

Chemical properties and physical fractions of organic matter in oxisols under integrated agricultural production systems

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ABSTRACT

The main cause of decreased soil fertility and soil organic matter content is intensive crop farming with inadequate management. This study aimed to evaluate soil chemical properties, total organic carbon content, physical granulometric fractions (particulate organic carbon and mineral-associated organic carbon), carbon stocks, and carbon management indices of oxisols in different integrated agricultural production systems (IAPSs) with reference to values in a haymaking area and native forest. The experiments were performed using completely randomized design, considering nine differently managed areas, including seven IAPSs and two reference areas (haymaking area and native forest); four soil samples from the 0.00-0.05, 0.05-0.10, and 0.10-0.20 m layers were randomly collected from each area and the abovementioned variables were evaluated. The results showed no differences in variables between the managed and reference areas, indicating the maintenance of fertility and carbon fractions. Therefore, the tested management strategies promote beneficial modifications of soil properties. Producers should adopt different IAPS management strategies for soil preservation.

Keywords: carbon management index, soil organic matter, soil management, soil organic carbon.

Propriedades químicas e frações físicas da matéria orgânica em latossolo vermelho sob sistemas integrados de produção agropecuária

RESUMO

A principal causa da diminuição da fertilidade do solo e do conteúdo de matéria orgânica do solo é o cultivo intensivo de culturas com manejo inadequado. Este trabalho tem como objetivo avaliar os atributos químicos do solo, carbono orgânico total (COT), frações granulométricas físicas, estoques de carboidratos (st) e o índice de manejo de carbono (IMC) em diferentes sistemas de produção agrícola integrada (SIPA), área de fenação e floresta nativa em um Latossolo Vermelho. Os experimentos foram realizados em delineamento inteiramente casualizado, considerando nove áreas de manejo diferenciado, incluindo sete SIPAs e duas áreas de referência (área de fenação e floresta nativa); quatro amostras de solo das camadas de 0,00-0,05, 0,05-0,10 e 0,10-0,20 m foram coletadas aleatoriamente em cada área e avaliadas as variáveis acima mencionadas. Os resultados não mostraram diferenças nas variáveis entre as áreas manejada e de referência, indicando a manutenção da fertilidade e das frações de carbono. Portanto, as estratégias de manejo testadas promovem modificações benéficas nas propriedades do solo. Os produtores devem adotar diferentes estratégias de gestão da SIPA para a preservação do solo.

Palavras-chave: índice de manejo de carbono, matéria orgânica do solo, manejo do solo, carbono orgânico do solo.

1. Introduction

In an attempt to harmonize agricultural production with soil conservation, new concepts have been developed based on soil preservation, nutrient cycling, and crop diversification. Intensification through succession, rotation, and crop–livestock integration within the same production unit may improve soil chemical, physical, and biological properties, thereby increasing productivity of the activities involved (Silva et al., 2011; Costa et al., 2015).

Using integrated agricultural production systems (IAPSSs), in which several activities operate in a synergistic way within the same area, satisfactory results can be obtained in terms of soil conservation. IAPSSs can even preserve soil and enhance its productivity (Silva et al., 2011; Costa et al., 2015; Sales et al., 2018). Previous studies have reported that in Oxisols, adoption of IAPS is efficient in terms of maintenance and improvement of nutrient availability, total organic carbon (TOC), carbon stock (st), humification, and physical granulometry fractions of soil organic matter (SOM), among others (Loss et al., 2014; Costa et al., 2015).

Study of SOM components, such as granulometric physical fractions, may aid in the evaluation of changes occurring over a short period due to their greater sensitivity to the management adopted (Assmann et al., 2014; Conceição et al., 2014). Physical granulometric fractionation allows for the determination of carbon fractions, including particulate organic carbon (POC) associated with sand fraction, which is the coarsest mineral fraction of soil, and mineral-associated organic carbon (MOC) associated with silt and clay. POC plays an important role in nutrient cycling and is considered a labile fraction of soil. MOC is linked to intense humification, being less sensitive to changes related to soil management, particularly over a short period (Conceição et al., 2014; Assmann et al., 2014).

Based on granulometric physical fractions of carbon, carbon management index (CMI) can be determined (Blair et al., 1995), which takes into account the lability of SOM and seeks to integrate its quantitative and qualitative characteristics for evaluating the performance of a given management system (Rossi et al., 2012a). In managed lands, a CMI higher than or similar to that in a reference (native) area (100) indicates the ability of different management systems to improve soil quality in terms of its organic fraction, whereas a CMI below that in a reference area indicates negative effects on SOM (Conceição et al., 2014).

