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Physical fractions of organic matter and mineralizable soil carbon as quality indicators in areas under different forms of use in the Cerrado-Pantanal Ecotone

Paulo Guilherme da Silva Farias · Camila Beatriz da Silva Souza · Jean Sérgio Rosset · Jefferson Matheus Barros Ozório · Elói Panachuki · Jolimar Antonio Schiavo · Paulo Ricardo Lima · Leandro Marciano Marra

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Abstract Understanding soil organic matter (SOM) dynamics is essential to employ management that contribute to the improvement of soil quality (SQ). The aim of this study was to characterize the SOM and evaluate the emission of mineralizable C (C-CO_2) in different management systems. The soil was collected in five managed areas: exposed soil (ES), conventional tillage system (CTS), no-tillage system (NTS), permanent pasture (PP) and sugarcane (SC), in addition to a forest area (NF), in the layers of 0–5, 5–10, and 10–20 cm. Total organic carbon (TOC), physical-granulometric fractionation of SOM were performed, determining the contents and stocks of particulate organic matter (C-POM; StockPOM) and mineral organic matter (C-MOM; StockMOM), in addition to calculating SQ indices. In addition to C-CO_2 emissions from the soil. The areas of PP and NTS presented the highest levels of TOC in the surface layer. The highest levels of C-MOM and StockMOM were observed in the PP area, besides higher CSI (carbon stock index), reaching 1.67 in the 10–20 cm layer. The areas of PP and SC were similar to the NF in all layers regarding CMI (carbon management index). In CTS, there were higher peaks in emissions and accumulation of C-CO_2. It is evident that the improvements in the SQ in the areas of PP, SC, and NTS caused mainly by the deposition of plant material and by soil revolving not being performed. In the CTS, high emission peaks of C-CO_2 show that the lack of conservation management practices contributes to the emission of greenhouse gases.

Keywords Lability · Management systems · C-CO_2 emission · Soil quality

Introduction

The substitution of natural areas by management systems aimed at agricultural production can negatively alter the physical (Ozório et al., 2019; Sales et al., 2018), chemical (Assunção et al., 2019; Souza et al., 2017, 2018), and biological attributes of the soil (Barbosa et al., 2018).

Conservation management systems, such as the no-tillage system (NTS) and well-managed pastures, are capable of maintaining or even increasing carbon stocks in the soil (Ozório et al., 2019; Rosset et al., 2019), contributing to the maintenance of productive capacity and mitigation of carbon dioxide (CO_2) emissions into the atmosphere, compared

P. G. da Silva Farias (✉) · C. B. da Silva Souza · E. Panachuki · J. A. Schiavo
State University of Mato Grosso Do Sul, Aquidauana University Unit, Aquidauana, MS 79200-000, Brazil
e-mail: pauloguilhermesf@hotmail.com

J. S. Rosset · P. R. Lima · L. M. Marra
State University of Mato Grosso Do Sul, University Unit, Mundo Novo, MS 79980-000, Brazil

J. M. B. Ozório
State University of Mato Grosso Do Sul, Dourados University Unit, Dourados, MS 79804-970, Brazil

to management systems with intense soil revolving (Besen et al., 2018; Falcão et al., 2020).

Understanding the dynamics of SOM in different management systems helps in the employment of practices that contribute to the improvement of soil quality (SQ) (Rossi et al., 2011a, b; Santos et al., 2021). One of the methods to evaluate the SQ is by analyzing the SOM compartments, such as carbon (C) of the physical fractions of the SOM (Cambardella & Elliott, 1992; Conceição et al., 2005). Among these fractions is labile C/particulate organic matter (POM), which is a good indicator of SQ (Bongiorno et al., 2019), especially in a short period of time, and C more recalcitrant/mineral organic matter (MOM), which is the most stable fraction of SOM (Cambardella & Elliott, 1992), being less sensitive to changes in a short period of time (Rossi et al., 2012).

From data from physical-granulometric fractionation, it is possible to obtain the C management index (CMI), proposed by Blair et al. (1995), which relates the soil C stock and its lability, calculated based on a reference system (vegetation in natural state). CMI is an important tool to analyze the effects of different management practices under the soil, because it analyzes to the same extent the effects of the type of system adopted on the quantity and quality of SOM (Conceição et al., 2014; Ghosh et al., 2018a, b).

The region of the Cerrado-Pantanal Ecotone is an important region of ecological interest and has its economy based on agricultural production, mainly on extensive livestock production. Thus, studies have aimed at evaluating the impacts of different forms of use on soil quality. Among these studies, the evaluation of the different fractions of SOM and the activity of microorganisms are extremely important, acting in the identification of agricultural systems that act in the maintenance of soil quality and assisting in mitigating environmental impacts (Barbosa et al., 2018; Sales et al., 2018; Souza et al., 2017).

In view of the above, in order to evaluate the influence of management systems on soil attributes, the aim of this study was to physically characterize soil organic matter and quantify the mineralizable carbon emission of the soil in different management systems in the Cerrado-Pantanal Ecotone region.

