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Influence of sugarcane management on the carbon management index and soil aggregation

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ABSTRACT

This study aimed to evaluate the physical fractions of soil organic matter (SOM), carbon management indexes (CMI), and the aggregation in soil areas of sugarcane cultivation. Five sugarcane cultivated areas were evaluated, in addition to a reference area of native forest (NF). Samples of disturbed soil, soil layers and undisturbed were collected In the disturbed samples, total carbon (TC), physical-granulometric fractionation of SOM were determined with subsequent CMI calculations. Aggregation analysis was performed in the undisturbed samples, and the weighted mean diameter (WMD), geometric mean diameter (GMD), and percentage of aggregates retained in the different sieve classes were determined, in addition to determining the TC contents of each aggregate class. The NF presented the highest levels of TC, particulate carbon (C-POM), and mineral carbon (C-MOM). Among the managed areas, the area that received filter cake and vinasse application stood out with higher TC, C-POM, and C-MOM levels in the most subsurface layer. All areas cultivated with sugarcane presented CMI lower than the area with NF. The worst aggregation indexes were observed in the area with management with burning in the pre-harvest and only filter cake application. The best aggregation indexes were in the NF. The area with the practice of burning, but with the joint application of filter cake and vinasse for 16 consecutive years, provided the highest aggregation of soil and best CMI among the areas cultivated with sugarcane.

Keywords: Environmental assessment, Waste application, Soil structure.

Influência do manejo da cana-de-açúcar no índice de manejo de carbono e agregação do solo

RESUMO

Este trabalho teve como objetivo avaliar as frações físicas da matéria orgânica do solo (MOS), os índices de manejo de carbono (IMC) e a agregação em áreas de cultivo de cana-de-açúcar. Foram avaliadas cinco áreas cultivadas com cana-de-açúcar, além de uma área de referência de mata nativa (MN). Foram coletadas amostras de solo perturbado, camadas de solo e amostras indeformadas. Nas amostras perturbadas, carbono total (CT), fracionamento físico-granulométrico da MOS foram determinados com cálculos subsequentes de IMC. A análise de agregação foi realizada nas amostras indeformadas, determinando-se o diâmetro médio ponderado (DMP), o diâmetro médio geométrico (DMG) e a porcentagem de agregados retidos nas diferentes classes de peneiras, além de determinar os teores de CT de cada classe de agregados. O MN apresentou os maiores teores de CT, carbono particulado (C-MOP) e carbono mineral (C-MOM). Dentre as áreas manejadas, destacou-se a área que recebeu torta de filtro e aplicação de vinhaça com maiores teores de CT, C-MOP e C-MOM na camada mais subsuperficial. Todas as áreas cultivadas com cana-de-açúcar apresentaram IMC inferior à área com MN. Os piores índices de agregação foram observados na área com manejo com queima na pré-colheita e apenas aplicação de torta de filtro. Os melhores índices de agregação foram no MN. A área com prática de queima, mas com aplicação conjunta de torta de filtro e vinhaça por 16 anos consecutivos, proporcionou a maior agregação de solo e melhor IMC entre as áreas cultivadas com cana-de-açúcar.

Palavras-chave: Avaliação ambiental, Aplicação de resíduos, Estrutura do solo.

1. Introduction

The conversion of native areas into agricultural areas in the most diverse regions of Brazil added to the most different types of soil, climate, and cultivation technology, can cause significant changes in physical (Sales et al., 2018; Ozório et al., 2019), chemical (Souza et al., 2017; Souza et al., 2018; Assunção et al., 2019) and biological attributes of the soil (Barbosa et al., 2018) over the years of cultivation.

Given the need for alternative energy sources, Brazil is privileged, as it is the largest producer of sugarcane globally (Camargo et al., 2019) and a pioneer in ethanol production. Sugarcane still stands out as one of the crops used when replacing native areas for cultivation systems, in which the intensification of crops, added to inadequate soil management, has the acceleration of soil degradation processes (Freitas et al., 2018; Takeshita et al., 2020).

With the increase in the area cultivated with sugarcane, there is an increase in the production of waste from the sugar-alcohol industry, such as vinasse and filter cake. These wastes can be used in agriculture as sources of nutrients, reducing environmental contamination and fertilization costs (Fravet et al., 2010), with benefits to soil chemical (Rosset et al., 2014) and physical attributes, favoring the growth of the root system (Bilgili et al., 2019), which contributes to the stabilization of soil aggregates.

Areas managed with sugarcane crops in Brazil have undergone changes in recent years, mainly due to the prohibition of straw burning before harvest (Franchini et al., 2020). Studies report that sugarcane harvesting without the use of pre-harvest burning increases total carbon (TC) contents in soil (Campos et al., 2016), which favors soil physical, chemical, and biological quality (Bordonal et al., 2018a), in addition to improving soil aggregation (Blair, 2000. In addition to TC, the size and stability of aggregates are key indicators of soil quality (SQ) (Melo et al., 2019). The understanding of the processes of structure formation of the soil involves the knowledge of the interaction of the physical, chemical, biological, and geological aspects of the edaphic environment (Falcão et al., 2020).

