilizer were not removed from the system). Organic + mineral fertilization were used. Soybeans with high production potential at the time the samples were taken. Agroforestry (AF02): The system began its integrated production format in 2017, in an area previously cultivated with monoculture soybeans. Covering an area of 50 ha, the owners are working with a wide range of crops in an integrated production format. System integrates Eucalyptus, Avocado, Jatobá, Cedar, Banana, Coffee, Guapuruvu, Papaya and Mombasa, respecting the individuality of each crop and seeking to promote the organic production of specialty coffees. Pasture (PA02): Monoculture pasture system adjacent to the agroforestry system. There was no signs of degradation, with ample animal support capacity and high investment in fertilization. Cerrado vegetation (NV02): Forest fragment without any human intervention. Considered a "Cerrado típico e fechado". High biomass production observed.
Teaching, Research and Extension Unit of the Instituto Federal Goiano (IF)	Morrinhos	Soybean-corn succession (SMS03): system has been cultivated over the last five years in succession with soybeans (first crop sown in October/November) and corn (sown in February/March). The system uses minimum tillage, with little soil disturbance. Fertilizers are used to correct and maintain the crops. Total of ± 300 kg of 00-20-20 is added to the soybean crop and ± 400 kg of 04-14-08 to the corn crop. In the corn crop, 150 kg of urea is also added as top dressing. Integrated livestock-forest (ILF03**)**: System with eucalyptus trees transplanted in January 2018, with a spacing of 10 × 4 m, where corn was sown between the branches in December 2018, followed by a consortium of sunflower and piatã forage in March 2019, since then the system has been a livestock-forest integration. Pasture (PA03): Pure *Urochloa Brizantha* pasture that has not been fertilized in any way for more than five years, at which point activities began in the IPF03 component adjacent to the area. Cerrado vegetation (NV03): Forest fragment adjacent to the ILF03, SMS03 and PA03 systems. This is a Cerrado fragment considered to be "Cerrado Ralo", with little tree composition.

in which: CSI is the carbon storage index; TOC treat is the total organic carbon content in the cultivation system; TOC ref is the total organic carbon content of the reference area; Lab is the SOM lability; POC is the particulate organic carbon content; MAOC is the mineral-associated organic carbon content; LabI is the lability index; Lab treat is the SOM lability in the cultivation system; Lab ref is the SOM lability in the reference area; and CMI is the carbon management index.

Densimetric physical fractionation (Sohi et al., 2001; Machado, 2002) measured only SOM free light fraction (FLF), which was extracted with sodium iodide solution (NaI) 1.80 Mg m^{-3} (± 0.02), using 5 g of ADFE weighed in 50 mL centrifuge bottles and added with 35 mL of NaI. Bottles were manually homogenized for 30 s to ensure that the less dense organic fractions were on top of the solution. Samples were then centrifuged at 18,000 rpm for 15 min at 18 °C for sedimentation of mineral particles in the soil.

Supernatant organic fraction (FLF) was suctioned with the NaI solution and separated by vacuum filtration (47 mm Sterifil Aseptic System, Millipore) using previously weighed glass fiber filters (47 mm, 2 microns, Whatman grade GF/A). This fraction was washed with distilled water to remove excess NaI from the sample and the filter, which were subsequently dried at 65 °C, weighed, and macerated in a mortar. Organic carbon content was determined in FLF of the SOM according to Yeomans and Bremner (1988).

Light organic matter (LOM) in water was obtained by the water flotation method (Anderson and Ingram, 1989; Loss et al., 2014). The LOM mass was quantified using 50 g of ADFE placed in a 250 mL beaker with 100 mL of 0.1 mol L^{-1} NaOH solution for 16 h. Subsequently, the suspension was homogenized with a glass rod, and the material sieved through a 250 µm mesh to remove the clay and silt fractions. The material retained on the sieve (LOM and sand) was quantitatively transferred back to the beaker, and the volume was completed with water.

All the floating material was sieved through a 250 µm mesh to separate the LOM and the sand fraction. Water was added again to the beaker, and manually homogenized until the remaining LOM was suspended to be sieved through the 250 µm mesh. This process was repeated until all floating material was removed. Organic material retained on the sieve (LOM) was transferred to previously weighed glass containers, which were placed in an oven at 65 °C until reaching a constant weight (~72 h), and then the whole set was weighed. The LOM is estimated by mass difference (Equation 7).

$$\text{LOM} = \frac{[(\text{Container} + \text{LOM}) - \text{Container}]}{\text{Msoil}} \qquad \text{Eq. 7}$$

in which: LOM is the light organic matter in water (g kg^{-1}); Container + LOM is the weight of the container + LOM (mg); Container is the weight of the container (mg); and Msoil is the weight of the ADFE used for extraction (g).

Humic substances were extracted and separated by the differential solubility of organic matter in basic or acidic media (fulvic and humic acids) and the residue (humin) (Benites et al., 2003). Organic carbon was determined in the fulvic acid fraction (FAF), humic acid fraction (HAF), and humin (HUM), also according to Yeomans and Bremner (1988). From these results, we calculated the percentage of each humic substances in relation to the TOC.

Results were statistically analyzed using a single-factor completely randomized design. Data were analyzed for normality of residuals and homoscedasticity using the Shapiro-Wilk and Bartlett tests, respectively. Parameters lacking normal distribution or homogeneity were transformed by the Box-Cox test and retested. Subsequently, the data underwent analysis of variance (ANOVA) with the F-test when the assumptions of normality and homogeneity were met (whether for transformed parameters or not), and their means were compared using the Tukey test.

Some parameters did not meet the assumptions for ANOVA, even after transformation, and were examined using the non-parametric Kruskal-Wallis test along with Fisher's Least Significant Difference (LSD) with Bonferroni adjustment. A principal component analysis (PCA) was also conducted based on the Pearson correlation matrix, using the evaluated properties. All statistical tests were conducted at a 5 % significance level using the R software (R Core Team, 2020) with the "Openxlsx", "ExpDes.pt", and "Ggplot2" packages.