Material and methods

Soil collections were performed in an experimental area located at the State University of Mato Grosso do Sul, University Unit of Aquidauana, MS, Brazil (Fig. 1). The region is located between the coordinates 20° 27′ S and 55° 40′ W, with an average altitude of 174 m, being inserted in the region of the Cerrado-Pantanal Ecotone according to a study of the planning of the regions of the state of Mato Grosso do Sul (Semade, 2015) (Fig. 1). The climate of the region is classified by the international system of Köppen (Peel et al., 2007), as sub-humid hot tropical, with records of average annual precipitation of 1250 mm and average annual temperature of 26 °C. According to Schiavo et al. (2011), based on the Brazilian Soil Classification System (Santos et al., 2018), the soil of the study area is classified as Argissolo Vermelho distrófico típico (Santos et al., 2018), equivalent Acrisols (IUSS Working Group WRB, 2015), and Ultisols (Soil Survey Staff, 2014), physically deep, moderately drained, and with loamy sand texture. The experimental area has flat to smoothly wavy topography with an average slope of 0.03 m m^{-1}.

Five management systems and an adjacent reference area (native forest (NF)–cerrado stricto sensu vegetation) without anthropic action were evaluated, making up six differentiated systems. The management systems were implemented in 2012, i.e., with a known history of six years (soil collection performed in 2018). From the installation of the experiment, the management systems are handled according to Table 1.

In the period prior to the installation of the management systems, the soil where the experimental plots were installed had been being cultivated with the succession of pastures and annual crops for 20 years. During this period, the crops were carried out in CTS, and before the implantation of annual crops in alternation with pastures, a soil revolving operation with light disk harrowing was carried out up to a depth of 0.2 m, followed by two operations with leveling harrowing up to a depth of 0.1 m. Before the installation of the experiment (September 2012), soil collection was performed for chemical and particle size characterization in the layers of 0–0.2 and 0.2–0.4 m. The results are found in Table 2.

Soil samples were collected in four replicates per management system, and each composite sample was

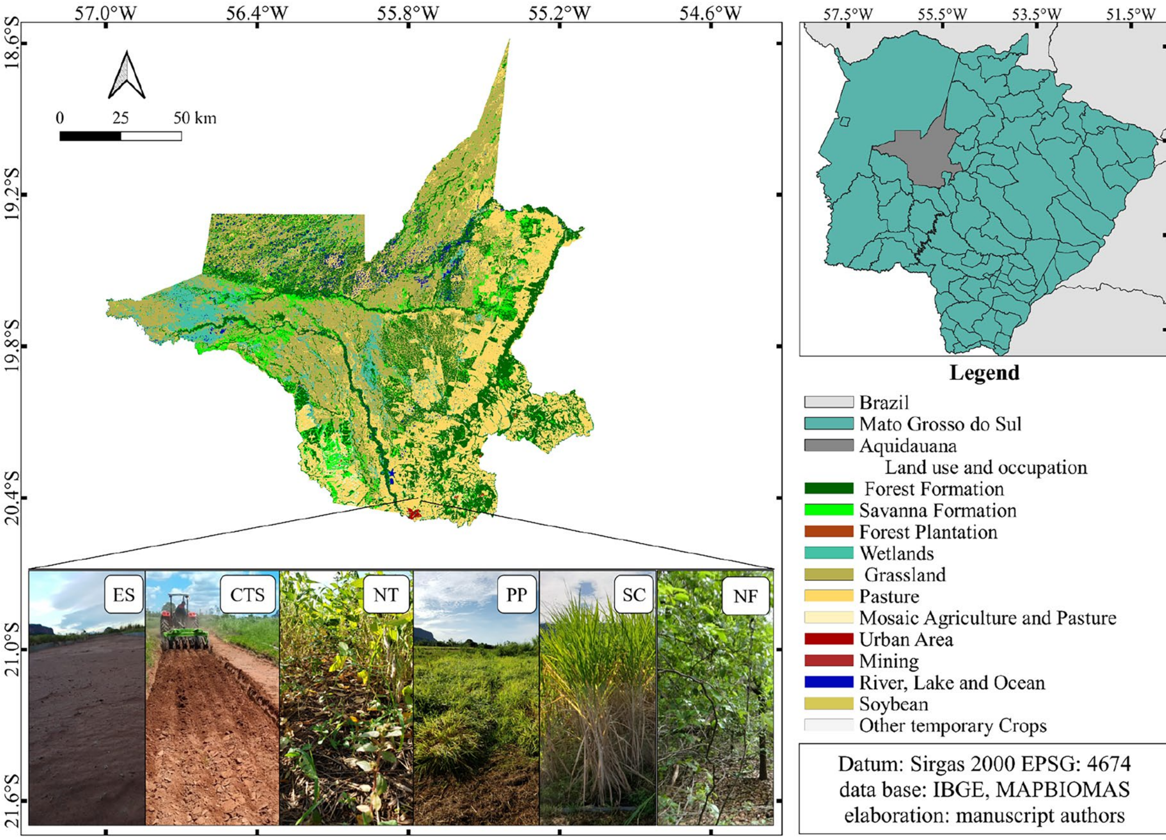

Fig. 1 Map of location and land use and occupation of the municipality of Aquidauana in the State of Mato Grosso do Sul (source: QGIS, version 3.14 "Pi"), land use and occupation data obtained from the MapBiomas Project (2021). Legend of map figures: ES, exposed soil; CTS, conventional tillage system; NTS, no-tillage system; PP, permanent pasture; SC, sugarcane; NF, native forest (area adjacent to the experimental plots with a straight line distance of 400 m)