Another effective method in evaluating SQ is analyzing SOM compartments, such as carbon (C) of the physical-granulometric fractions of SOM (Cambardella and Elliott, 1992). Among these fractions is the particulate organic matter (POM), which has a high potential for indication of SQ (Rosset et al., 2019), mainly in a short period, and mineral organic matter (MOM), being the most stable fraction of SOM, besides being less sensitive to changes in a short period (Rossi et al., 2012).

Moreover, with the physical-granulometric fractionation of the SOM, it is possible to obtain the C management index (CMI) proposed by Blair et al. (1995). This index relates the quantity and quality of C based on a reference system. CMI is also an essential tool for analyzing the SQ (Ghosh et al., 2018). Given the different forms of sugarcane cultivation concerning soil management and crops adopted, this study aimed to evaluate the physical fractions of organic matter, aggregation, and carbon management indexes of a Latossolo Vermelho cultivated with sugarcane, under different harvest management and application of waste of the sugar-alcohol industry.

2. Material and Methods

Soil collection was carried out at the LDC-SEV Plant (Louis Dreyfus Commodities - Santelisa Vale), located in Maracaju, MS (Figure 1). Maracaju - MS is located between coordinates 21º37' S and 55º08' O, with an average altitude of 400 m. The climate of the region, according to the Köppen classification, is Aw-type - tropical humid (Peel et al., 2007), with an average annual rainfall of 1200 mm, maximum and minimum temperatures of 33 °C, and 19.6 °C, respectively (Semade, 2015).

The soil of the sampled areas was classified as Latossolo Vermelho with clayey texture (Santos et al., 2018), equivalent Ferralsols (Iuss Working Group Wrb, 2015) and Oxisols (Soil Survey Staff, 2014), with particle-size composition in the 0-0.2 m layer of 191, 218, and 591 g kg^{-1} of sand, silt, and clay, respectively (Rosset et al., 2014). Soil collection for fractionation granulometric was performed in the 0-0.05, 0.05-0.10, and 0.10-0.20 m soil layers. The composite samples were formed by ten simple samples, with five replicates for each area and layer. For the aggregate stability analyses, soil collection was carried out in the 0-0.10 m layer, where undisturbed soil blocks with dimensions of 0.20 x 0.20 x 0.10 m were removed with preservation of the soil structure, with five replications.

The treatments consisted of different areas that received harvest management and application of different wastes, described as 1) harvest area without the use of burning associated with vinasse application. The other areas had a burning process that preceded the harvest, differentiated by the use or not of the wastes: 2) without application, 3) application of vinasse, 4) application of filter cake, and 5) joint application of filter cake and vinasse. In addition to these areas, an area of native forest with Cerrado *stricto sensu* vegetation was used as a reference for evaluation. Detailed descriptions of the sampled areas are shown in Table 1. The chemical characterization of vinasse and filter cake used in sugarcane management systems is found in Table 2.

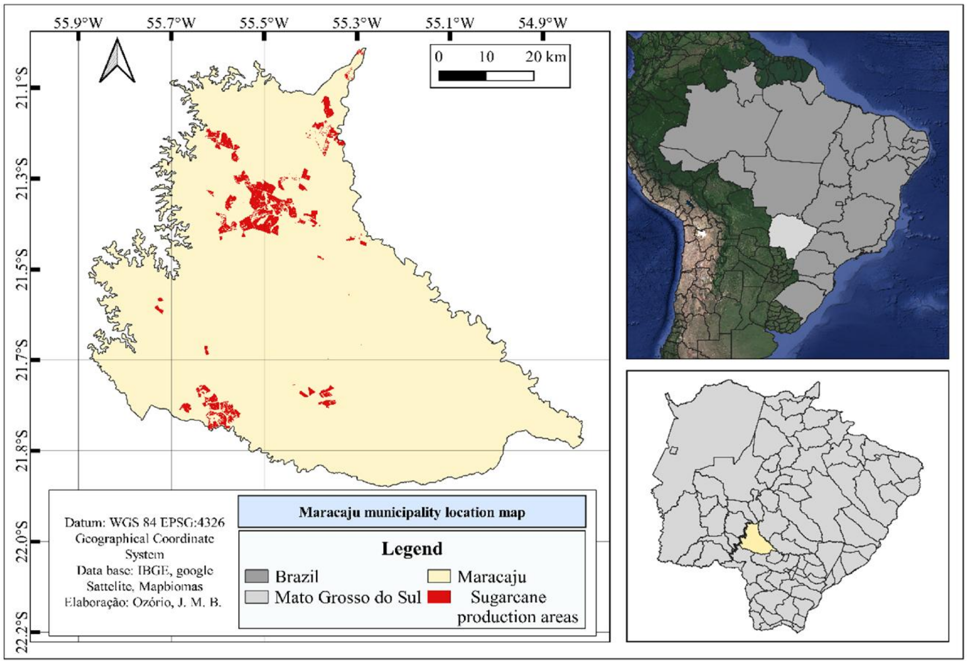

Figure 1. Map of location and land use and occupation in Maracaju, MS, in 2019. The database used is the source of the Mapbiomas Project (2021).