RESULTS

Total organic carbon and carbon storage

In the BV area, TOC levels ranged between 21.99–40.87 g kg^{-1} at the 0.00-0.05 m layer, and 14.57–24.35 g kg^{-1} at the 0.05-0.10 m layer. While in the ML area, the levels ranged between 22.83–33.60 g kg^{-1} at the 0.00-0.05 m layer, and 14.62-23.44 g kg^{-1} at the 0.05-0.10 m layer. In the IF area, they ranged between 14.63-33.20 and 8.80-21.88 g kg^{-1} at the 0.00-0.05 and 0.05-0.10 m layers, respectively (Table 2). The TOC levels differed only in the BV area, where the ICLF01 and PA01 systems presented carbon contents similar to those quantified in the NV01 at the 0.05-0.10 m layer (Table 2). In the ML and IF areas, we highlight the SMS02, SMS03, ILF03, and PA03 systems, which increased TOC levels by 21 and 60 % (SMS02), 68 and 114 % (SMS03), 127 and 118 % (ILF03), and 84 and 149 % (PA03) at the 0.00-0.05 and 0.05-0.10 m layers, respectively, compared to their native vegetation systems.

Table 2. Carbon contents and their respective physical and chemical fractions (g kg^{-1}) with different cultivation and soil management systems in the Cerrado region, Goiás, Brazil.

Soil use	0.00-0.05 m layer					0.05-0.10 m layer			
	TOC	POC	MAOC	LOM	FLF	TOC	POC	MAOC	LOM
					BV area				
SM01	21.99 b	5.03	16.96 b	4.73 b	0.49	14.57 b	4.17	10.40 b	10.03
ICLF01	22.11 b	7.82	14.28 b	7.18 ab	0.36	17.81 ab	5.67	12.14 ab	6.13
PA01	22.83 b	6.40	16.42 b	13.48 a	0.32	18.65 ab	3.14	15.68 ab	9.65
NV01	40.87 a	10.53	30.34 a	9.20 ab	0.83	24.35 a	6.94	17.41 a	6.30
CV%	20.1 (1)	46.0 (1)	29.1 (2)	44.4 (1)	96.1 (2)	21.7 (1)	64.4 (1)	20.6 (1)	35.6 (1)
					ML area				
SMS02	33.60	11.17	22.43	20.85 ab	0.67	23.44	6.56 a	16.89	19.45
AF02	22.83	6.80	16.03	15.43 b	0.27	15.01	1.08 b	14.05	7.73
PA02	30.10	10.11	19.99	48.65 a	1.23	16.13	4.51 ab	11.63	17.48
NV02	27.60	8.19	19.41	21.34 ab	1.64	14.62	2.18 b	12.45	14.38
CV%	29.8 (1)	48.6 (1)	36.4 (1)	58.6 (1)	80.8 (2)	31.1 (1)	51.9 (1)	34.9 (1)	71.8 (2)
					IF area				
SMS03	24.61	4.10	21.86	14.60 bc	0.46	18.82	2.51	15.63	7.73
ILF03	33.20	4.92	28.28	18.00 ab	0.50	19.22	2.28	16.93	11.35
PA03	26.87	3.71	23.75	36.73 a	0.65	21.88	1.57	20.31	15.20
NV03	14.63	2.21	12.42	5.88 c	0.16	8.80	0.34	8.47	4.48
CV%	53.1 (1)	55.6 (1)	70.5 (1)	53.5 (2)	67.4 (1)	78.2 (1)	78.9 (1)	90.5 (2)	53.2 (1)

Averages followed by different lowercase letters differ between cultivation and soil management systems. (1) ANOVA + Tukey's test without data transformation at 5 % significance level; and (2) ANOVA + Tukey's test with data transformation at 5 % probability level. BV: Boa Vereda farm; ML: Mata do Lobo farm; IF: *Instituto Federal Goiano;* SM01: Soybean monoculture in the BV area; ICLF01: Integrated crop-livestock-forest in the BV area; PA01: Pasture in the BV area; NV01: Cerrado vegetation in the BV area; SMS02: Soybean-corn succession in the ML area; AF02: Agroforestry in the ML area; PA02: Pasture in the ML area; NV02: Cerrado vegetation in the ML area; SMS03: Soybean-corn succession in the IF area; ILF03: Integrated livestock-forest in the IF area; PA03: Pasture in the IF area; NV03: Cerrado vegetation in the IF area; TOC: Total organic carbon; POC: Particulate organic carbon; MAOC: mineral-associated organic carbon; LOM: Light organic matter in water; FLF: Carbon in the light-free fraction; and CV: Coefficient of variation.

The CSt results (Table 3) are corroborated by TOC results (Table 2). Higher CSt results were found only in the BV NV01 system, at the 0.00-0.05 m layer (~ 22 Mg ha^{-1}) (Table 3). In the ML and IF areas, some systems increased CSt values compared to Cerrado vegetation, although with no statistical difference, with increases of 22 and 59 % in SMS02, 70 and 115 % in SMS03, 130 and 119 % in ILF03, and 85 and 150 % in PA03 at the two layers evaluated.