Table 1 History and description of the different management systems installed

MS	Management history
ES	Managed with two plows using a disk plow up to a depth of 0.2 m and two leveling harrows at a depth of 0.1 m in the direction of the slope, without any cultivated plant species
CTS	Managed with two plows using a disc plow to a depth of 0.2 m and two leveling harrows at a depth of 0.1 m in the direction of the slope, with the alternating cultivations of soybean, corn, turnip, sunn hemp, and fallow in the summer and summer crops winter
NTS	Managed without soil disturbance, with alternating cultivation of soybean, corn, turnip, sunn hemp, millet, and fallow in summer and winter crops
PP	Continuously managed with the species *Brachiaria ruziziensis* without the practice of grazing with meat or milk animals
SC	Continuously managed with sugarcane using the RB 855,536 variety with annual cuts, without the practice of pre-harvest burning
NF*	Area adjacent to the experimental plots with vegetation of cerrado stricto sensu native forest. Used as a reference of the original condition of the soil

MS Management Systems, *ES* Exposed Soil, *CTS* Conventional Tillage System, *NTS* No-tillage System, *PP* Permanent Pasture, *SC* Sugarcane, *NF** Native Forest (area adjacent to the experimental plots with a straight line distance of 400 m)

Table 2 Physical and chemical attributes of the dystrophic Red Argisol of the experimental area at the time prior to the implementation of the experiment

Camada (m)	Sand	Silt	Clay	pH	C	OM	P	Ca	Mg	K	Al	m	V
	—g kg^{-1}—				—%—		mg dm^{-3}	—$cmol_c$ dm^{-3}—				—%—	
0.0–0.2	815	124	61	5.69	0.73	1.26	47.23	2.40	0.54	0.39	0.00	0.00	54.01
0.2–0.4	785	138	77	5.67	0.57	0.98	38.97	2.41	0.37	0.31	0.00	0.00	54.53

Source: Nagel (2014)

pH hydrogenionic potential, *C* Carbon, *OM* Organic Matter, *P* Phosphorus, *Ca* Calcium, *Mg* Magnesium, *K* Potassium, *Al* Aluminum, *m* Aluminum saturation, *V* base saturation

represented by five simple samples in the layers of 0–5, 5–10, and 10–20 cm. Undisturbed samples were also collected with the aid of a volumetric ring with four replicates in all plots/replicates and layers for subsequent soil density analyses (Ds).

Soil density analysis was performed by the volumetric ring method (Claessen, 1997). Total organic carbon (TOC) was determined by oxidation of organic matter by potassium dichromate in sulfuric medium and titrated with ammoniacal ferrous sulfate (Yeomans & Bremner, 1988).

The physical-granulometric fractionation of SOM was performed according to the method described by Cambardella and Elliott (1992). The indices for evaluation of soil organic fraction quality carbon stock index (CSI), SOM lability (L), lability index (LI), and carbon management index (CMI) were calculated as follows: CSI was obtained by the ratio between the TOC content of the treatment and the reference content. The L of the SOM of each treatment was obtained by the ratio between the C-POM and C-MOM contents. The LI was obtained by the ratio between the lability of the SOM of the treatment and that of the reference. The CMI was estimated by the product between LI and CSI $\times$ 100 (Blair et al., 1995). In addition, the carbon stocks of POM and MOM were calculated according to the equivalent mass method (Reis et al., 2018; Signor et al., 2016).

The analysis of mineralizable soil carbon (C-CO_2) released was performed according to the methodology of Mendonça and Matos (2005) under laboratory conditions. The titrations/evaluations were performed at intervals of 24 h in the first 7 days, 48 h between the 8th and 17th day, and 96 h between the 18th and 33rd day, as performed by Ozório et al. (2020).

The results were analyzed in a completely randomized design and submitted to variance analysis with *F*-test application, and the mean values compared to each other by the Tukey test at 5% probability with the aid of the GENES program (Cruz, 2006). In addition, a principal component analysis (PCA) was generated with the aid of the R Core Team program (2021), using the "prcomp" command of the vegan package (Oksanen et al., 2019), with the variables TOC, StockC, Sd, and SI.

Results and discussion

Regarding the Sd, in general, there were no significant differences between the managed systems, and for the 0–5 cm layer, there were differences only between PP, ES, and SC, with values of 1.19, 1.47, and 1.53 Mg m^{-3}, respectively. For the 5–10 cm layer, the PP presented lower Sd only in relation to the ES. This fact can be explained by the fact that there is no animal trampling, since the portion of PP cultivation is without grazing throughout the experimental period, in addition to the large biomass production and root volume of *Brachiaria* species (Santos et al., 2019).

In the 10–20 cm layer, there was a difference only between the NF and ES, with the NF presenting lower Sd. This fact is explained by the high carbon content and the intense biological activity of roots and fauna, which build tunnels, cavities, and galleries (Ferreira et al., 2020). In more subsurface layers of the soil, there is an increase in Sd in the managed plots, which is caused by the rearrangement of soil particles (Souza et al., 2005; Streck et al., 2004), because at the time of the implementation of the experiment, there was conventional tillage of the soil, and the implementation time was not enough to reduce Sd.