Table 1. History and description of the experimental areas studied.

System of use and management	Sugarcane cultivation areas	Soil tillage
Without burning with vinasse (RV)	Mechanized harvesting without burning for three years.	With a disc harrow and application of 4 and 2 t ha^{-1} of limestone and gypsum, respectively, in addition to a vinasse application per year (3 years).
Burning without waste (BW)	Manual harvesting using burning.	With a disc harrow and application of 5 and 2 t ha^{-1} of limestone and gypsum, respectively. There are no waste applications in this area.
Burning with vinasse (BV)	Manual harvesting using burning.	With a disc harrow and application of 3 and 2 t ha^{-1} of limestone and gypsum, respectively, in addition to a vinasse application per year (16 years).
Burning with filter cake (BFC)	Mechanized harvesting using burning.	With a disc harrow and application of 3 and 2 t ha^{-1} of limestone and gypsum, respectively, in addition to a filter cake application per year (3 years).
Burning with filter cake + vinasse (BFCV)	Manual harvesting using burning.	With a disc harrow and application of 3 and 2 t ha^{-1} of limestone and gypsum, respectively, in addition to a filter cake and vinasse application per year (16 years).
Native Forest (NF)	------	Area adjacent to areas cultivated with sugarcane, used as a reference to the original soil condition.

The total carbon content (TC) was analyzed by dry combustion and the quantification of CO_2 released with an infrared sensor of the Shimadzu analyzer, model TOC-VCPN with SSM-5000A (Shimadzu from Brazil, São Paulo, SP), using samples of approximately 0.5 g. The physical-granulometric fractionation of SOM was performed according to the method described by Cambardella and Elliott (1992). In 20 g of soil, 60 ml of sodium hexametaphosphate solution (5 g L^{-1}) was added, and the samples were shaken for 16 hours in a horizontal shaker. After homogenization, wet sieving was performed using a 53 µm sieve.

The material retained in the 53 µm sieve was considered the particulate organic matter (POM) associated with the sand fraction. The material that was not retained was considered the mineral organic matter (MOM) associated with silt and clay fractions. Then, the material retained in the 53 µm sieve was dried in an oven at 50 ^{o}C to be ground and analyzed for C content, following the same procedure of TC. C-MOM was obtained from the difference between TC and C-POM. Subsequently, the indexes to evaluate the quality of the SOM were calculated, which were the carbon stock index (CSI), lability (L), lability index (LI), and carbon management index (CMI), according to Blair et al. (1995).

Table 2. Chemical composition of the vinasse and filter cake used in the sampled areas.

Variables	Vinasse	Filter cake*
N	0.13 g L^{-1}	11.90 g kg^{-1}
P	0.01 g L^{-1}	10.00 g kg^{-1}
K	0.64 g L^{-1}	4.10 g kg^{-1}
Ca	0.28 g L^{-1}	17.75 g kg^{-1}
Mg	0.12 g L^{-1}	3.23 g kg^{-1}
S	0.33 g L^{-1}	6.00 g kg^{-1}
Na	18.80 mg L^{-1}	180.00 mg kg^{-1}
Cu	0.20 mg L^{-1}	130.00 mg kg^{-1}
Fe	9.20 mg L^{-1}	36.00 g kg^{-1}
Zn	0.20 mg L^{-1}	133.00 mg kg^{-1}
Mn	4.20 mg L^{-1}	710.00 mg kg^{-1}
Moisture	-	69.74 %

* Results expressed in dry mass.

To determine the stability of aggregates, soil samples were submitted to sieving in water according to Kemper and Chepil (1965). Initially, dry sieving was performed with the air-dried samples to separate the aggregates with diameters between 8.00 mm and 4.00 mm in a mechanical shaker for two minutes. From the fraction retained in the 4.00 mm sieve, 50 g of aggregates were separated, an amount that was moistened with water by capillarity, on filter paper for 10 minutes.

After this process, the samples were placed in a mechanical shaker of vertical oscillation of the Yoder type, at a frequency of 30 oscillations per minute, for 10 minutes, using a set of sieves with opening meshes of 2.00 mm, 1.00 mm, 0.5 mm, 0.25 mm, 0.125 mm and 0.053 mm. The fraction of aggregates retained in each sieve was placed in aluminum cups with the aid of water jets and taken to the oven at a temperature of 55 ºC. After 48 hours, on average, the samples were weighed, and the results were corrected according to the initial humidity of the sample.