Evaluation of different management systems based on their effects on soil nutrient and carbon levels in different SOM components may allow for the measurement of the degree of soil preservation using those production systems and assist in the determination of their possible outcomes (Silva et al., 2011). In this

context, the present study aimed to evaluate soil chemical properties, TOC, physical granulometric fractions, st, and CMI of Oxisols in different IAPSSs compared with values in two reference areas, including a haymaking area and a native forest.

2. Material and Methods

2.1. Location, climate, and soil of the study area

This study was performed at the Experimental Farm “Professor Antônio Carlos dos Santos Pessoa” of the State University of the West of Paraná (UNIOESTE), located in the municipality of Marechal Cândido Rondon, Paraná, Brazil (WGS84, 24°31′58.24″S 54°01′12.08″W, 390 m altitude).

According the Köppen classification, the climate of the region is of type Cfa— humid subtropical, with dry winters, well-distributed rainfall throughout the year, and hot summers. Mean annual temperature ranges between 22 and 23°C and mean annual rainfall between 1600 and 1800 mm (Alvares et al., 2014). Weather data during the experimental period (2014–2017) were obtained from an automatic climatological station located near the experimental site (Figure 1).

Soil at the experimental area is classified as Oxisol with a very clayey texture. The contents of clay, silt, and sand were respectively 681.0 g·kg⁻¹, 266.5 g·kg⁻¹, and 52.5 g·kg⁻¹ in the 0.00–0.10 m layer and respectively 751.5 g·kg⁻¹, 199.1 g·kg⁻¹, and 49.4 g·kg⁻¹ in the 0.10–0.20 m layer.

2.2. Characterization of the experimental area

The management system evaluated comprised six areas cultivated in autumn–winter, with succession of oat and soybean in spring–summer. The areas differed in terms of the seeding density of oat and the presence of animals grazing on oat. In an additional area, there was natural reseeding of ryegrass and forage turnip during winter, with soybean succession in spring–summer. In addition, two reference areas, including a hay production area (Tifton 85) and a native forest were evaluated (Table 1).

2.3. Field sampling and analysis

Soil samples were collected in March 2017, at end of the soybean cycle, almost 1 year after forage sowing. In each area, 50 m² plots were defined. Five single samples were collected using Dutch Auger and pooled as samples from the 0.00–0.05, 0.05–0.10, and 0.10–0.20 m layers.

The following soil chemical properties were evaluated according to the methodology described by Pavan et al. (1992): pH in CaCl₂; Ca²⁺, Mg²⁺, P, and K⁺ contents; potential acidity (H+Al); exchangeable Al³⁺; sum of bases (SB); cation exchange capacity (CEC); and base saturation (V). Total organic carbon (TOC) was determined by wet oxidation using a 0.167 mol·L⁻¹

potassium dichromate solution and concentrated sulfuric acid, with heating in a digester block, as described by Mendonça and Matos (2017).

Granulometric physical fractionation was performed as described by Mendonça and Matos (2017) to determine POC associated with sand fraction and MOC associated with silt and clay. The respective st values for TOC, POC, and MOC were calculated using the equivalent layer method. To compare values among areas, soil mass equivalents were corrected for by adjusting the values of layers used in calculations according to equation (1), described by Sales et al. (2018).

$$st = (C \times D_s \times (D_{ref} / D_s) \times e) / 10 \quad (1)$$

where, st is carbon stock ($Mg \cdot ha^{-1}$), C is soil organic carbon content ($g \cdot kg^{-1}$), and D_s is bulk density ($kg \cdot dm^{-3}$), determined according to the methodology described by Teixeira et al. (2017); D_{ref} is bulk density in reference areas ($kg \cdot dm^{-3}$); and e is the thickness of the sampled layer (cm).

From the obtained TOC, POC, and AOC, CMI was calculated, according to Conceição et al. (2014). Moreover, the following indices were adapted: carbon stocks index (CSI) obtained based on TOC_{st} values of the

managed and reference areas (secondary forest), liability (L) obtained based on POC_{st} and MOC_{st}, and liability index (IL) obtained based on the L values of the managed and reference areas.

CMI was performed using the following formula: $CMI = CSI \times IL \times 100$. Among the two reference areas (Forest and Haying), native forest was used as the standard reference for CMI calculation ($CMI=100$), because it represents an environment without anthropogenic interference.

2.4. Experimental design and statistical analysis

The experiments were performed using completely randomized design, across seven management systems and two reference areas. Four additional samples were collected at random (independent) from each area as replicates (pseudoreplicates) (Ferreira et al., 2012). Data obtained were submitted to analysis of variance. When significant by the F test ($p \leq 0.05$), mean values among the managed and reference areas were compared using Dunnett test and values between areas were compared using Tukey test. All analyses were performed using Genes (Cruz, 2013).