Physical granulometric fractionation

The POC (particulate organic carbon) ranged between 5.03-10.53 g kg^{-1} (0.00-0.05 m) and 3.14-6.94 g kg^{-1} (0.05-0.10 m) in BV; between 6.80-11.17 g kg^{-1} (0.00-0.05 m) and 1.08-6.56 g kg^{-1} (0.05-0.10 m) in ML; and between 2.21-4.92 g kg^{-1} (0.00-0.05 m) and 0.34-2.51 g kg^{-1} (0.05-0.10 m) in IF. While MAOC (mineral-associated organic carbon) values varied between 14.28-30.34 g kg^{-1} (0.00-0.05 m) and 10.40-17.41 g kg^{-1} (0.05-0.10 m) in BV; 16.03-22.43 g kg^{-1} (0.00-0.05 m) and 11.63-16.89 g kg^{-1} (0.05-0.10 m) in ML; and 12.42-28.29 g kg^{-1} (0.00-0.05 m) and 8.47-20.31 g kg^{-1} (0.05-0.10 m) in IF. Only the BV and ML areas showed significant difference, mainly in the subsurface layer, with higher POC contents in the SMS02 and PA02 systems at the 0.05-0.10 m layer; and higher MAOC contents in the NV01 system at the 0.00-0.10 m layer, and in the ICLF01 and PA01 systems at the 0.05-0.10 m layer (Table 2).

Overall, MAOC levels exceeded POC levels across all systems and layers studied. The IF systems showed substantial increases in both POC and MAOC fractions compared to native vegetation, highlighting the impact of intensive farming practices on soil organic carbon dynamics (Table 2). However, POC levels increased 86 % (SMS03), 123 % (ILF03) and 68 % (PA03) on the surface; and 638 % (SMS03), 571 % (ILF03), and 362 % (PA03) in the subsurface in IF systems compared to Cerrado vegetation. The same systems showed increased MAOC fraction levels of 76 and 85 % (SMS03), 128 and 100 % (ILF03), and 91 and 140 % (PA03) at both evaluated layers, respectively, compared to Cerrado vegetation.

Densimetric physical fractionation and water-floatable LOM

Carbon content exhibited no difference between systems in SOM FLF (Table 2). The analysis of the mass of water-floatable LOM (g) showed that this organic fraction was more efficient in showing differences between soil use and management systems, especially in the topsoil. Pasture systems (PA01, PA02, and PA03) showed the highest LOM levels at the 0.00-0.05 m layer, followed by the BV ICLF01 system, ML SMS02 and NV02 systems, and IF ILF03 system. There were no LOM content differences between systems at the 0.05-0.10 m layer (Table 2).

Table 3. Carbon storage values (CSt,) in different cultivation and soil management systems in the Cerrado region, Goiás, Brazil.

Soil use	BV area		Soil use	ML area		Soil use	IF area	
	0.00-0.05 m	0.05-0.10 m		0.00-0.05 m	0.05-0.10 m		0.00-0.05 m	0.05-0.10 m
	Mg ha^{-1}							
SM01	12.19 b	8.85	SMS02	16.40	13.71	SMS03	15.80	12.08
ICLF01	12.27 b	10.71	AF02	11.22	8.74	ILF03	21.45	12.29
PA01	12.71 b	11.27	PA02	14.74	9.45	PA03	17.22	14.09
NV01	22.50 a	14.62	NV02	13.48	8.64	NV03	9.31	5.62
CV%	14.0(1)	23.8(1)	CV%	30.9(1)	27.3(1)	CV%	53.8 (1)	78.9(1)

Averages followed by different lowercase letters differ between cultivation and soil management systems. (1) ANOVA + Tukey's test without data transformation at 5 % significance level; and (2) ANOVA + Tukey's test with data transformation at 5 % probability level. BV: Boa Vereda farm; ML: Mata do Lobo farm; IF: Instituto Federal Goiano; SM01: Soybean monoculture in the BV area; ICLF01: Integrated crop-livestock-forest in the BV area; PA01: Pasture in the BV area; NV01: Cerrado vegetation in the BV area; SMS02: Soybean-corn succession in the ML area; AF02: Agroforestry in the ML area; PA02: Pasture in the ML area; NV02: Cerrado vegetation in the ML area; SMS03: Soybean-corn succession in the IF area; ILF03: Integrated livestock-forest in the IF area; PA03: Pasture in the IF area; NV03: Cerrado vegetation in the IF area; and CV: Coefficient of variation.

Chemical fractionation

In SOM HUM substances (Table 4), carbon content levels behaved similarly to TOC, POC, MAOC, and CSt (Tables 2 and 3). HUM carbon content and HUM proportion in TOC (%HUM) showed no statistical difference between systems (Table 4).

Table 4. Carbon content of humic fractions and their proportions in total organic carbon (and %) in different cultivation and soil management systems in the Cerrado region, Goiás, Brazil