With the mass of the fractions retained in each sieve, the weighted mean diameter (WMD) Kiehl (1979), geometric mean diameter (GMD) (Kemper and Rosenau, 1986), and the percentage of aggregates retained in each sieve were calculated. From the aggregates retained in the different classes of sieves, samples were taken to determine the TC in each fraction of these aggregates through dry combustion.

The data were evaluated in a completely randomized design, where sugarcane management systems were considered treatments. After analysis of variance, when significant, the means were grouped according to the Scott-Knott test at 5% probability. Additionally, a Pearson correlation analysis was performed between the granulometric fractions of the SOM, C management indexes, aggregation indexes, and the C of the aggregate fractions.

3. Results and Discussion

In the NF area, the highest levels of TC were verified in the 0-0.05 m and 0.05-0.1 m layers, with contents of 57.64 g kg^{-1} and 40.86 g kg^{-1}, respectively. These results demonstrate that the form of soil use since the conversion of native areas, through intense soil management in sugarcane cultivation over the years of cultivation, influenced the loss of TC in the most superficial layers. Similar results were observed in several studies with sugarcane crops in several soil conditions, climate, and management adopted. (Satiro et al., 2017; Bordonal et al., 2018b; Lal, 2018; Gomes et al., 2019).

In the 0.05-0.1 m layer, intermediate levels of TC were verified in the areas of BV and BFCV, with contents of 21.88 and 27.38 g kg^{-1}, respectively. The lowest levels were observed in RV, BW, and BFC areas, with 16.11, 16.22, and 17.92 g kg^{-1}, respectively. It is essential to highlight that the TC of the BFCV area was similar to the NF in the most subsurface layer evaluated. The other areas did not differ from each other, ranging from 17.16 g kg^{-1} to 19.48 g kg^{-1} of TC. The results showed that, even with burning the crop in pre-harvest, the joint application of filter cake and vinasse increased the TC content by 0.10-0.20 m. Similar results were also observed by Vasconcelos et al. (2014) in a study that evaluated the physical quality of Latossolo Amarelo under different sugarcane management systems.

The different sugarcane cultivation systems directly influenced the amount of C of the granulometric fractions. There was a higher amount of C-MOM concerning C-POM in all areas and layers evaluated, indicating the presence of more humified C (Table 3). The C-POM contents of the NF area differed from the managed areas of sugarcane in the first two layers, being similar to the BFCV area at 0.10-0.20 m. A consistent result with the similarity between the levels of TC presented by these areas in this layer (Table 3). Bilgili et al. (2019) report that applying mineral fertilizers and organic residues can influence the increase of TC and, consequently, in C-POM and C-MOM over the time of application. In the 0-0.05 and 0.05-0.1 m layers, the managed areas showed no difference in C-POM contents.

The different sugarcane managements influenced C-MOM content compared to the levels verified in the NF area, with the largest differences observed in the 0-0.05 m layer (Table 3). In this layer, the highest levels were observed in the NF area, followed by the BFCV area, with contents higher than 20.00 g kg^{-1}. The lowest levels were verified in RV, BW, and BFC areas. Soil management in the preparation of areas for cultivation and replanting of the crop hinders the process of stabilization of C, reducing the levels of recalcitrant C (Oliveira et al., 2019), mainly in the first soil layer, where the soil/atmosphere ratio occurs with greater intensity (Olaya et al., 2017).

In the 0.05-0.10 and 0.10-0.20 m layers, the BFCV and NF areas had higher levels of C-MOM, higher than 19.00 g kg^{-1}; and 15.00 g kg^{-1} in the 0.05-0.10 and 0.10-0.20 m layers. These results show that the combination of filter cake with vinasse contributes to promoting the increase of SOM in more stable C fractions over the years of applications. Only the BFCV area obtained CSI similar to the NF area in all evaluated layers (Table 3). This indicates that the other evaluated systems, which do not have the combination of filter cake and vinasse, had a lower potential to stock C in the soil over the years of cultivation.

In all areas and layers, L values were below 1.00, which represents a predominance of the most recalcitrant fraction of C concerning the fraction of greater lability. The L of the SOM showed differences only in the 0.05-0.10 m layer. The areas of BFC and BFCV presented lower values than the other areas studied (Table 3). Higher L values are common in surface layers due to particulate SOM input on the soil surface (Salton et al., 2008). The L showed low sensitivity in identifying changes in SOM, given the importance of this variable to evaluate the quality of SOM, relating labile fractions (C-POM) and recalcitrant (C-MOM) (Benbi et al., 2015; Jha et al., 2017; Rosset et al., 2019; Ozório et al., 2020c).

