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Physicogenic and biogenic aggregates under different management systems in the Cerrado region, Brazil

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ABSTRACT: An important strategy for the sustainable management of Cerrado soils is no-till (NT) systems, which may improve soil properties, particularly aggregation. Soil aggregates can be categorized according to their formation pathways into physicogenic (Phy) and biogenic (Bio). This study aimed (i) to quantify the relative proportion of physicogenic and biogenic aggregates and (ii) evaluate the levels of total organic carbon and their respective humic and physical fractions in the aggregates' formation pathways. The following managed and unmanaged sites were evaluated: a 6-year no-till site (6NT), an 18-year no-till site (18NT), a conventional tillage site (CT), and a reference Cerrado site (RS). Retained aggregates were analyzed morphologically, separated into Phy and Bio, and quantified. Subsequently, aggregates were subjected to total organic carbon (TOC) determination, fulvic acid carbon, humic acid carbon, humin carbon, particulate organic carbon (POC), mineral-associated organic carbon, and free light fraction carbon (FLFC). The proportion of Bio aggregates increased with decreasing management intensity. When TOC and humic acid carbon levels were compared between sites, it was found that Bio aggregates from 18NT and 6NT contained higher carbon content than Bio aggregates from CT. Particulate organic carbon and FLFC differed between aggregate types, with higher POC values observed in Bio aggregates from CT and 18NT and higher FLFC values in Bio aggregates from CT, 6NT, and 18NT. The practices adopted in the conservation management system favored biogenic aggregation in the Cerrado region, which can be proven through the study of the fractions of soil organic matter contained in these aggregates. The biogenic aggregation changed the SOM dynamics. Principal component analysis showed a clear distinction between conventional and conservationist management systems.

Keywords: aggregate formation pathways, no-till system, carbon sequestration.

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INTRODUCTION

The Cerrado is the second-largest biome in Brazil, with a variety of land uses that are strongly affected by environmental conditions (e.g., soil acidity and sandy texture in the surface) and anthropogenic activities (e.g., deforestation and fires) (Loss et al., 2013). Soils that present limitations for crop production can be modified by using different management practices. One of the most efficient strategies for improving soil properties and increasing sustainability is using conservationist agriculture approaches, such as no-till systems (NT) (Denardin et al., 2012).

Some of the advantages of NT include enhancement of soil organic matter (SOM) content and aggregation (Andrade et al., 2018). Aggregates have various functions in the soil and are directly involved in SOM stabilization, particularly under management systems with little or no soil disturbances. Soil aggregates can be classified according to their formation as physicogenic (formed by physical and chemical processes), biogenic (formed by the action of biological agents) (Bullock et al., 1985) or intermediate between these two classes. The intermediate aggregate can be a physicogenic aggregate linked to a small coprolite or biogenic that has lost its rounded shape (Pulleman et al., 2005).

The distinction between types of aggregates is made according to their genesis or formation pathways based on morphological characteristics, such as shape, size, presence of roots, and porosity (Bullock et al., 1985; Pulleman et al., 2005; Batista et al., 2013a; Melo et al., 2019). Aggregates also differ in the levels of SOM, especially those formed by macrofauna and plant root activities (Loss et al., 2014; Rossi et al., 2016; Silva Neto et al., 2016; Fernandes et al., 2017; Loss et al., 2017; Pinto et al., 2018; Ventura et al., 2018; Mergen Junior et al., 2019a,b; Melo et al., 2019; Schultz et al., 2019).

Biogenic aggregates usually contain high levels of nutrients, contribute to SOM protection (carbon sequestration), and have high physical stability (Silva Neto et al., 2010) compared to other morphological types. Because of these characteristics and the fact that they are sensitive to soil management practices, biogenic aggregates can be used as indicators of soil quality (Loss et al., 2014, 2017; Silva Neto et al., 2016; Melo et al., 2019). The sensitivity in the formation of these aggregates can be associated with the existing integration between the organisms and the management. Impacts on soil and biological activity result in changes in the formation of biogenic and physiogenic aggregates (Pulleman and Marinissen, 2004).