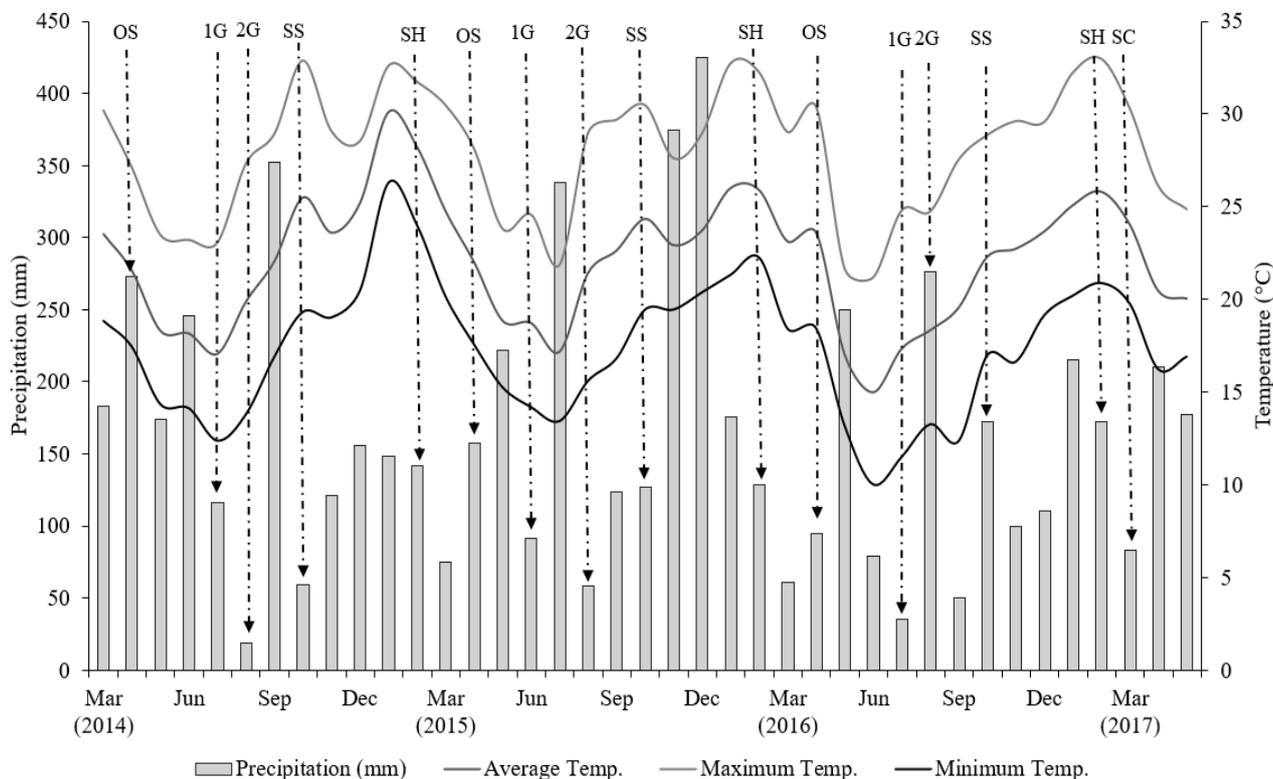


Figure 1. Monthly maximum, mean, and minimum ambient temperature and monthly accumulated rainfall during the experimental period.

OS: oat seeding, SS: soybean seeding, SH: soybean harvest, SC: soil collection, 1G and 2G: once and twice grazing, respectively.

Source: UNIOESTE, Marechal Cândido Rondon, PR.

Table 1. Description of the study areas.