In addition, the NTS and CTS areas did not differ in any of the evaluated layers. This is probably because the NTS had only been employed for 6 years in the area, being in the phase of particle rearrangement (Souza et al., 2005; Streck et al., 2004) and SOM accumulation (Falcão et al., 2020; Rosset et al., 2014), with little change in soil structure, since changes in the physical attributes of the edatrophic environment in areas of NTS take longer to be effective (Anghinoni, 2007), as demonstrated in the study of Rosset, Lana, et al. (2014).

It is worth mentioning that in none of the systems and soil layers studied, the values of Sd exceeded the critical limit value for plant development in sandy and medium texture soils, stipulated at 1.75 Mg m^{-3}, which, from this value, plants have difficulty penetrating their roots (Reinert et al., 2008; Sales et al., 2016).

In the 0–5 cm layer, higher levels of TOC were observed in the areas of PP and NTS, with levels of 37.37 g kg^{-1} and 36.38 g kg^{-1}, respectively, being similar to each other (Table 3). This high concentration of TOC in these areas is due to the higher deposition of straw in the soil, since there is no grazing in the PP area and no soil revolving in the NTS area, added to the crop rotation in this same area. High TOC contents in NTS and PP areas were also found by Falcão et al. (2020) and Gazolla et al. (2015).

The lowest TOC contents in all studied layers were observed in the areas of ES and CTS (Table 3), evidencing that systems that do not preserve vegetation cover, added to the periodic revolving of the soil cause damage to the edaphic environment, reducing the content of C, corroborating studies also developed in the state of Mato Grosso do Sul (Falcão et al., 2020; Martins et al., 2020; Troian et al., 2020).

In 6 years of cultivation, the CTS area accumulated only 31%, 57%, and 55% of the TOC presented by the NTS area in the 0–5, 5–10, and 10–20 cm layers, respectively. This is due to the higher deposition of straw in the NTS (Brown et al., 2018), and the non-soil revolving, an activity that causes the breakdown of the aggregates, exposing the fractions of the SOM to microbial attack, causing rapid decomposition (Assunção et al., 2019; Lisboa et al., 2012; Rosset et al., 2019).

There were no differences between the TOC contents in the 0–5 and 5–10 cm layers of the SC and NF areas, with 27.26 and 27.55 g kg^{-1} and 25.27 and 22.80 g kg^{-1}, respectively. This is due to the non-burning of sugarcane in the annual pre-harvest of the crop, which favors high deposition of plant material, and consequent accumulation of TOC. Similar results were found by Rosset et al. (2014b) and by Oliveira Filho et al. (2017) in an experiment with sugarcane without burning, where equal or higher values of TOC were found in the SC system in relation to NF up to a depth of 30 cm.

The C contents and stocks of the physical fractions of the SOM, in addition to the carbon management indexes are presented in Table 3. In all layers studied, the areas of PP, SC, and NF presented the highest levels of C-POM, being higher than 4.00 g kg^{-1}, not differing from each other. These higher C-POM contents are attributed to the higher accumulation of TOC in these areas (Table 3), due to higher straw deposition on the soil surface. Similar results were observed by Costa et al. (2020), where an area with PP presented C-POM contents equal to or higher than the reference area (native forest) in all studied layers, analyzing the soil up to the depth of 0.20 cm.

Table 3 Soil density (Sd), total organic carbon content (TOC), particulate organic matter carbon (C-POM) and mineral organic matter (C-MOM), carbon stock of the MOP fraction (stock POM) and MOM (stock MOM) and values of the carbon stock index (CSI), lability (L), lability index (LI), carbon management index (CMI), and in the different management systems in the municipality of Aquidauana, Mato Grosso do Sul

MS	Sd	TOC	C-POM	C-MOM	Stock POM	Stock MOM	CSI	L	LI	CMI
	Mg m^{-3}	———g kg^{-1}———			——Mg ha^{-1}—-					
0–5 cm										
ES	1.47a	6.31d	0.73c	5.57d	0.99c	7.47d	0.22d	0.12ab	0.62a	14.86c
CTS	1.40ab	11.52c	1.03c	10.48c	1.39c	14.06c	0.42c	0.10b	0.52a	20.82c
NTS	1.42ab	36.38a	3.30b	33.08a	4.43b	44.37a	1.32a	0.10b	0.48a	63.68b
PP	1.19b	37.37a	4.59a	32.77a	6.16a	43.96a	1.36a	0.14ab	0.68a	91.88a
SC	1.53a	27.26b	4.54a	22.72b	6.09a	30.47b	0.99b	0.20ab	0.97a	95.65a
NF	1.34ab	27.55b	4.72a	22.83b	6.33a	30.62b	1.00b	0.21a	1.00a	100.00a
CV (%)	6.46	5.12	11.45	6.10	11.43	6.10	7.92	30.19	32.53	12.63
5–10 cm										
ES	1.60a	7.00e	0.78c	6.21 e	1.14c	8.97e	0.31d	0.12b	0.48b	15.09c
CTS	1.51ab	16.05d	0.68c	15.37d	0.99c	22.20d	0.70c	0.04c	0.17c	12.23c
NTS	1.53ab	27.99b	3.04b	24.94b	4.40b	36.03b	1.23b	0.12b	0.47b	58.23b
PP	1.37b	35.23a	4.62a	30.60a	6.68a	44.20a	1.55a	0.15b	0.59b	91.18a
SC	1.52ab	25.27bc	4.46a	20.81bc	6.44a	30.06bc	1.11b	0.22a	0.84a	92.33a
NF	1.44ab	22.80c	4.66a	18.14 cd	6.74a	26.20 cd	1.00b	0.26a	1.00a	100.00a
CV (%)	4.98	8.02	9.13	9.53	9.17	9.53	10.88	16.32	17.28	11.72
10–20 cm										
ES	1.71a	6.38f	0.61c	5.77 e	0.87c	8.23e	0.32e	0.10 cd	0.33 cd	11.21c
CTS	1.56ab	12.79e	0.94c	11.85d	1.34c	16.90d	0.64d	0.08d	0.26d	16.89c
NTS	1.52ab	23.13c	3.31b	19.82b	4.73b	28.26b	1.16bc	0.17bc	0.55bc	63.92b
PP	1.48ab	33.19a	4.44a	28.75a	6.33a	40.99a	1.67a	0.16bcd	0.51bcd	84.34ab
SC	1.56ab	25.36b	4.56a	20.79b	6.50a	29.65b	1.28b	0.22b	0.72ab	91.93a
NF	1.42b	19.86d	4.66a	15.20c	6.65a	21.67c	1.00c	0.31a	1.00a	100.00a
CV (%)	7.62	6.55	12.09	8.34	12.1	8.34	7.92	21.06	22.15	15.13