For the LI, there was a difference between the areas evaluated in the layers 0-0.05 m and 0.05-0.10 m (Table 3). In the 0.10-0.20 m layer, the areas being assessed were similar, showing that in this layer, L was not affected when compared to the NF area. The CMI, which assesses the impacts of different management systems regarding the quantity and quality of SOM compared to the reference area (Rosset et al., 2019; Ozório et al., 2020b), evidenced differences between the areas (Table 3). The CMI of the managed areas was considerably lower than the reference area for the surface layer. In the 0.05-0.10 m layer, the BV area presented an intermediate CMI value of 65.36, and the other areas had a CMI lower than 45.00. CMI values below 100 indicate the negative impact of management practices on the quantity and quality of SOM (Blair et al., 1995).

Table 3. Total organic carbon (TC), particulate organic matter carbon (C-POM), and mineral organic matter (C-MOM) contents and values of carbon stock index (CSI), lability (L), lability index (LI), and carbon management index (CMI) in the different management systems in Maracaju, Mato Grosso do Sul

Areas	TC	C-POM	C-MOM	CSI	L	LI	CMI
		g kg^{-1}			-------------------------------------		
				0-0.05 m			
RV	19.84b	8.63b	11.21d	0.34c	0.77a	0.84a	28.56b
BW	17.02c	8.18b	8.84d	0.29c	0.93a	1.01a	29.59b
BV	28.85b	10.87b	17.97c	0.50b	0.61a	0.66b	33.00b
BFC	21.32c	8.87b	12.75d	0.37c	0.70a	0.76b	28.12b
BFCV	33.15b	12.21b	20.93b	0.58a	0.58a	0.63b	36.54b
NF	57.64a	27.59a	30.05a	1.00a	0.92a	1.00a	100.00a
CV(%)	20.66	23.35	21.91	30.11	24.25	24.36	29.10
				0.05-0.1 m			
RV	16.11c	7.04b	8.07b	0.39b	0.87a	1.13a	44.07c
BW	16.22c	7.28b	8.93b	0.40b	0.82a	1.06a	42.40c
BV	21.88b	10.55b	11.33b	0.54b	0.93a	1.21a	65.34b
BFC	17.92c	5.40b	12.52b	0.44b	0.43b	0.56b	24.64c
BFCV	27.38b	7.96b	19.42a	0.67a	0.41b	0.53b	35.51c
NF	40.86a	17.83a	23.03a	1.00a	0.77a	1.00a	100.00a
CV(%)	23.68	29.41	23.45	31.02	22.52	19.30	31.67
				0.1-0.2 m			
RV	17.16b	6.18b	10.98b	0.61b	0.56a	0.81a	49.41b
BW	17.17b	6.91b	10.26b	0.61b	0.67a	0.97a	59.17b
BV	19.48b	7.53b	11.95b	0.69b	0.63a	0.91a	62.79b
BFC	17.84b	5.32b	12.52b	0.63b	0.43a	0.62a	39.06b
BFCV	25.58a	10.50a	15.08a	0.91a	0.70a	1.01a	91.91a
NF	28.13a	11.52a	16.61a	1.00a	0.69a	1.00a	100.00a
CV(%)	13.43	26.03	14.30	14.48	28.00	30.33	37.48

RV: Without burning with vinasse. BW: Burning without waste. BV: Burning with vinasse. BFC: Burning with filter cake. BFCV: Burning with filter cake + vinasse. NF: Native forest. Means followed by equal letters, in the column, in each layer, belong to the same group by the Scott-Knott test at 5% probability.

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In the 0.10-0.20 m layer, the BFCV area presented CMI value similar to the NF area. The other areas had the lowest CMI, being less than 63.00. This result indicates that the combination of filter cake and vinasse wastes contributed to maintaining the quantity and quality of SOM in the most subsurface layer (Table 3). This mitigation of negative impacts in this area is caused by the stimulation of the root development of sugarcane by the continuous addition of organic residues, which add C in subsurface layers (Vasconcelos et al., 2014; Signor et al., 2014). The structural analysis of the soil, evaluated by the WMD and GMD indexes (Figure 2) and by the number of aggregates retained in each sieve class (Table 4), allowed the identification of differences between the studied areas. The WMD and GMD showed no difference between the areas of RV, BW, BV, BFCV and NF, differing from the BFC area, which presented the lowest values for these two indicators (Figure 2).

These results indicate that even with the application of filter cake for three years in this area, the practice of successive burning impaired the structural quality of the soil. Falcão et al. (2020), in a study with different management systems in an Argissolo with sandy texture in the Cerrado of Mato Grosso do Sul, obtained results lower than those of this study for the variables WMD and GMD in sugarcane area without waste application. This indicates that applying the different types of residues added to the clayey texture of the Latossolo contributes to the maintenance of the aggregates since the soil organic matter acts as a cementing agent of the mineral particles of the soil over time (Tisdall and Oades, 1982).