Soil use	HUM	HAF	FAF	%HUM	%HAF	%FAF
	g kg^{-1}			%		
			BV area 0.00–0.05 m layer			
SM01	1.56	4.24	7.66 a	6.88	19.64 a	35.67 a
ICLF01	1.30	4.81	8.27 a	5.65	22.08 a	37.49 a
PA01	2.00	2.39	6.25 ab	5.32	6.49 b	14.61 b
NV01	2.14	3.21	2.45 b	9.50	14.40 ab	10.85 b
CV%	49.9(1)	40.7(3)	41.7(2)	52.1(1)	31.8(1)	38.5(2)
			BV area 0.05-0.10 m layer			
SM01	1.34	4.04 a	6.96	10.36	27.74 a	44.89
ICLF01	1.78	3.41 ab	6.08	9.85	19.48 b	33.30
PA01	2.62	1.88 b	3.76	11.43	9.02 c	15.11
NV01	2.29	2.11 b	2.23	13.18	11.44 bc	12.31
CV%	32.4(1)	31.4(1)	58.7(1)	50.7(1)	28.1(2)	54.7(2)
			ML area 0.00-0.05 m layer			
SMS02	2.86	2.95	2.26 bc	8.91	8.61	7.00 b
AF02	1.56	3.98	1.61 c	7.84	19.27	7.82 b
PA02	2.66	3.54	3.48 ab	9.37	12.60	12.95 ab
NV02	2.38	3.82	5.17 a	8.72	13.92	18.55 a
CV%	28.4(3)	32.7(1)	29.4)	36.6(1)	40.5(2)	36.6(1)
			ML area 0.05-0.10 m layer			
SMS02	2.51	3.20	2.74	10.49	14.00	12.59
AF02	1.25	1.59	2.23	9.07	12.11	17.38
PA02	2.20	2.66	3.15	14.70	16.97	19.01
NV02	2.33	2.56	3.53	17.06	17.39	24.01
CV%	35.8(1)	53.7(1)	40.1(1)	42.4(1)	55.4(1)	39.3(1)
			IF area 0.00-0.05 m layer			
SMS03	2.55 a	2.86 a	3.20 a	10.41 a	11.86 a	13.44 a
ILF03	2.55 a	2.76 a	3.53 a	9.54 a	11.61 a	12.88 a
PA03	2.02 a	2.30 a	3.22a	9.94 a	14.07 a	14.59 a
NV03	2.09 a	2.14 a	2.79 a	15.69 a	17.13 a	19.93 a
CV%	29.3(1)	42.6(1)	49.4(1)	49.0(1)	69.7(1)	45.7(1)
			IF area 0.05-0.10 m layer			
SMS03	2.24 a	2.15 a	2.90 a	12.95 a	12.51 a	17.44 a
ILF03	2.02 a	2.75 a	3.00 a	13.95 a	19.60 a	20.16 a
PA03	1.96 a	2.26 a	3.19 a	17.09 a	23.35 a	27.73 a
NV03	2.02 a	1.48 a	3.14 a	24.75 a	16.78 a	37.74 a
CV%	20.4 1)	32.5 1)	17.2 1)	54.3 1)	69.3 3)	54.5 1)

Averages followed by different lowercase letters differ between cultivation and soil management systems. (1) ANOVA + Tukey's test without data transformation at 5 % significance level; (2) ANOVA + Tukey's test with data transformation at 5 % probability level; and (3) Teste de Kruskal-Wallis + diferença mínima significativa de Fisher (LSD) com correção de Bonferroni. BV: Boa Vereda farm; ML: Mata do Lobo farm; IF: Instituto Federal Goiano; SM01: Soybean monoculture in the BV area; ICLF01: Integrated crop-livestock-forest in the BV area; PA01: Pasture in the BV area; NV01: Cerrado vegetation in the BV area; SMS02: Soybean-corn succession in the ML area; AF02: Agroforestry in the ML area; PA02: Pasture in the ML area; NV02: Cerrado vegetation in the ML area; SMS03: Soybean-corn succession in the IF area; ILF03: Integrated livestock-forest in the IF area; PA03: Pasture in the IF area; NV03: Cerrado vegetation in the IF area; HUM: Humin carbon; HAF: Humic acid carbon; FAF: Fulvic acid carbon; and CV: Coefficient of variation.

As for carbon content in HAF, only the BV SM01 and ICLF01 systems showed higher HAF levels at the 0.00-0.05 m layer. As regards carbon contents in FAF, only in BV SM01 and ICLF01 systems and the ML NV02 and PA02 systems showed higher FAF levels at the 0.00-0.05 m layer (Table 4). The greatest HAF and FAF contributions to TOC contents (%HAF and %FAF) were identified in the BV SM01 and ICLF01 systems (0.00-0.05 m) and the ML NV02 system (0.00-0.05 m) (Table 4).

SOM management indices

In general, the analyzed parameters showed no differences (lability, Lab; lability index, LabI; and carbon storage index, CSI) (Table 5). In the BV area, the ICLF01 system presented the highest CMI values (~ 116 and 130) in both layers. In the ML area, the SMS02 and PA02 systems had higher CMI values in the subsurface layer than the Cerrado vegetation (~ 259 and 189, respectively). The IF area also had high CMI values at the 0.00-0.05 and 0.05-0.10 m layers: ~346 and 1091 in SMS03; ~ 326 and 1464 in ILF03; and ~ 199 and 1103 in PA03 (Table 5).

Table 5. Soil organic matter management indices with different cultivation and soil management systems in the Cerrado region, Goiás, Brazil

Soil use	0.00-0.05 m layer				0.05-0.10 m layer			
	Lab	LabI	CSI	CMI	Lab	LabI	CSI	CMI
				BV area				
SM01	0.32	0.86	0.55	47.02	0.50	1.12	0.63	67.86
ICLF01	0.61	2.38	0.56	116.66	0.47	1.61	0.79	130.24
PA01	0.45	1.51	0.58	84.79	0.20	0.57	0.81	46.84
CV%	56.6 (1)	81.6 (2)	20.8 (1)	69.6 (1)	89.0 (2)	61.2 (1)	38.8 (1)	62.7 (1)
NV01	0.39	1.00	1,00	100	0.40	1.00	1.00	100
				ML area				
SMS02	0.51	0.77	1.23	93.92	0.39	1.60	1.71	259.18 a
AF02	0.44	0.72	0.83	56.31	0.14	0.58	1.09	43.75 b
PA02	0.57	0.94	1.12	90.07	0.42	1.78	1.17	189.46 ab
CV%	40.7 (1)	51.3 (1)	35.6 (1)	4.7 (1)	53.7 (1)	60.8 (1)	43.3 (1)	56.6 (1)
NV02	0.67	1.00	1.00	100	0.25	1.00	1.00	100
				IF area				
SMS03	0.30	1.66	1.87	346.24	0.22	5.50	2.24	1091.79
ILF03	0.26	2.03	2.56	326.95	0.22	9.76	2.21	1464.75
PA03	0.29	2.14	2.20	199.03	0.24	9.85	2.39	1103.58
CV%	93.0 (1)	110.0 (1)	71.2 (1)	89.6 (1)	120.4 (1)	136.0 (1)	70.4 (1)	88.9 (1)
NV03	0.20	1.00	1.00	100	0.05	1.00	1.00	100