Means followed by equal letters in the column, in each layer, do not differ from each other by the Tukey test ($p \leq 0.05$)

CV Coefficient of Variation, *MS* Management Systems, *ES* Exposed Soil, *CTS* Conventional Tillage System, *NTS* No-tillage System, *PP* Permanent Pasture, *SC* Sugarcane, *NF* Native Forest

Higher levels of C-POM were observed in the NTS than in the CTS in all layers evaluated, with the CTS presenting C-POM contents equivalent to the NTS in the order of 31%, 22%, and 28% for the layers of 0–5, 5–10, and 10–20 cm, respectively. This is due to the area with CTS being frequently revolved, potentiating C oxidation (Melo et al., 2016).

The management systems with the highest C-MOM contents were PP and NTS in the 0–5 cm layer, with 32.77 g kg^{-1} and 33.08 g kg^{-1}, respectively (Table 3). These higher levels are mainly due to the higher levels of TOC in these areas (Table 3) and, moreover, to the process of humification of SOM, due to the non-revolving, in which the POM newly deposited on the soil through the action of organisms undergoes decomposition and stabilization process, which contributes to a gradual increase in the levels of MOM (Ozório et al., 2020; Rosset et al., 2019).

In the layers of 5–10 and 10–20 cm, the PP area presented higher levels of C-MOM, with 30.60 g kg^{-1} and 28.75 g kg^{-1}, respectively (Table 3). This can be explained by the large volume of grass roots in the deepest layers of the soil, which demonstrates the contribution in the accumulation of C through the root system (Martins et al., 2020; Salton et al., 2008).

Similarly as for C-POM, CTS presented lower C-MOM contents in relation to NTS in all layers. For this fraction of C more recalcitrant in the soil, the CTS accumulated 32%, 61%, and 60% in relation to the NTS in the layers of 0–5, 5–10, and 10–20 cm, respectively. These comparative results show that C-POM is more sensitive to changes in management systems in relation to C-MOM, because the loss of this labile fraction was more evident in relation to C-MOM after 6 years of cultivation. These results demonstrate the efficiency of the NTS in promoting maintenance of soil quality, even in the first years of cultivation (implementation phase of the system) (Anghinoni, 2007).

Regarding the stock of particulate organic matter (StockPOM), the areas of PP, SC, and NF presented the highest values in all layers, being higher than 5 Mg ha^{-1} (Table 3). This is due to the greater amount of waste deposited on the soil surface in these systems (Falcão et al., 2020; Ferreira et al., 2020), and the non-revolving, thus keeping the SOM protected inside the aggregates. On the other hand, the ES and NTS areas presented lower StockPOM, with respective values of 0.99 Mg ha^{-1} and 1.39 Mg ha^{-1} for the 0–5 cm, 1.14 Mg ha^{-1} and 0.99 Mg ha^{-1} for the 5–10 cm layer, and 0.87 Mg ha^{-1} and 1.34 Mg ha^{-1} in the 10–20 cm layer (Table 3). These lower values in relation to conservation systems are due to the lowest levels of TOC, C-POM, and C-MOM (Table 3).

The areas of NTS and PP presented higher StockMOM in the 0–5 cm layer, with respectively 44.37 Mg ha^{-1} and 43.96 Mg ha^{-1}. While in the layers of 5–10 and 10–20 cm, the PP area showed higher StockMOM values (Table 3), as also reported by Nanzer et al. (2019). These results demonstrate the efficiency of pastures in maintaining or increasing the SQ when well-managed, and pasture when used in degraded areas of crops can contribute to the improvement of edaphic properties (Nanzer et al., 2019).

The areas of NF and SC were similar in the storage of MOM in the 0–5 cm layer, but the PP and NTS areas were lower. The PP, SC, NTS, and NF systems showed higher StockMOM when compared to the NTS and ES systems. These higher StockMOM values in these areas are due to the physical protection of MOM by microaggregates, since in these systems there is no breakdown of aggregates by soil revolving (Melo et al., 2016; Nanzer et al., 2019), which is evidenced by the ES and CTS presenting the lowest stocks of MOM in all the evaluated layers (Table 3).