Due to agricultural management, soil aggregation can provide physical protection against rapid SOM decomposition. The organic material quality and quantity can be affected by the soil type and the management system adopted (Batista et al., 2013a). We hypothesized that different soil management systems (conservationist and conventional) can influence the proportion of biogenic aggregates and that the aggregate formation pathways can affect SOM dynamics in a different way. This study aimed (i) to quantify the relative proportion of physicogenic and biogenic aggregates, and (ii) to evaluate the levels of total organic carbon and their respective humic and physical fractions in the aggregate formation pathways.

MATERIALS AND METHODS

Location, climate, and soil conditions

The study area (19° 39' 10.17" S and 47° 58' 15.65" W, 790–819 m a.s.l.) is located in the Federal Institute of Triângulo Mineiro (IFTM), Uberaba, Minas Gerais, Brazil (Figure 1). The climate is tropical savanna (Köppen classification system: Aw), with wet summers, dry and cold winters, mean annual precipitation of 1600 mm, and mean annual temperature of 22.6 °C. The soil is classified as *Latossolo Vermelho Distrófico típico*, according to Santos et al. (2018), which corresponds to a Typic Hapludox (Soil Survey Staff, 2006).

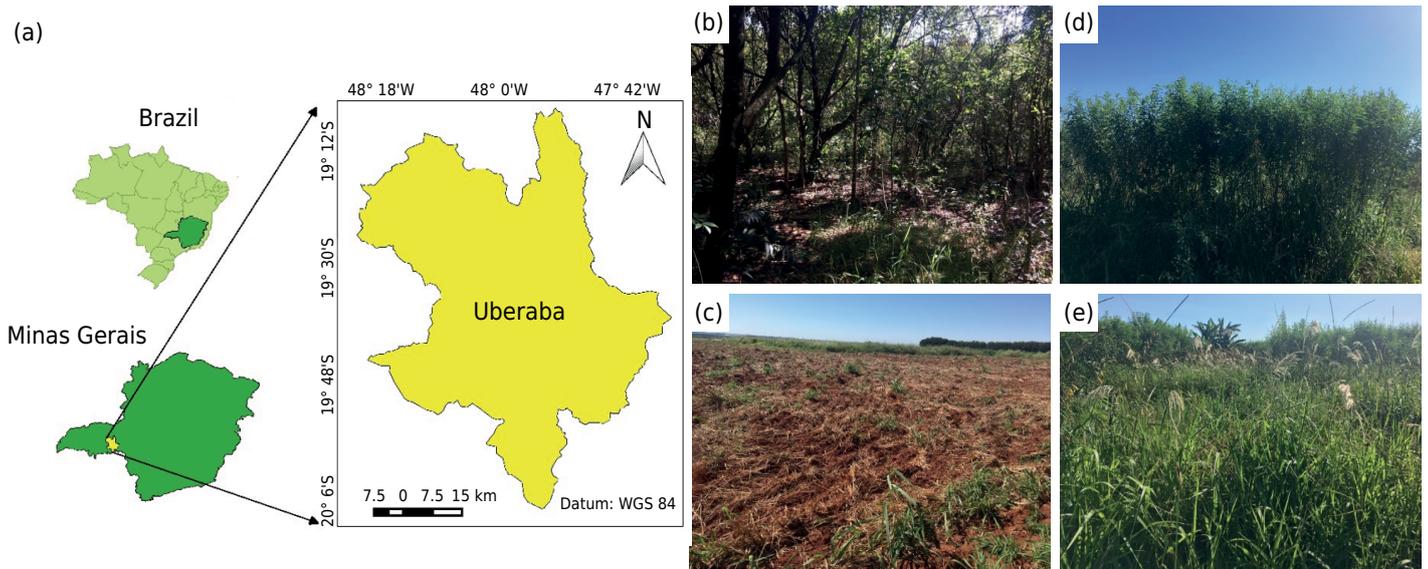


Figure 1. Location of the municipality of Uberaba, Minas Gerais, Brazil (a). Field photographs of the reference site (b), a well-preserved area in the Brazilian Cerrado without any history of wood extraction; 20-year conventional tillage site (c); 6-year no-till site with *Crotalaria* as cover crop (d); 18-year no-till site with *Brachiaria* as cover crop (e).