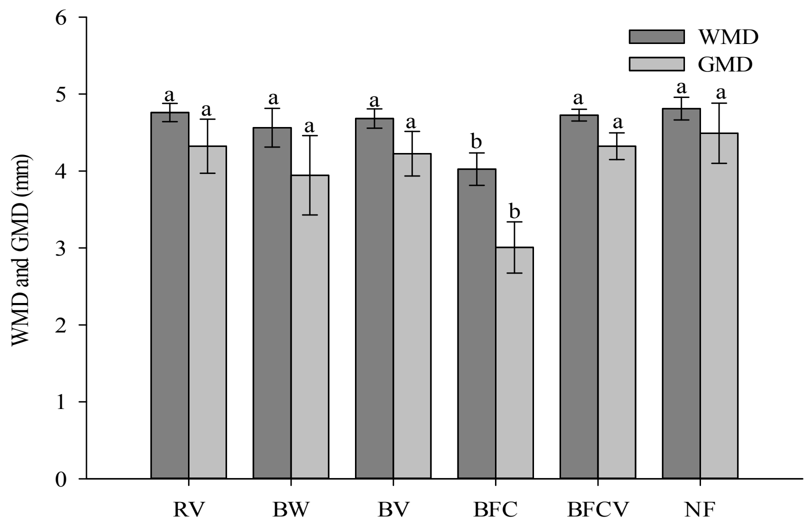

Figure 2. Weighted mean diameter (WMD) and geometric mean diameter (GMD) according to the application of wastes from the sugar and alcohol industry and sugarcane harvesting practices. RV: Without burning with vinasse. BW: Burning without waste. BV: Burning with vinasse. BFC: Burning with filter cake. BFCV: Burning with filter cake + vinasse. NF: Native forest. Means followed by equal letters, in the column, in each layer, belong to the same group by the Scott-Knott test at 5% probability.

Table 4. Percentage of soil aggregate size according to the harvesting management systems and waste application in sugarcane crop.

	Sieve size (mm)						
	>2	1-2	0.5-1	0.25-0.5	0.125-0.25	0.053-0.125	<0.053
	---%--						
	0-0.1 m						
RV	94.46a	1.44b	1.16b	1.00b	0.71b	0.36b	0.87a
BW	89.71a	3.16b	2.30b	2.04b	1.51b	0.65b	0.64a
BV	92.43a	2.60b	1.84b	1.43b	0.85b	0.46b	0.39a
BFC	76.58b	7.41a	6.70a	4.22a	2.76a	1.18a	0.95a
BFCV	93.47a	2.61b	1.41b	1.00b	0.67b	0.37b	0.48a
NF	95.63a	1.12b	1.01b	0.91b	0.60b	0.26b	0.46a
CV (%)	4.45	46.99	47.64	57.20	54.34	65.73	85.17

RV: Without burning with vinasse. BW: Burning without waste. BV: Burning with vinasse. BFC: Burning with filter cake. BFCV: Burning with filter cake + vinasse. NF: Native forest. Means followed by equal letters, in the column, in each layer, belong to the same group by the Scott-Knott test at 5% probability.

Resende et al. (1997), Six et al. (2000), Six et al. (2002) explain the greater stability of aggregates in soils of tropical regions, such as Latossolos, also due to clay mineralogy, mainly the type 1:1. The clay content and the kind of clay influence the preservation of organic C (Torn et al., 1997). Balesdent et al. (2000) state that the ability to protect TC by macroaggregates is higher when clay content increases and soil tillage practices are reduced. However, there is a greater influence of SOM in more superficial layers, where most of the TC is concentrated; consequently, the SOM in these layers will strongly influence the stabilization of aggregates over the years of cultivation.

Soil aggregation is also essential in the physical protection of SOM within aggregates (Sithole et al., 2019), in the increase of porous spaces, which regulates the infiltration of water in the soil (Patra et al., 2019), in reducing the density and resistance of the soil to root penetration (Nunes et al., 2019), favoring the interaction of ecosystem processes in the soil (Lal, 2018).

Regarding the percentage of aggregates retained in the different sieve classes, all areas had the majority of aggregates retained in the 2 mm sieve. Still, only the BFC area with the lowest percentage, 76.58%, differed from the other areas. Analyzing the aggregates retained in the smallest sieve mesh, all the evaluated areas showed no difference between them, presenting less than 1% of the aggregates retained in the sieves. In the classes of intermediate sieves, the BFC area presented higher values concerning the other areas evaluated (Table 4). These results show that the soil of the BFC area was more easily unstructured concerning other areas cultivated with sugarcane.

Evaluating soil aggregation under different sugarcane management systems, Oliveira et al. (2010) observed that for all management conditions considered, there was a greater distribution in the class of aggregates greater than 3.35 mm, especially the soil under NF, followed by the soil under the application of vinasse and filter cake. In the present study, the areas that received RV, BV, and BFCV application showed a trend of better aggregation rates, also compared to the area that did not receive the application of these residues.