The areas of PP, NTS, and SC presented CSI values higher than 1.00 in all layers evaluated, except for the SC area in the 0–5 cm layer (Table 3). CSI values above 1.00 represent C storage higher than the NF area (Blair et al., 1995). In the layers of 5–10 and 10–20 cm, the PP area presented higher values CSI in relation to the other areas studied, with values of 1.55 and 1.67, respectively. Differently from what was observed in the areas of ES and NTS with maximum values 0.70 (Table 3). This is due to the rapid mineralization of the SOM that is deposited, which is caused due to the high temperature, rainfall and, mainly due to the breakdown of the aggregates by soil revolving, which exposes the SOM to the microbial attack.

The NTS presented higher CSI when compared with CTS in all layers evaluated (Table 3). Similar results were found by Loss et al. (2011) in Red-Yellow Argisol in the Atlantic Forest biome and by Conceição et al. (2014) in dystrophic Red Argisol in the Pampa-Atlantic Forest Ecotone.

Evaluating the L of the SOM, all values were below 1.0, which indicates predominance of the MOM fraction in relation to POM. In the 0–5 cm layer, there were differences only between the NF, CTS, and NTS, with values of 0.21, 0.10, and 0.10, respectively. Regarding the 5–10 cm layer, the SC presented L values similar to the reference area, demonstrating that the system is maintaining the quality of the organic fraction in relation to the NF (Blair et al., 1995). Lability is a great indicator of SQ (Benbi et al., 2015; Jha et al., 2017), demonstrating the relationship between the labile and recalcitrant fractions of the SOM, and this relationship is essential to keep the SQ over the years of cultivation (Majumder & Kuzyakov, 2010). In the 0–5 cm layer, all managed systems demonstrated LI values similar to the NF. In the 5–10 cm layer, a higher LI value was observed in the SC area than the other management systems, but similar to the NF (Table 3).

The areas of PP and SC presented higher CMI among the managed areas, being similar to the area of NF in all layers, reaching 95.65 in the SC area in the 0–5 cm layer. This is probably because they are type C4 plants, which contribute to the accumulation of C in the soil due to the longer decomposition time (Rossi et al., 2011a, b).

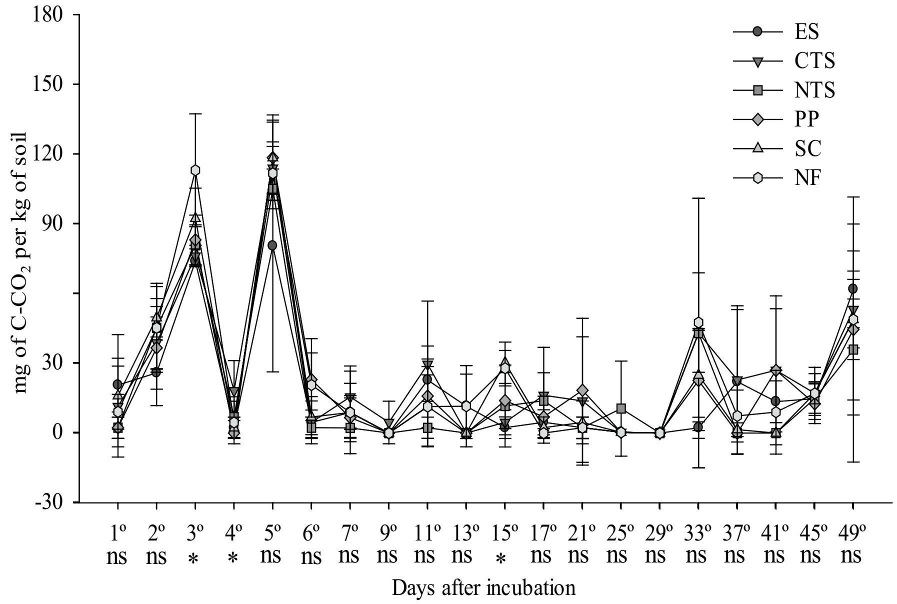

Fig. 2 Daily evolution of $C\text{-}CO_2$ in soil samples in the 0–0.05 m layer, incubated until the 49th day of evaluation in different management systems in the municipality of Aquidauana, Mato Grosso do Sul. The error bars being calculated as a function of the standard deviation of the means * = significant by the F a test 5%. Ns, not significant by the *F* test at 5%; ES, exposed soil; CTS, conventional planting system; NTS, no-tillage system; PP, permanent pasture; SC, sugarcane; NF, native forest

Due to the higher levels of TOC, C-POM, and C-MOM, in addition to the amount of these fractions (Table 3), the NTS in all the evaluated layers presented CMI higher than the area with CTS, reaching values of 63.92 in the 10–20 cm layer. Loss et al. (2011), with higher CMI in an area cultivated with NTS. The ES, CTS, and NTS presented lower CMI when compared to NF. These results demonstrate that the short time of implementation of the NTS was not sufficient to increase the quantity and quality of the SOM indicated by the CMI (Rosset et al., 2019).