History of the study sites

We analyzed three managed sites and a natural area: a site under no-till for 6 years (6NT) where annual crops (corn, soybean, and bean) are rotated with cover crops (millet, *Brachiaria*, and *Crotalaria*), a site under no-till for 18 years (18NT) cultivated with the same annual and cover crops as 6NT, a site under conventional tillage (CT) cultivated with annual crops (corn, soybean, and bean) for 20 years, and a reference Cerrado site (RS) without any known history of anthropogenic activity (Figure 1).

In 6NT and 18NT, cover crops are managed under similar conditions, differing only in establishment time. In CT, the soil is plowed and harrowed before planting. In all managed sites, the annual crops' fertilization follows the recommendations of Ribeiro et al. (1999): corn is fertilized with NPK 08-28-16 at 400 kg ha⁻¹, and additional fertilization with 140 kg ha⁻¹ N and 80 kg ha⁻¹ K split between 20 and 40 days after planting; soybean is fertilized with NPK 00-20-15 at 200 kg ha⁻¹ supplemented with 2.5 % Zn and 2.5 % Mn (equivalent to 40 kg ha⁻¹ P₂O₅, 60 kg ha⁻¹ K₂O, 5 kg ha⁻¹ Zn, and 5 kg ha⁻¹ Mn) at the time of planting; and common bean crops receive a base application of 350 kg ha⁻¹ NPK 08-28-16 supplemented with 0.5 % Zn.

Sample collection and soil aggregate separation

Sampling was carried out in January 2019, and the predecessor crop was soy (*Glycine max* L.) in the succession corn/soy or beans. Five pseudoreplicate samples of soil (peds) were collected at layers of 0.00-0.05 and 0.05-0.10 m. After sampling, the material was air-dried, sieved through 9.7 and 8.0 mm mesh sieves, and stored until use.

Identification and quantification of physicogenic and biogenic aggregates

Soil aggregates in size range of 8.0-9.7 mm were examined under a magnifying glass and separated manually, identifying only two classes (physicogenic and biogenic) according to their morphological characteristics. Aggregates were identified by a method adapted from Pulleman et al. (2005) using the morphological markers described by Bullock et al. (1985), as follows: biogenic aggregates are characterized by rounded shapes as a result of passage through the intestinal tract of soil macrofauna, mainly Oligochaeta (worms), and may contain root fragments or may show signs of root activity; physicogenic aggregates have angular shapes resulting from the interaction between carbon, clay, and cations during soil wetting and drying cycles (Figure 2).

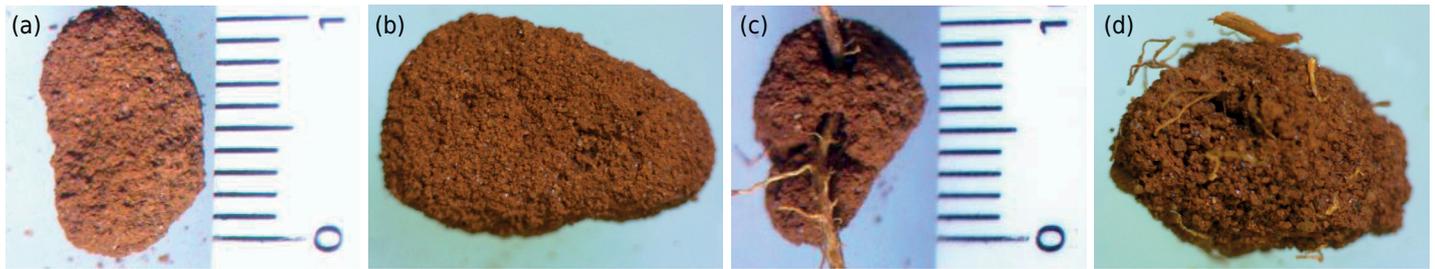


Figure 2. Representative photographs of 8.0–9.7 mm soil aggregates were categorized according to their morphological characteristics. Physicogenic (a and b) and biogenic aggregates (c and d).