Area	Description
No-till system (O40)	During autumn–winter, oat (<i>Avena sativa</i> L.) was cultivated at a seeding density of 40 kg·ha ⁻¹ during the agricultural years 2014-2015, 2015-2016, and 2016-2017. Basic fertilization was performed with 250 kg·ha ⁻¹ of the commercial formulation 10-15-15 (N, P ₂ O ₅ , and K ₂ O) and 120 kg·ha ⁻¹ of nitrogen in the form of urea, supplied in two applications (at the beginning of tillering and 30 days after the first application). During spring–summer, soybean was cultivated. Basic fertilization was performed with 270 (2014-2015), 290 (2015-2016), and 310 (2016-2017) kg·ha ⁻¹ of the commercial formulation 02-20-18 (N, P ₂ O ₅ , and K ₂ O), and phytosanitary treatments were applied as needed.
Integrated agricultural production systems (O40G1)	Crops and management during autumn–winter and spring–summer were the same as those in O40. Additionally, grazing was performed once on oats when the crop height was between 0.25 and 0.35 m, and animals were moved when the crop height was between 0.15 and 0.2 m.
Integrated agricultural production systems (O40G2)	Crops and management during autumn–winter and spring–summer were the same as those in O40. Additionally, grazing was performed twice on oat plants when the crop height was between 0.25 and 0.35 m, and animals were moved when the crop height was between 0.15 and 0.2 m.
No-till system (O60)	Crops and management during autumn–winter and spring–summer were the same as those in O40, but oat seeding density was 60 kg·ha ⁻¹ .
Integrated agricultural production systems (O60G1)	Crops and management during autumn–winter and spring–summer were the same as those in O60. Additionally, grazing was performed once on oats when the crop height was between 0.25 and 0.35 m, and animals were moved when the crop height was between 0.15 and 0.2 m.
Integrated agricultural production systems (O60G2)	Crops and management during autumn–winter and spring–summer were the same as those in O60. Additionally, grazing was performed twice on oat plants when the crop height was between 0.25 and 0.35 m, and animals were moved when the crop height was between 0.15 and 0.2 m.
Natural reseeding (RNAN)	Since the soil seed bank was the natural reseeding of ryegrass and forage turnip, phytotechnical management was not performed during winter–autumn. During spring–summer, soybean was cultivated using basic fertilization with 270 (2014-2015), 290 (2015-2016) and 310 (2016-2017) kg·ha ⁻¹ of the commercial formulation 02-20-18 (N, P ₂ O ₅ , and K ₂ O). Phytosanitary treatments were applied as needed.
Haymaking area (Haying)	In this area, hay (Tifton 85, <i>Cynodon</i> sp.) has been produced over the last 10 years, with periodic fertilization using pig slurry. Six annual cuts are practiced, and 70.72 m ³ ·ha ⁻¹ of pig slurry was applied for cutting in addition to maintenance fertilizer.
Secondary forest (Forest)	This is a permanently preserved fragment of native forest, classified as semideciduous seasonal forest. The following species are observed: <i>Anadenanthera colubrina</i> (Vell.) Brenan var. <i>cebil</i> (Griseb.) Altschul, <i>Peltophorum dubium</i> (Spreng.) Taub, <i>Uncaria</i> sp., <i>Handroanthus</i> sp., <i>Aspidosperma polyneuron</i> Müll.Arg, <i>Caesalpinia leiostachya</i> (Benth.) Ducke, <i>Ceiba speciosa</i> (St.-Hill.) Ravenna, and <i>Euterpe edulis</i> Mart., among others.

3. Results and Discussion

3.1. Soil chemical properties under different management systems

There were differences in the P content of the 0.00-0.05 m layer and CEC of the 0.05-0.10 and 0.10-0.20 m layers across various management systems. These results may be related to the deposition and accumulation of residues, of both animal and plant origin, combined with climatic factors, all of which can lead to decomposition through the activity of soil microbes. The resultant formation of free ions in soil alters the contents of various nutrients (Flores et al., 2008; Costa et al., 2015; Mattei et al., 2018; Piano et al., 2020).

Chemical properties at different soil layers varied across different managed and reference areas (Table 2). pH and H+Al were slightly higher in managed areas, although not significantly different from values in reference areas. These results may be explained by soil management for enhancing pH and controlling toxic

elements (Barros, 2013; Melo et al., 2017). In addition, deposition of organic residues tends to increase SOM content as well as hydrogen cation release by the action of soil organic acids formed (Machado et al., 2019).

P levels in O40G2, O60, O60G1, and O60G2 were significantly higher than those in forest but similar to those in haying, probably due to P fertilization and nutrient cycling enabled by deposited organic residues (Piano et al., 2017). Melo et al. (2017) also observed high P levels in agricultural areas, which may be due to the inherent variability in nutrient levels within common cultivated areas because of differences in the dose, source, and form of fertilizer application. The low P levels observed in forest may be due to the adsorption of secondary minerals, uptake, and fixation by plants and low cycling of this element in soil. In addition, native forests naturally present low P levels (Rossi et al., 2012a; Stieven et al., 2018). High soil P levels in the haying area may be due to the application of pig slurry.