From the first to the third day of soil incubation, there was an increase in $C\text{-}CO_2$ emission, with a sharp emission fall on the fourth day, with a new rise on the fifth day of incubation. From the sixth day of soil incubation, there was a drastic decrease

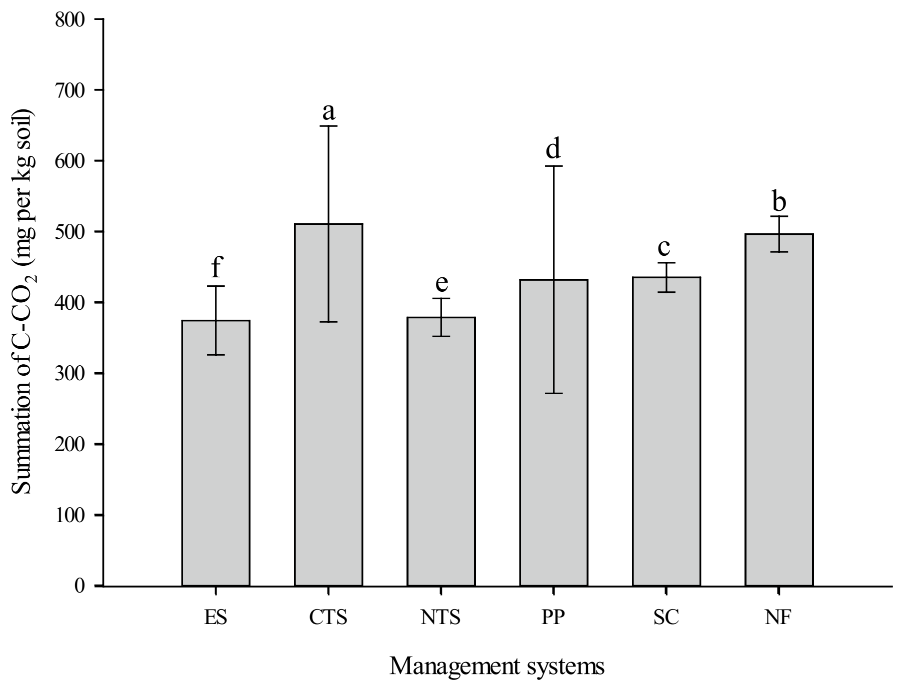

Fig. 3 Accumulation of $C\text{-}CO_2$ during the entire incubation period of the soil in different management systems in the municipality of Aquidauana, Mato Grosso do Sul. Means followed by equal letters do not differ from each other by the Tukey test ($p \leq 0.05$). The error bars being calculated as a function of the standard deviation of the means. ES, exposed soil; CTS, conventional tillage system; NTS, no-tillage system; PP, permanent pasture; SC, sugarcane; NF, native forest

in the maximum values of C-CO_2 emission peaks (Fig. 2). This decrease in emissions happens due to the death of a certain amount of microorganisms, favoring the reduction of subsequent emissions. However, in general, the later peaks are because dead microorganisms serve as food for the remnants (Gonçalves et al., 2002; Loss et al., 2013), an effect known as priming (Ghosh et al., 2018a, b). This pattern was also observed by Rosset et al. (2019) and Ozório et al. (2020) in studies in the Western region of the State of Paraná and by Santos et al. (2021) in the state of Mato Grosso do Sul.

In general, it is observed that the CTS area presented high peaks of C-CO_2 emission even though it had lower TOC and POM levels to areas with systems without soil revolving and also the NF area (Table 3). This is because soon after the incorporation of plant residues after harvest in the CTS area, soil samples were collected, and soil revolving contributes to the breakdown of aggregates and exposure of SOM, which favors its decomposition by microorganisms (Bandyopadhyay & Lal, 2014; Rosset et al., 2019).

It is observed that the area with CTS presented the highest accumulation of C-CO_2 emission, with 511.17 mg kg of soil^{-1}, being even higher than the NF that presented 496.79 mg kg of soil^{-1} (Fig. 3). This fact is due to soil revolving in the period prior to collection as previously highlighted.