The highest levels of TC were found in the aggregates of the largest sizes (>2 and 1-2 mm). The NF area presented the highest levels in these aggregate classes, with 69.44 g kg^{-1} and 29.75 g kg^{-1}, respectively, differing from the other areas, followed by the BFCV area. (Figure 3). The levels of TC, C-POM, and C-MOM were positively correlated with the values of CSI, 0.63, 0.54, and 0.65, in addition to the positive correlation with CMI, 0.49, 0.53, and 0.40, respectively (Table 5).

These results corroborate the results of higher levels of labile and recalcitrant C, in addition to the best C management indexes in this area of BFCV, concerning the other areas cultivated with sugarcane (Table 3). According to Tisdall and Oades (1982), macroaggregates are formed by the union of macroaggregates, by the action of binding agents (microbial activity, polysaccharides derived from plants, and temporary agglutinating agents such as roots and fungi hyphae).

According to Elliott (1986), one of the consequences of this hierarchy of aggregates is the increase in C concentrations, with the growing aggregate size class. For the other classes of aggregates, the highest levels are found in areas containing vinasse applications (BV and BFCV). Vicente et al. (2012), in a study conducted on the southern coast of the state of Pernambuco, showed the contribution of vinasse to increase soil TC contents and greater formation of intermediate aggregates.

The NF area obtained the highest TC content in the 0-0.10 layer, reaching 51.54 g kg^{-1}, followed by the areas of BFC and BV with contents of 29.79 and 23.87 g kg^{-1}, respectively. For this layer, the areas managed with RV, BW, BV, BFC, and BFCV presented, respectively, 34.84, 29.93, 46.30, 35.12, and 57.80% of the TC of the NF. Results such as this show how much the areas of native vegetation favor soil quality, mainly in the maintenance of SOM, corroborating several studies also carried out in the state of Mato Grosso do Sul (Salton et al., 2008; Schiavo; Colodro, 2012; Ozório et al., 2019; 2020c; Falcão et al., 2020; Troian et al., 2020; Martins et al., 2020). The correlation analyses between aggregation indexes, soil organic matter fractions, carbon management indexes, and carbon contents in the different classes of aggregates are presented in Tables 5 and 6.

These positive correlations demonstrate that management practices that alter soil attributes influence the quality and quantity of SOM. It can be observed that there were significant correlations between the soil TC contents of the 0-0.1 m layer and the aggregation indexes WMD, GMD, aggregates larger than 2 mm, in addition to the TC contents in aggregates larger than 2 mm and between 1 and 2 mm ($r = 0.41^*$ and $r = 0.44^{**}$) (Table 6). These results prove the benefits of higher soil TC contents with aggregation also in clayey soils under tropical climate conditions. Blair (2000), also in areas of sugarcane cultivation, did not observe significant correlations between the levels of TC with no soil aggregation index.

Table 5. Pearson correlation (r) between granulometric soil organic matter fractions and carbon management indexes.

	Sand	Silt	Clay	TC	C-POM	C-MOM	CSI	L	LI
Silt	0.45**								
Clay	-0.77**	-0.93**							
TC	-0.10^{ns}	-0.31**	-0.27*						
C-POM	-0.13^{ns}	-0.38**	0.33**	0.95**					
C-MOM	-0.06^{ns}	-0.21*	0.18^{ns}	0.96**	0.82**				
CSI	-0.15^{ns}	-0.30**	0.28**	0.63**	0.54**	0.65**			
L	-0.20*	-0.26*	0.27**	0.15^{ns}	0.43**	-0.13^{ns}	-0.09^{ns}		
LI	-0.23*	-0.29**	0.31**	-0.01^{ns}	0.22*	-0.22*	-0.14^{ns}	0.72**	
CMI	-0.21*	-0.37**	0.36**	0.49**	0.53**	0.40**	0.85**	0.25*	0.60**

^{ns}not significant at 5%. *, **significant at 5% and 1% probability, respectively, by the t-test

Table 6. Pearson correlation (r) between aggregation indexes and total soil carbon and aggregate fractions.