Table 2. Soil chemical properties under different management systems

Areas	pH	P	H+Al	K ⁺	Ca ²⁺	Mg ²⁺	SB	CEC	V
	CaCl	mg·dm ⁻³			cmolc·dm ⁻³				%
0.00-0.05 m									
O40	5.64 ab	16.83 aB	5.56 ab	0.60 ab	4.11	2.40 a	7.11	12.66 b	56.13 a
O40G1	5.76 ab	16.33 aB	4.73 ab	0.68 ab	4.21	2.60 ab	7.48 b	12.20 b	61.10 ab
O40G2	5.81 ab	43.78 bA	4.65 ab	0.60 ab	3.52	2.14 a	6.26	10.90	57.07 ab
O60	6.02 b	37.60 bA	3.97 ab	0.77 b	3.81	2.38 a	6.96	10.93	63.47 ab
O60G1	5.68 ab	49.35 bA	4.22 ab	0.63 ab	3.78	2.28 a	6.68	10.91	60.91 ab
O60G2	5.70 ab	35.30	5.76 a	0.66 ab	3.46	2.28 a	6.40	12.16 b	52.61 a
RNAN	5.48 ab	16.93 aB	4.85 ab	0.58 ab	4.82 b	2.91 ab	8.31 ab	13.16 ab	63.64 ab
Forest	5.11 a	4.22 a	5.10 a	0.34 a	7.45 a	2.25 a	10.04 a	15.14 a	66.43 a
Haying	6.02 b	56.30 b	3.64 b	0.60 b	5.80 b	3.34 b	9.73 b	13.37 b	72.73 b
0.05-0.10 m									
O40	5.09 a	17.15 ab	6.43 a	0.33 ab	3.09 b	1.69 a	5.10 b	11.53 bAB	44.55
O40G1	5.31 ab	19.73 ab	6.03 a	0.43 ab	3.36 b	1.82 ab	5.61 b	11.64 bAB	47.91 a
O40G2	5.26 ab	41.30 b	5.56 a	0.56 ab	2.76	1.65 a	4.97	10.52 bB	46.55 a
O60	5.35 ab	28.44 b	5.72 a	0.47 ab	2.74	1.67 a	4.87	10.59 bAB	46.13 a
O60G1	5.19 ab	36.33 b	4.91 a	0.47 ab	3.01 b	1.77 a	5.25 b	10.17 bB	51.21 a
O60G2	5.38 ab	39.24 b	7.05 a	0.44 ab	2.92	1.71 a	5.07 b	12.12 abA	41.75
RNAN	4.98 a	17.03 ab	5.40 a	0.45 ab	3.06 b	1.71 a	5.21 b	10.61 bAB	49.24 a
Forest	4.98 a	3.20 a	5.28 a	0.26 a	6.04 a	1.95 a	8.24 a	13.52 a	61.00 a
Haying	5.95 b	23.63 b	3.20 b	0.37 b	4.34 b	2.63 b	7.34 b	10.54 b	68.74 b
0.10-0.20 m									
O40	4.76 ab	15.28 ab	6.12 a	0.39 ab	3.63 ab	1.95 ab	5.96 ab	12.08 abA	49.38 ab
O40G1	5.52 ab	14.41 ab	5.14 ab	0.49 b	3.95 ab	2.18 ab	6.62 ab	11.76 abAB	55.78 ab
O40G2	5.44 ab	28.11 b	4.88 ab	0.45 ab	3.07 b	1.59 a	5.10 ab	9.98 bB	50.50 ab
O60	5.60 ab	27.34 b	4.98 ab	0.47 ab	3.22 b	1.79 a	5.49 ab	10.46 bAB	52.35 ab
O60G1	5.51 ab	28.24 b	4.59 ab	0.49 b	3.29 b	1.79 a	5.56 ab	10.15 bAB	54.12 ab
O60G2	5.53 ab	18.25 ab	6.22 a	0.35 ab	3.16 b	1.72 a	5.23 ab	11.45 abAB	45.91 b
RNAN	5.25 ab	15.53 ab	4.92 ab	0.48 ab	3.87 ab	1.99 ab	6.34 ab	11.25 abAB	55.92 ab
Forest	5.06 a	3.62 a	5.67 a	0.19 a	4.92 a	1.72 a	6.82 a	12.49 a	54.50 a
Haying	5.51 b	15.92 b	3.53 b	0.22 b	4.02 b	2.59 b	6.84 b	10.37 b	65.74 b

Note: Values with the same lowercase letters in the columns are not significantly different from the reference values using Dunnett test at a 5% probability level. Values with the same uppercase letters in the columns are not significantly different from one another using Tukey test at a 5% probability level.

K⁺ levels in the reference areas did not differ from those in the managed areas, with the exception of O60, O40G1, and O60G2, where K⁺ levels were significantly higher than those in the forest area but not than those in the haying area. The high K⁺ levels in these areas may be related to the persistence of this element in plant tissue, protected from losses by erosion and leaching, gradual release to the soil, and deposition because of the use of mineral fertilization (Costa et al., 2015).

Ca²⁺ levels in all layers were lower in the managed areas than in the reference areas. However, levels in some managed areas did not differ from those in the haying and forest areas, which may be related to the uptake of this element by plants, export in the soybean grain, and complexation with toxic elements, such as iron and aluminum, as well as to the low nutrient cycling of this element in soil (Flores et al., 2008; Stieven et al., 2018). Similarly, Stieven et al. (2018) evaluated Oxisol chemical properties in integrated systems across three years and observed decreased Ca²⁺ levels. These results may be attributed to the importance of this element for plants and crop yield.