Averages followed by different lowercase letters differ between cultivation and soil management systems. (1) ANOVA + Tukey's test without data transformation at 5 % significance level; and (2) ANOVA + Tukey's test with data transformation at 5 % probability level. BV: Boa Vereda farm; ML: Mata do Lobo farm; IF: Instituto Federal Goiano; SM01: Soybean monoculture in the BV area; ICLF01: Integrated crop-livestock-forest in the BV area; PA01: Pasture in the BV area; NV01: Cerrado vegetation in the BV area; SMS02: Soybean-corn succession in the ML area; AF02: Agroforestry in the ML area; PA02: Pasture in the ML area; NV02: Cerrado vegetation in the ML area; SMS03: Soybean-corn succession in the IF area; ILF03: Integrated livestock-forest in the IF area; PA03: Pasture in the IF area; NV03: Cerrado vegetation in the IF area; Lab: Lability; LabI: Lability index; CSI: Carbon storage index; CMI: Carbon management index; and CV: Coefficient of variation.

Table 6. Matrix of the Principal Component Analysis (PCA). The relative contribution corresponds to the Pearson correlation (r) between each main component (PC, axis) and the parameters

Variables	0.00-0.05 m layer		0.05-0.10 m layer	
	PC1	PC2	PC1	PC2
TOC	**0.90**	−0.30	**0.93**	0.29
POC	0.36	0.13	0.18	0.51
MAOC	**0.80**	−0.40	**0.91**	0.14
LOM	0.41	0.49	0.26	0.48
HUM	0.46	**0.70**	0.25	0.19
HAF	−0.26	−0.09	−0.21	**0.88**
FAF	−0.31	−0.57	−0.24	**0.70**
%HUM	−0.24	**0.82**	−0.60	−0.17
%HAF	**−0.73**	0.13	**−0.72**	0.48
%FAF	**−0.70**	−0.37	**−0.71**	0.43
CSt	**0.87**	−0.35	**0.92**	0.25
FLF	0.38	0.38		

Values in bold: High correlation (−0.70 ≥ r ≥ 0.70). TOC: Total organic carbon; POC: Particulate organic carbon; MAOC: mineral-associated organic carbon; LOM: Light organic matter in water; HUM: Humin carbon; HAF: Humic acid carbon; FAF: Fulvic acid carbon; %HUM: Proportions humin carbon; %HAF: Proportions humic acid carbon; %FAF: Proportions fulvic acid carbon; CSt: Carbon storage values; and FLF: Carbon in the light-free fraction.

DISCUSSION

Impact of cultivation and soil management systems on carbon level and storage

The NV01 system exhibited high total organic carbon (TOC) levels (Table 2), attributed to substantial input of plant residues into the topsoil from local vegetation with minimal human intervention. Ecologically stable environments, such as soils with native vegetation cover little impacted by human activities, often exhibit organic carbon incorporation rates from plant residues that balance with mineralization losses as CO_2 (Castellano et al., 2015), a process enhanced by soil microbial activity (Gazolla et al., 2015). These findings support previous studies (Silva et al., 2011; Loss et al., 2011; Nanzer et al., 2019; Oliveira et al., 2023), which reported higher TOC values in native vegetation areas compared to no-tillage systems and ICL areas.

The elevated TOC levels observed at the 0.05-0.10 m layer in ICLF01 and PA01 systems, similar to NV01 (Table 2), reflect the beneficial effect of introducing forage species in these systems. Forages accumulate more biomass than annual crops, which often do not provide adequate soil cover (Loss et al., 2011). Studies by Franzluebbers and Stuedemann (2008) suggest that isolated and integrated pastures increase soil carbon content due to significant vegetative development in both the shoot and root systems.

The percentage increase in TOC levels in the SMS02, SMS03, and ILF03 systems compared to their respective native vegetation systems (Table 2) can be attributed to corn and *Urochloa* grass intercropping, particularly in SMS with systems under no-tillage, despite low straw formation. This practice enhances the deposition of slowly decomposing crop residues and increases organic matter levels through the root system of grasses like corn and *Urochloa* grass, with the latter being notable for its extensive root system distributed through the soil profile (Salton et al., 2011).

Using different crops associated with no-tillage systems can significantly increase carbon stocks in clay-textured Latosols (Ferreira et al., 2022). This finding is supported by our results, which indicated that the adoption of soybean/corn succession systems (SMS02 and SMS03), as well as the incorporation of forage crops into the system (ILF03), resulted in considerable increases in soil carbon stocks (Table 3).