	WMD	GMD	>2	1-2	0.5-1	0.25-0.5	0.125-0.25	0.053-0.125	<0.053	C >2	C 1-2	C 0.5-1	C 0.25-0.5	C 0.125-0.25
GMD	0.99**													
>2	0.99**	0.98**												
1-2	-0.95**	-0.91**	-0.97**											
0.5-1	-0.98**	-0.94**	-0.99**	0.96**										
0.25-0.5	-0.94**	-0.91**	-0.94**	0.89**	0.94**									
0.125-0.25	-0.87**	-0.91**	-0.85**	0.73**	0.81**	0.74**								
0.053-0.125	-0.75**	-0.80**	-0.72**	0.59**	0.66**	0.55**	0.96**							
<0.053	0.44**	-0.55**	-0.42*	0.30^{ns}	0.33*	0.34*	0.44**	0.41*						
C >2	0.31*	0.34*	0.31*	-0.30^{ns}	-0.26^{ns}	-0.27^{ns}	-0.32*	-0.31*	-0.23^{ns}					
C 1-2	0.14^{ns}	0.17^{ns}	0.13^{ns}	-0.13^{ns}	-0.08^{ns}	-0.13^{ns}	-0.14^{ns}	-0.12^{ns}	-0.19^{ns}	0.78**				
C 0.5-1	-0.20^{ns}	-0.16^{ns}	-0.20^{ns}	0.21^{ns}	0.24^{ns}	0.23^{ns}	0.15^{ns}	0.19^{ns}	-0.23^{ns}	0.38*	0.49**			
C 0.25-0.5	-0.08^{ns}	-0.09^{ns}	-0.08^{ns}	0.12^{ns}	0.06^{ns}	-0.02^{ns}	0.10^{ns}	0.16^{ns}	0.01^{ns}	0.04ns	0.39*	0.30^{ns}		
C 0.125-0.25	-0.17^{ns}	-0.20^{ns}	-0.18^{ns}	0.23^{ns}	0.15^{ns}	0.12^{ns}	0.13^{ns}	0.19^{ns}	0.04^{ns}	-0.24ns	-0.04^{ns}	0.34*	0.49**	
TC 0-10	0.41*	0.44**	0.41*	-0.39*	-0.37*	-0.38*	-0.40*	-0.36*	-0.25^{ns}	0.94**	0.70**	0.32*	0.06^{ns}	-0.24^{ns}

^{ns} not significant at 5%. *, **significant at 5% and 1% probability, respectively, using the t-test.

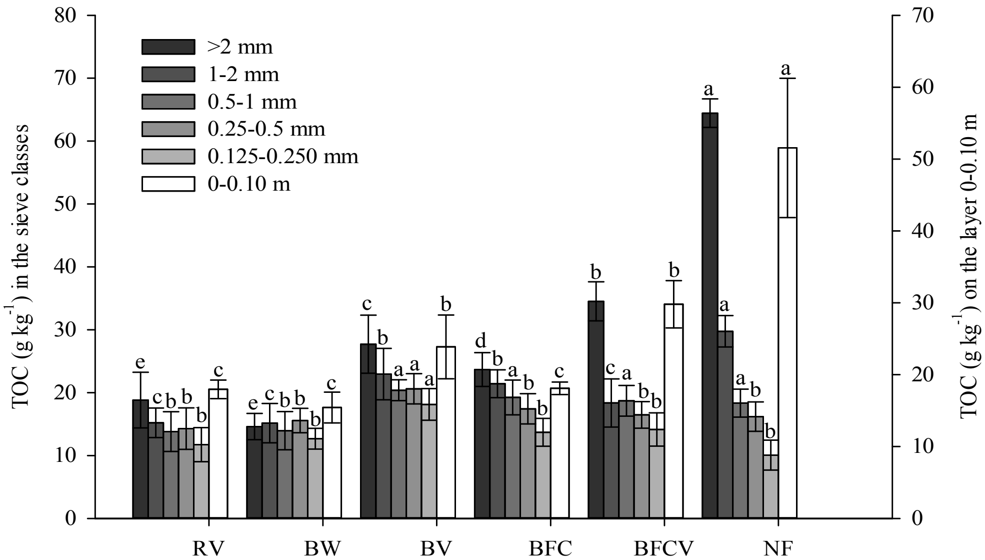

Figure 3. Total carbon (TC) in different classes of aggregate sizes in different sugarcane management systems. RV: Without burning with vinasse. BW: Burning without waste. BV: Burning with vinasse. BFC: Burning with filter cake. BFCV: Burning with filter cake + vinasse. NF: Native forest. Means followed by equal letters, in the column, in each layer, belong to the same group by the Scott-Knott test at 5% probability

4. Conclusions

The native forest area has the highest carbon content and the best soil aggregation indexes. Among the sugarcane areas, the area where burning is practiced in the pre-harvest with the application of filter cake demonstrates the worst rates of soil aggregation. The area with the practice of burning and with the joint application of filter cake and vinasse for 16 years was the one that had the highest aggregation of the soil and best carbon management indexes among the areas cultivated with sugarcane. There was a correlation between carbon content and soil aggregation indexes.

Authors' Contribution

Jean Sérgio Rosset, Jolimar Antonio schiavo, Elói Panachuki and Julio Cesar Salton conceived the project, the experiment, the analyzes and interpreted the data. Jefferson Matheus Barros Ozório, Camila Beatriz da Silva Souza and Paulo Guilherme da Silva Farias contributed to the interpretation of the results and the writing of the manuscript. All authors provided critical feedback about the writing of the paper.

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