Mg²⁺ levels did not differ between the managed and reference areas. These results may be related to the high natural levels of this element in soil, which may be derived from basalt, dolomitic limestone applied for pH correction, or decomposition of winter crop residues (Piano et al., 2017).

Soil sorption complexes differed between most managed and reference areas, because interchangeable base levels were low, specifically for SB and CEC. Nonetheless, the observed values were interpreted as medium to high and were within the range of soil chemical properties reported for Paraná (SBSCS, 2019). Similarly, Schiavo et al. (2011) observed lower soil sorption complexes in IAPSS than in natural areas, although these low indices did not negatively affect soil.

3.2. Total organic carbon, physical granulometric fractions, and carbon stocks

TOC and TOCst of the 0.10-0.20 m layer differed across management systems. The highest values are indicated using the letter "A" in Table 3 ($p \leq 0.05$, Tukey test). These results may be related to the higher root

volume of summer and winter crops as well as grazing. Grazing uproots plants, increasing carbon stocks at deep soil layers (Piñeiro et al., 2010). In addition, favorable climatic conditions may have contributed to this increase (Gonçalves et al., 2011).

Previous studies have observed increased levels and stocks of carbon at deep soil layers in IAPSSs, which may be attributed to high regeneration of root system due to the grazing of aerial plant parts (Gazolla et al., 2015; Costa et al., 2015). Another factor that may have contributed to increased carbon stocks at deep soil layers is daily precipitation (Figure 1). According to Gonçalves et al. (2011), in regions with mild temperatures (22.13-25.9°C), precipitation is the most important factor related to increased soil carbon content due to increased decomposition rate.

The lower TOC and TOCst in surface soil layers in managed areas than in reference areas, particularly forest, may be related to the short time (3 agricultural years) since the conversion of the conventional system, where periodic soil turning and low crop residue addition were performed, to the management system for the experiment. Loss et al. (2013, 2014) reported differences

in TOC and TOCst between production systems and forest and attributed these reduced carbon levels to the low contribution of organic residues deposited on the soil surface, oxidation of organic matter, soil turnover, and other disturbances in the edaphic environment.

There were no differences in TOC and TOCst between the managed and haying areas, likely because of substitution. Substitution may offer an opportunity to produce fodder and grains, that is crop–livestock integration, within the same area, consequently providing enhanced economic returns, protection against erosion, increased organic residue deposition, and elevated soil nutrient and carbon levels.

There were no differences in POC and POCst between most managed and reference areas at all layers, with the exception of 0.05-0.10 m layer in O40G1, where POC and POCst were significantly higher than values at the reference areas (Table 3). These results indicate increased carbon fraction and stock due to the addition of high volume of crop residues with a low C/N ratio (Mattei et al., 2018; Piano et al., 2017; Piano et al., 2019), climatic factors (Gonçalves et al., 2011), and preservation of soil structure (Santos et al., 2018).

Table 3. Levels and stocks of total organic carbon (TOC and TOCst), particulate organic carbon (POC and POCst), and organic carbon associated with silt and clay minerals (MOC and MOCst) in different soil management systems

Areas	TOC g·kg ⁻¹	POC	MOC	TOCst Mg·ha ⁻¹	POCst	MOCst
0.00-0.05 m						
O40	27.32 ab	20.80 a	6.52	10.09 ab	7.68 a	2.41
O40G1	25.01 b	20.51 a	4.51	9.24 b	7.58 a	1.67
O40G2	24.31 b	18.71 ab	4.87	8.98 b	6.91 ab	1.80
O60	25.40 b	18.51 ab	6.89 b	9.38 b	6.84 ab	2.54 b
O60G1	27.21 ab	18.10 ab	9.12 b	10.05 ab	6.69 ab	3.37 b
O60G2	24.73 b	17.98 ab	6.75	9.14 b	6.64 ab	2.49
RNAN	23.52 b	18.74 ab	4.79	8.69 b	6.92 ab	1.77
Forest	31.73 a	15.28 a	16.45 a	11.72 a	5.65 a	6.08 a
Haying	25.49 b	11.84 b	13.65 b	9.42 b	4.38 b	5.04 b
0.05-0.10 m						
O40	22.11 b	14.48 ab	7.63 b	8.71 b	5.71 ab	3.01 b
O40G1	21.57 b	16.04	5.53	8.50 b	6.32	2.18
O40G2	21.42 b	13.93 ab	7.49	8.44 b	5.49 ab	2.95
O60	20.68 b	14.13 ab	6.55	8.15 b	5.57 ab	2.58
O60G1	23.62 ab	14.06 ab	9.56 b	9.30 ab	5.54 ab	3.76 b
O60G2	23.10 b	14.77 ab	8.33 b	9.10 b	5.82 ab	3.28 b
RNAN	19.59 b	15.13 b	4.46	7.72 b	5.96 b	1.76
Forest	27.11 a	8.73 a	18.38 a	10.68 a	3.44 a	7.24 a
Haying	21.76 b	8.90 b	12.86 b	8.57 b	3.51 b	5.07 b
0.10-0.20 m						
O40	21.29 abB	16.92 b	4.37 b	19.43 abB	15.45 b	3.99 b
O40G1	22.38 abAB	16.99 b	5.40 b	20.43 abAB	15.50 b	4.93 b
O40G2	23.03 aAB	15.10 b	7.93 b	21.02 aAB	13.78 b	7.24 b
O60	22.05 abB	14.77 b	7.28 b	20.13 abB	13.48 b	6.65 b
O60G1	25.55 aA	15.60 b	9.95 b	23.32 aA	14.24 b	9.08 b
O60G2	22.78 aAB	15.72 b	7.06 b	20.79 aAB	14.34 b	6.45 b
RNAN	21.68 abB	17.27 b	4.41 b	19.79 abB	15.76 b	4.03 b
Forest	23.51 a	7.43 a	16.09 a	21.46 a	6.78 a	14.68 a
Haying	20.13 b	12.96 b	7.18 b	18.38 b	11.83 b	6.55 b