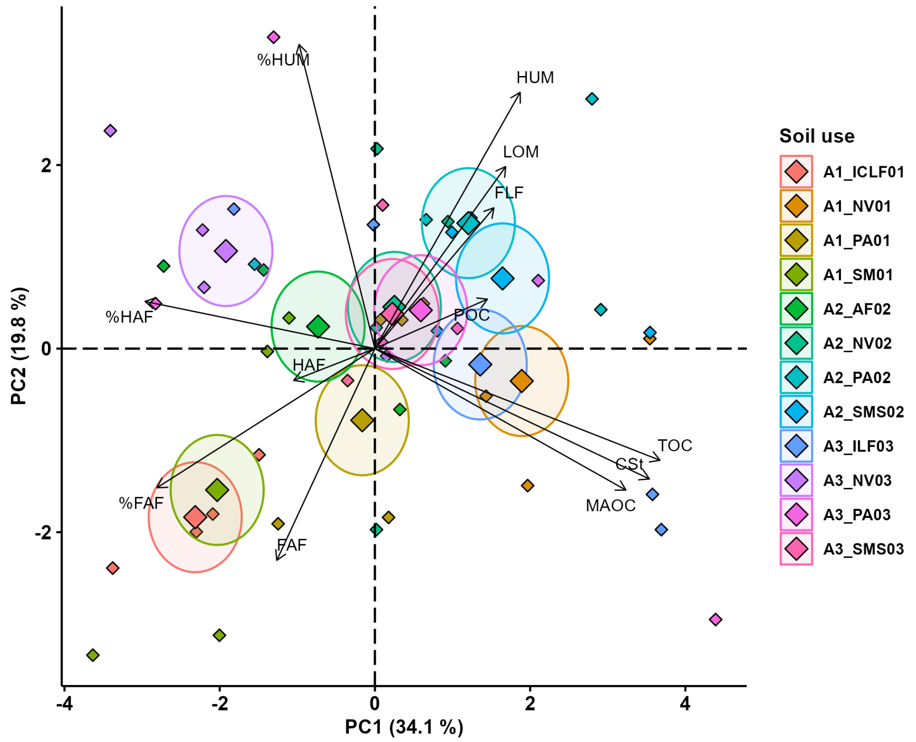

Figure 2. Principal component analysis (PCA) of SOM fractions at the 0.00-0.05 m layer in different cultivation and soil management systems in the Cerrado region, Goiás, Brazil. SM01: Soybean monoculture in the BV area; ICLF01: Integrated crop-livestock-forest in the BV area; PA01: Pasture in the BV area; NV01: Cerrado vegetation in the BV area; SMS02: Soybean-corn succession in the ML area; AF02: Agroforestry in the ML area; PA02: Pasture in the ML area; NV02: Cerrado vegetation in the ML area; SMS03: Soybean-corn succession in the IF area; ILF03: Integrated livestock-forest in the IF area; PA03: Pasture in the IF area; NV03: Cerrado vegetation in the IF area; TOC: Total organic carbon; POC: Particulate organic carbon; MAOC: mineral-associated organic carbon; LOM: Light organic matter in water; HUM: Humin carbon; HAF: Humic acid carbon; FAF: Fulvic acid carbon; %HUM: Proportions humin carbon; %HAF: Proportions humic acid carbon; %FAF: Proportions fulvic acid carbon; CSt: Carbon storage values; and FLF: Carbon in the light-free fraction.

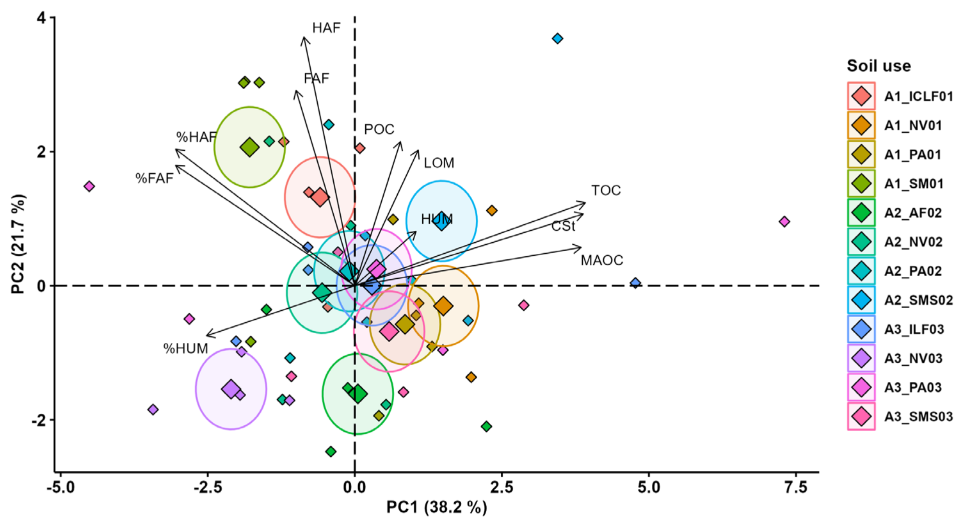

Figure 3. Principal component analysis (PCA) of SOM fractions at the 0.05-0.10 m layer in different cultivation and soil management systems in the Cerrado region, Goiás, Brazil. SM01: Soybean monoculture in the BV area; ICLF01: Integrated crop-livestock-forest in the BV area; PA01: Pasture in the BV area; NV01: Cerrado vegetation in the BV area; SMS02: Soybean-corn succession in the ML area; AF02: Agroforestry in the ML area; PA02: Pasture in the ML area; NV02: Cerrado vegetation in the ML area; SMS03: Soybean-corn succession in the IF area; ILF03: Integrated livestock-forest in the IF area; PA03: Pasture in the IF area; NV03: Cerrado vegetation in the IF area; TOC: Total organic carbon; POC: Particulate organic carbon; MAOC: mineral-associated organic carbon; LOM: Light organic matter in water; HUM: Humin carbon; HAF: Humic acid carbon; FAF: Fulvic acid carbon; %HUM: Proportions humin carbon; %HAF: Proportions humic acid carbon; %FAF: Proportions fulvic acid carbon; CSt: Carbon storage values; and FLF: Carbon in the light-free fraction.

The higher carbon reserves in the ILF03 system likely result from a higher carbon to nitrogen (C/N) ratio due to leaf litter accumulation in the topsoil, facilitated by significant carbon assimilation from eucalyptus crops. Previous studies by Silva et al. (2011) indicated that a five-year-old eucalyptus tree could fix approximately 39 kg of carbon in the shoots, significantly enhancing CSt in the topsoil, particularly at the 0.00-0.10 m layer (Ribeiro et al., 2023). Carbon accumulation varies regionally due to climate conditions (Carvalho et al., 2010), soil type (Pereira et al., 2010), management practices, and the duration of each system's implementation (Carvalho et al., 2009).

Impact of cultivation and soil management systems on carbon level in SOM physical fractions

The relatively short period of crop and management system implementation may have influenced the patterns observed in TOC, POC, and MAOC results (Table 2). Longer management periods are expected to stabilize and balance SOM compartments, enhancing their functionality in the soil (Rossi et al., 2012).