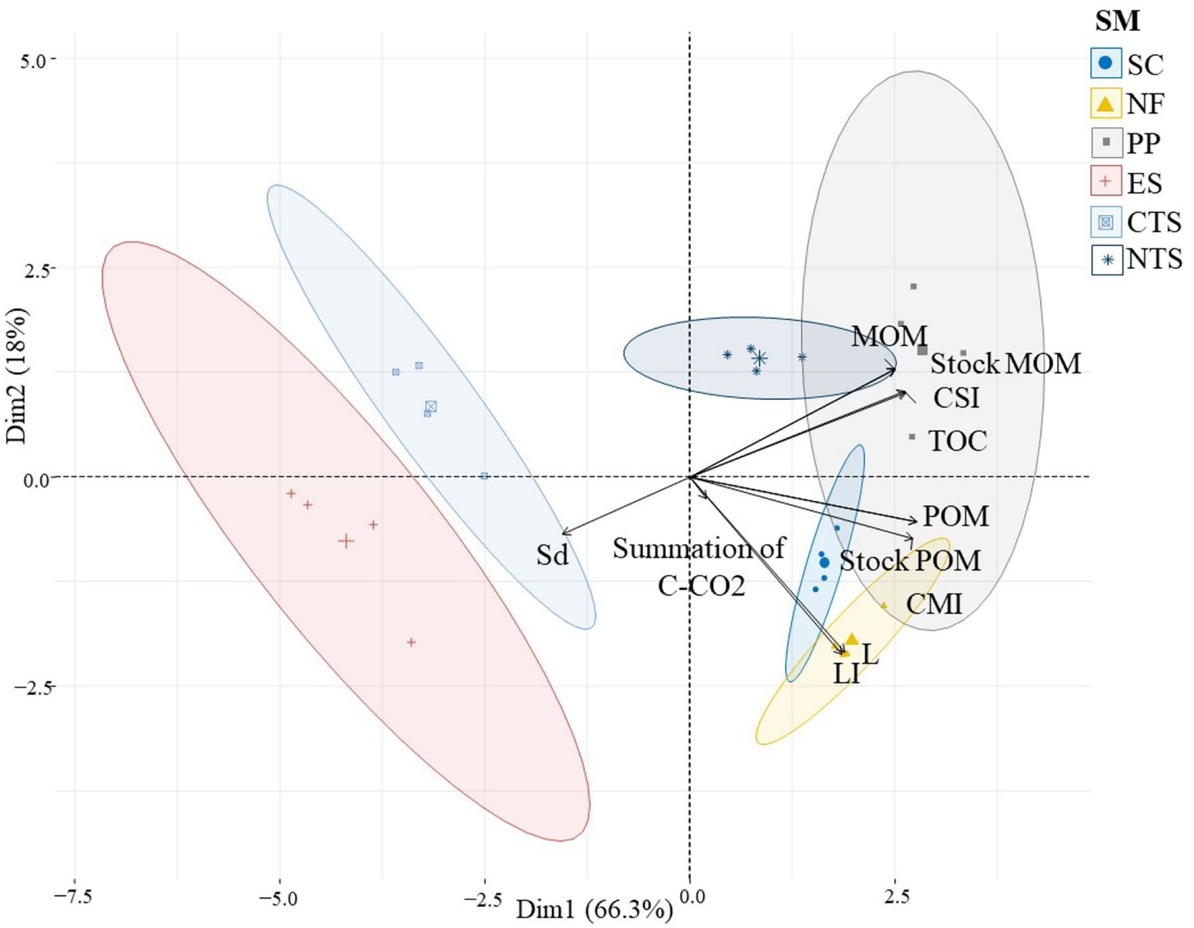

Fig. 4 Principal component analysis of the variables TOC, Sd, POM, MOM, StockPOM, StockMOM, CSI, L, LI, CMI and C-CO_2 sum in the different management systems evaluated in the Pantanal region of Mato Grosso do Sul. MS, management systems; ES, exposed soil; CTS, conventional tillage system; NTS, no-tillage system; PP, permanent pasture; SC, sugarcane; NF, native forest

Differently from what occurred in the ES area that presented lower C-CO_2 emissions, even with soil revolving. However, in the ES area, there is no planting of any plant species, so, even if there is periodic revolving of the soil, there are no significant minimum amounts of TOC and POM to benefit microbial activity and, consequently, C-CO_2 emissions. It is important to highlight that systems such as ES, which do not have vegetation cover, are prone to erosive processes, in view of the low structural stability, which is linked to low levels of C (Bonilla et al., 2015).

The NTS presented one of the lowest C-CO_2 emissions from the soil, 379.28 mg kg of soil^{-1}, which may be linked to the protection of organic matter by the aggregates in rearrangement after 6 years of conduction, thus hindering the degradation of the soil by microorganisms, which demonstrates the efficiency of conservation systems in stocking C and improving soil quality (Hazarika et al., 2009; Tisdall & Oades, 1982).

In the principal component analysis (PCA), the axis explains 66.6% of the data, the sum of axes 1 and 2 explain 84.5% of the variability of the data (Fig. 4). The main variation observed is the separation of the ES and CTS areas from the other evaluated areas. The variable Sd and sum of C-CO_2 showed greater correction with the NTS and ES areas, which shows the inefficiency of these systems in reducing Ds (Falcão et al., 2020), as well as the difficulty of keeping C in the soil, being easily emitted into the atmosphere, results also obtained by Medeiros et al. (2020).

On the other hand, the contents of TOC, POM, and MOM, as well as the stocks of POM and MOM were associated with the areas of NTS, PP, SC, and NF (Fig. 4), evidencing the contribution of these systems to improve soil quality. Different studies report the contribution of these systems to promote soil quality, through the variables presented (Assunção et al., 2019; Bordonal et al., 2018; Ferreira et al., 2020; Martins et al., 2020; Ozório et al., 2019, 2020; Salton et al., 2008; Troian et al., 2020).

Conclusions

Systems with conservation management promoted improvements in soil quality demonstrated by higher organic carbon contents and carbon management indexes. Conventional systems promoted losses of organic matter and greater emission of C-CO2 from the soil, demonstrating the inefficiency of conventional management in reducing greenhouse gas emissions.

With the data obtained in this research, it is possible to verify the collaboration of conservation systems for soil quality; however, we suggest further research regarding the time of stabilization of soil organic matter under different management systems in different ecosystems.

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Data availability All data referring to this study are available with the corresponding author and will be made available upon request by email.

Code availability Data from this study were analyzed using the R and R studio program.

Declarations

Conflict of interest The authors declare no competing interests.

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