Note: Values with the same lowercase letters in the columns are not significantly different from the reference values using Dunnett test at a 5% probability level. Values with the same uppercase letters in the columns are not significantly different from one another using Tukey test at a 5% probability level.

Assmann et al. (2014) reported that increased POC levels indicate a positive effect of residue deposition on soil, which helps maintain or increase microbial activity and soil quality. Meanwhile, low crop residue deposition promotes the oxidation of existing SOM, thereby reducing carbon stocks, further leading to the degradation of soil and loss of its quality. According to previous studies (Rossi et al., 2012b; Loss et al., 2013; Santos et al., 2018), variations in POC and POCst indicate changes in the soil quality of a recently adopted management system. In contrast, TOC and TOCst do not always indicate such changes, as these are sensitive indicators of changes in levels of soil carbon, reduction of which may indicate an increase in carbon dioxide emission.

MOC and MOCst in superficial soil layers were lower in managed areas than in reference areas, except in O40, O40G1, O40G2, O60G2, and RNAN. At deep soil layers, however, there were no differences in MOC and MOCst between the managed and haying areas. Differences in MOC and MOCst between the managed areas and forest may be related to the greater stability of and shorter time to recover this fraction (Santos et al., 2018). This is due to the substitution of native vegetation by conventional

agricultural production systems, removal of aboveground residues, movement and excessive soil preparation with mechanical breakdown of aggregates, and low deposition of crop residues, all of which contribute to carbon loss over the years (Lima et al., 2015).

According to previous studies (Rossi et al., 2012a; 2012b; Santos et al., 2018), MOC, unlike COP, is less sensitive to changes related to soil management systems, particularly short-term changes, indicating the need for longer production cycles to verify the real contribution of carbon levels to this fraction. Loss et al. (2014) reported a negative linear correlation between the formation of physical granulometric fractions. As such, to obtain higher MOC levels, higher POC levels and greater activity of soil microbes are essential. Therefore, the evaluated management systems may have contributed to the recovery of MOC due to the higher POC levels observed in this study (Santos et al., 2018).

3.3. Carbon management index

CSI, L, and IL varied across soil layers in different management systems. CSI, L, and IL in RNAN were significantly different from values in other areas (Table 4).

Table 4. Carbon stock index (CSI), liability (L), liability index (IL), and carbon management index (CMI) of different management systems