Higher POC levels in ML PA02 systems at the 0.05-0.10 m layer and in IF systems at the 0.00-0.10 m layer (ILF03 and PA03) than in native vegetation (Table 2) may be linked to the distribution of the *Urochloa* root system, particularly in deeper soil layers (Moreira and Siqueira, 2002). The association between *Urochloa* grass and the POC fraction is supported by the recent incorporation of plant material into the soil. Intercropping corn with *Urochloa* grass increases POC levels in winter crops, enhancing the input and effective retention of plant residues in both surface and subsoil layers. Our results (Table 2) align with previous studies by Loss et al. (2011) and Rossi et al. (2012), which identified higher POC levels in integrated crop-livestock systems compared to those using no-tillage system in *Latossolo Vermelho* soils in Goiás.

Increased MAOC levels in ICLF01 and PA01 systems, particularly at the 0.05-0.10 m layer (Table 2), result from significant input of grass-derived residues combined with clayey soil texture. Grasses decompose slowly due to their high C/N and lignin-nitrogen ratios, enhancing carbon accumulation associated with clay and silt particles, which form organo-mineral complexes (Silva and Mendonça, 2007). Loss et al. (2011) suggest that incorporating *Urochloa* grass into integrated crop-livestock systems promotes conditions for microaggregate formation, facilitated by iron and aluminum oxides in the clay fraction, leading to higher levels of protected MAOC.

Higher MAOC contents in the BV NV01 system partly result from higher TOC values in the area, especially at the 0.00-0.10 m layer (Table 2). The non-use of agricultural practices also stabilizes organic matter in the mineral fraction. Similar results were reported by Loss et al. (2011) and Rossi et al. (2012), who evaluated no-tillage system areas with and without integrated crop-livestock in an area of *Latossolo Vermelho* in the state of Goiás. Those authors found higher MAOC levels in native vegetation areas than in other land use and management systems. Increased MAOC levels in IF systems, mainly at the 0.00-0.10 m layer (Table 2), can be attributed to higher plant residue input in these systems than in native vegetation, because the IF NV03 area represents an affected forest fragment, which had most arboreal components removed.

Water-floatable LOM is considered a fast dynamics fraction in the soil, which makes its maintenance crucial to sustain agricultural systems due to its high nutrient cycling capacity in the short and medium term. This can justify the greater efficiency of the LOM fraction in differentiating the cultivation systems in the studied areas, especially in pasture systems. These systems stand out because they significantly contribute to this SOM fraction through rhizodeposition and root biomass (Pereira et al., 2010).

The SOM maintenance is essential for agricultural system sustainability because it has high potential for nutrient cycling in the short term. Higher LOM levels in the BV ICLF01, ML SMS02 and NV02, and IF ILF03 systems at the 0.00-0.05 m layer (Table 2) suggest these results are directly associated with the quantity and quality of plant residues added to the soil. Plant residues with different C/N ratios increase LOM recalcitrance, consequently increasing carbon levels in this fraction within a short period after the of these systems (Guareschi et al., 2012).

Impact of cultivation and soil management systems on carbon level in SOM chemical fractions

Contrasting with the results of this study, which showed that the HUM fraction had no statistical difference (Table 4), several studies on soils under tropical climate conditions indicate higher carbon levels in the HUM fraction than in other fractions (Assis et al., 2006; Barreto et al., 2008; Loss et al., 2009; Rossi et al., 2012). This result can be explained by the short system implementation period, which does not provide conditions for carbon increase in this fraction. Among other factors, the formation of the HUM fraction requires prolonged soil organism action over time, especially microbial activity (Gazolla et al., 2015).

In the BV ICLF01 system, the high values of HAF and FAF (Table 4) can be attributed to increased production of plant residues with a higher C/N ratio. These residues decompose more slowly, leading to a more rapid accumulation of these fractions in the soil (Mendonça et al., 2007). Similarly, the elevated FAF levels observed in the ML PA02 system (Table 4), are attributed to the presence of grass root systems and soil texture, which facilitate the formation of the HAF and FAF upon interaction with mineral particles (Rossi et al., 2011).

The chosen management systems and the relatively short implementation time may justify the consistent patterns observed in TOC, POC, MAOC, and CSt contents and HUM fractions across the different areas. Carbon accumulation in soil is a gradual process that becomes significant after 10-15 years of sustainable practices (Carvalho et al., 2009). Practices such as crop rotation and maintenance of crop residues on the soil surface contribute to slower decomposition of plant material deposited, ultimately stabilizing soil organic matter and improving soil chemical and physical properties (Gazolla et al., 2015).

Soil quality indices with native vegetation

The CMI evaluates CSt changes considering carbon lability in the soil (Nicoloso et al., 2005). The CMI values below 100 suggest practices that are harmful to organic matter maintenance and soil quality (Rossi et al., 2012). Thus, the BV ICLF01, ML SMS02, and PA02 (in the subsurface), as well as all IF systems (Table 5), showed a positive effect of the management implementation in increasing soil carbon content. The IF SMS03, ILF03, and PA03 systems (Table 5) also presented higher CMI values, mainly in the subsurface.

Both layers of the BV ICLF01 system had a positive effect in increasing soil carbon content, with higher CMI values than the other systems (Table 5). This pattern shows this system is promoting more effective carbon accumulation in the soil than the other systems (Rossi et al., 2012). The high CMI values in the SMS02 and SMS03 systems (Table 5) can be attributed to the consistent use of leguminous crops, aligning with findings from Blair and Crocker (2000), Dieckow et al. (2005), and Blair et al. (2006), which highlight the positive impact of legume inclusion in crop rotations on soil carbon accumulation.