Areas	CSI	L	IL	CMI
		0.00-0.05 m		
O40	0.91 aA	2.67 ab	2.59 ab	223.73 ab
O40G1	0.78 bBC	5.17 ab	5.02 ab	392.00 ab
O40G2	0.81 bABC	3.49 ab	3.39 ab	250.19 ab
O60	0.84 bABC	2.29 ab	2.23 ab	175.35 ab
O60G1	0.89 AB	1.74 ab	1.69 ab	149.37 ab
O60G2	0.81 bABC	2.41 ab	2.34 ab	174.02 ab
RNAN	0.76 bC	3.75 ab	3.64 ab	271.01 ab
Forest	1.00 a	1.20 a	1.00 a	100.00 a
Haying	0.77 b	1.44 b	1.39 b	115.02 b
		0.05-0.10 m		
O40	0.86 bAB	1.57 bAB	3.27 bAB	269.72 ab
O40G1	0.75 bCD	2.18 AB	4.54 AB	341.17
O40G2	0.77 b BCD	1.59 bAB	3.31 bAB	255.32 ab
O60	0.73 D	1.94 AB	4.04 AB	317.13
O60G1	0.90 bA	1.31 abAB	2.72 abAB	246.94 ab
O60G2	0.84 bABC	1.21 abB	2.51 abB	212.03 ab
RNAN	0.73 D	2.67 A	5.56 A	406.97
Forest	1.00 a	0.52 a	1.00 a	100.00 a
Haying	0.83 b	0.62 b	1.30 b	104.79 b
		0.10-0.20 m		
O40	0.93 aB	3.46 b	7.49 b	687.33 b
O40G1	0.92 aB	3.17 b	6.85 b	657.81 b
O40G2	0.95 aB	1.93 ab	4.18 ab	395.43 ab
O60	0.95 aB	1.85 ab	4.00 ab	376.51 ab
O60G1	1.13 A	1.45 ab	3.14 ab	340.74 ab
O60G2	0.95 aB	1.83 ab	3.95 ab	376.46 ab
RNAN	0.91 bB	3.70 b	8.00 b	722.62 b
Forest	1.00 a	0.45 a	1.00 a	100.00 a
Haying	0.84 b	1.70 b	3.67 b	310.54 b

Note: Values with the same lowercase letters in the columns are not significantly different from the reference values using Dunnett test at a 5% probability level. Values with the same uppercase letters in the columns are not significantly different from one another using Tukey test at a 5% probability level.

CSI of superficial soil layers was the lowest in RNAN, although this trend was not observed for TOC and TOCst. These results likely represent differences in the deposition of aboveground residues. This index may help differentiate managements that have similar TOC. Furthermore, the highest CSI was noted for the 0.10-0.20 m layer. CSI differed across management systems, corroborating the trends observed for TOC and TOCst.

Previous studies evaluating different IAPs reported increased CSI at the soil surface, which was attributed to the greater deposition of aboveground residues (Schiavo et al., 2011; Rossi et al., 2012b), corroborating the assertion that the evaluated management systems made a greater contribution to root residues at deep soil layers.

L and IL were high in RNAN due to low MOC and high COP, although this may be overestimation. High COP values indicate continuous deposition of crop residues; however, low MOC in RNAN indicates loss of carbon associated with mineral particles. Rossi et al. (2012b) and Piano et al. (2020) also obtained higher POCst and lower MOCst as a result of increased L and IL, ultimately increasing CSI, which is consistent with our results.

CSI of the last soil layer in O60G1 was higher than that in the reference areas, while L, IL and CMI of 0.05-0.10 m layer in O40G1, O60, and RNAN were comparable (Table 4). There were no differences among the evaluated layers or between the managed area and at least one reference area.

CSI of the first soil layer followed the same trends as TOC and TOCst, corroborating the results in different managed and reference areas. Higher L and IL values of all layers may be linked to values of POCst and MOCst, which were disproportionate to each other. According to Conceição et al. (2014), increased CSI, L, and IL reflect the relationships among the management systems and reference areas evaluated. Based on results obtained in different management systems, even a short adoption time would contribute to soil carbon maintenance.

CMI of all layers was considered high, which may be an overestimation, since POC and MOC were highly disproportionate, thereby masking the real results. Rossi et al. (2012b) also reported higher CMI values (159.8 and 113.7 for 0.00-0.05 m layer, 387.9 and 194.4 for 0.05-0.10 m layer, and 905.4 and 448.2 for 0.10-0.20 m layer) in areas with *Brachiaria* cultivated in succession with soybean and sorghum cultivated in succession with soybean crop, respectively, than in native forest (100).

Schiavo et al. (2011) evaluated different managements in areas with Oxisols of clayey texture and concluded that crop–livestock integration could achieve a CMI similar to or higher than the value for a natural vegetation area. They used Brazilian savannah as the reference area and obtained values of 101.77 and 111.61

for the 0.00-0.05 and 0.10-0.20 m layers, respectively, indicating soil carbon maintenance.

According to Silva et al. (2011), CMI values higher than or equal to the reference value indicate the potential of the evaluated management system to improve and promote the sustainability of agricultural systems in tropical regions through soil carbon maintenance. However, indices that precede CMI determination should be considered, as overestimation of these values is possible due to the low MOCst and high COPst, which can mask the actual effects of management systems; therefore, additional adoption time is needed to verify the effects of different management systems on soil.

4. Conclusions

Different IAPs, specifically O60G1 and O60G2, altered soil properties, including P content, CTC, TOC, POC, st, and CMI. The tested management systems may serve as alternatives for producers who wish to substitute exclusive hay production with crop–livestock integration in an area. Finally, adoption of these management systems can lead to better soil preservation and greater economic profits.

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