In contrast with our results, Salton et al. (2011) reported higher CMI in pasture systems. According to those authors, permanent pasture systems (*Urochloa decumbens*) had a CMI of 137, and integrated production systems (soybeans-*Urochloa* grass) had a CMI of 104. Those values were higher than the ones found in the reference area and systems with annual crops only. The pattern reported by the authors can be attributed to different management practices, soil types, climate conditions, and factors specific to each study.

Similarity between cultivation systems and native vegetation

The PCA considered only the first two principal components (PC1 and PC2), which together explained 53.9 and 59.9 % of the total data variability shown in figures 2 and 3, respectively. Figure 2 shows the formation of four very distinct groups: group (1), formed by the ILF03 and NV01 systems, shown in the lower right quadrant; (2), formed by the PA02, SMS02, NV02, PA03, and SMS03 systems, shown in the upper right quadrant; (3), formed by the ICLF01, SM01, and PA01 systems, shown in the lower left quadrant; and (4), formed by the AF02 and NV03 systems and shown in the upper left quadrant.

The secondary axis in figure 2 (PC2) explains the lower dissimilarity between land use and management systems and separates BV from ML and IF systems, except for ILF03, with ~ 19.8 % result variability. The main axis in figure 2 (PC1) presents the lower greatest contribution and separates the PA02, SMS02, PA03, ILF03, SMS03, NV01, and NV02 systems from the ICLF01, SM01, PA01, AF02, and NV03 systems, with ~ 34.1 % of data variance. The parameters most influential in forming PC1 (with high correlation, $-0.70 \geq r \geq 0.70$) included TOC (0.90), CSt (0.87), MAOC (0.80), %HAF (−0.73), and %FAF (−0.70) (Table 6). For PC2, the parameters with the greatest contributions were HUM (0.70) and %HUM (0.82) (Table 6).

At the 0.00-0.05 m layer, the parameters strongly contributing to PCA axes were the TOC, CSt, and carbon fractions with greater recalcitrance and stability (MAOC and HUM) (Figure 2). The fractions with greater lability and solubility (LOM, FLF, POC, FAF, and FAH) had no high correlation with PCA axes at this layer (Figures 2). These results associate the most stable and recalcitrant SOM fractions with carbon dynamics in the topsoil of diversified agricultural production systems; and its high correlation suggests that the high SOM in these areas still reflects the vegetation before system implementation.

Figure 3 shows that four groups were formed, but with a less clear separation compared to figure 2: group (1), formed by the PA01, NV01, and SMS03 systems, shown in the lower right quadrant; group (2), formed by the SMS02 system, shown in the upper right quadrant; group (3), formed by the NV03 system, shown in the lower left quadrant; and group (4), formed by the ICLF01 and SM01 systems, shown in the upper left quadrant. The AF02, PA02, PA03, ILF03, and NV02 systems are grouped in the center of the PCA or on top of one of the axes, with no defined separation pattern (Figure 3).

The ICLF01, SM01, and SMS02 systems were separated from the PA01, SMS03, NV01, and NV03 systems in PC2 (~ 21.7 %) (Figure 3), with the main parameters being HAF (0.88) and FAF (0.70) (Table 6). The parameters TOC (0.93), CSt (0.92), MAOC (0.91), %HAF (−0.72), and %FAF (−0.71) helped form the PC1 axis (~ 38.2 %) (Table 6), which separated the PA01, SMS03, SMS02, and NV01 systems from the ICLF01, SM01, and NV03 systems (Figure 3).

The PCA results showed a similar pattern at the 0.05-0.10 m (Figure 3) and 0.00-0.05 m layers (Figure 2). However, the HUM fraction had a considerably reduced correlation with PC2 (0.19); and the FAF and HAF fractions significantly increased their relative contribution to constructing this axis (0.70 and 0.88) (Table 6). This points to an improved humification process in the subsurface layer. This process is considered one of the mechanisms for organic matter stabilization in the soil and depends on soil and environmental conditions for greater or lesser activity.

The PCA results satisfactorily explained the pattern of system separation and grouping according to SOM fraction levels, especially at the 0.00-0.05 m layer (Figures 2 and 3). The BV area showed clearer system separation in the most relevant axis than the ML and IF areas, except for the ILF03 system (Figure 2). These results show the changes promoted by cultivation and soil management practices and systems in SOM compartments, especially in the topsoil.

The TOC, CSt, and MAOC were more associated with the ILF03 and NV01 systems in the topsoil, showing more favorable environments for SOM stabilization (TOC and MAOC) and subsequent carbon accumulation in the soil (CSt) (Figure 2). The ICLF01 and SM01 systems were more related to FAF, HAF, and the %HAF humification index in the subsurface layer (Figure 3). The HUM fraction was more associated with the PA02, SMS02, NV02, PA03, and SMS03 systems in the topsoil (Figure 2).

CONCLUSIONS

Soil organic matter fractions were similarly influenced by the cultivation and management systems across the study areas. However, there was a greater difference between systems in the Boa Vereda area than in the Mata do Lobo and Instituto Federal Goiano areas. The integrated crop-livestock-forest system in Boa Vereda exhibited greater vegetation diversity, which was associated with higher total organic carbon and mineral-associated organic carbon contents in the subsurface and higher carbon management index values.

The soybean-corn succession system in Mata do Lobo showed increased total organic carbon and carbon storage levels compared to native vegetation, which was linked to higher topsoil particulate organic carbon and carbon management index. The Instituto Federal Goiano systems demonstrated increased total organic carbon, carbon storage, particulate organic carbon, and mineral-associated organic carbon levels compared to native vegetation, and these were associated with higher carbon management index values.

Light organic matter was the most efficient parameter for differentiating soil organic matter input between cultivation and soil management systems, especially in systems with pasture. Soybean monoculture and integrated crop-livestock-forest systems in Boa Vereda had the highest humic acid carbon and fulvic acid carbon contents and their respective proportions in the topsoil, indicating favorable environments for soil organic matter stabilization through humification.

DATA AVAILABILITY

The data will be provided upon request.

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