Aggregates were weighed, and the percentage contribution of each aggregate type to the total weight of the sample was determined. Then, aggregates were crushed and passed through a 2.0 mm mesh sieve to obtain the air-dried fine earth fraction for SOM analysis (Teixeira et al., 2017).

SOM analyses

Total organic carbon (TOC) was determined by wet oxidation of organic matter with potassium dichromate in an acidic medium (Yeomans and Bremner, 1988). Humic substances were extracted based on organic matter's differential solubility in basic and acidic medium (fulvic and humic acids). The residue was used to obtain the humin fraction (Benites et al., 2003). Determination of carbon from fulvic acid (FAC), humic acid (HAC), and humin (HUMC) was carried out according to Yeomans and Bremner (1988).

Particle size fractionation was conducted using the method proposed by Cambardella and Elliot (1992), which consists of the separation of SOM into two fractions, the particulate fraction (related to the sand fraction of soil) and the mineral-associated fraction (related to clay and silt fractions of soil). Density fractionation (Sohi et al., 2001) was used to obtain the free light fraction of SOM. Determination of particulate organic carbon (POC) and free light fraction carbon (FLFC) was also performed according to Yeomans and Bremner (1988). Mineral-associated organic carbon (MAOC) was quantified as the difference between TOC and POC.

Statistical analysis

Experimental results were analyzed using a completely randomized design in a subdivided plot scheme (three management systems and two aggregate formation pathways). Prior to analysis, data were assessed for normality by the Shapiro-Wilk test and for homoscedasticity by Bartlett's test. When the assumptions of the tests mentioned above were not observed, the data were transformed by the Box Cox test.

Then, data were subjected to analysis of variance (*F*-tests), and mean values were compared by Tukey's test. Aggregate proportions and TOC values of managed sites were compared with those of the reference site using Dunnett's test. The significance level was set at $p < 0.05$, and the above-mentioned statistical analyses were performed using R software version 3.3.1 (R Development Core Team, 2015) and the package ExpDes.pt. (Ferreira et al., 2013).

Principal component analysis (PCA) of data from managed sites was performed using PAST software and Pearson's correlation analysis using Microsoft Excel. The PCA is used to reduce the data dimensions and, consequently, facilitate the analysis through the circle of correlations graph (Herlihy and Mccarthy, 2006). This analysis provides a better interpretation of the standard of management systems according to the evaluated attributes.

RESULTS

Proportion of physicogenic and biogenic aggregates

Physicogenic aggregates predominated in soil samples from all sites in all the layers evaluated (Figure 3). However, in areas under CT and NT, it is observed that the proportion of biological aggregates increases in parallel with the decrease in the intensity of management, thus, reducing the percentage difference between the formation pathways (Figure 3). The RS had almost equal proportions of physicogenic and biogenic aggregates (Figure 3). Aggregate proportions in 6NT and 18NT did not differ from those in RS (Dunnett's test, $p < 0.05$).

Total organic carbon (TOC)

The TOC content of aggregates varied greatly between management systems, specifically in biogenic aggregates in the 0.00-0.05 m layer (Figure 4). Biogenic aggregates from no-till soil (18NT and 6NT) had higher TOC content in the 0.00-0.05 m layer than biogenic aggregates from CT, with the highest TOC content in 18NT aggregates (Figure 4). However, no differences in TOC content were observed between biogenic and physicogenic aggregates at either soil (Figures 4 and 5). When analyzing TOC of the management systems in comparison to the RS, it is observed that the lower average values were verified in the management systems regardless of the type of aggregate (Dunnett's test, $p < 0.05$) (Figures 4 and 5).

Organic carbon in chemical SOM fractions

The organic carbon content of chemical SOM fractions is shown in table 1. Similar to that observed for TOC content, the greatest variation in carbon content was observed in the samples from layer of 0.00-0.05 m, particularly for HAC and HUMC. No differences in FAC were observed between management systems or aggregate types in either depth layer (Table 1). Humic acid differed between management systems in the 0.00-0.05 m layer. Biogenic aggregates from 18NT and 6NT had higher HAC than biogenic aggregates from CT (Table 1). Humin differed between aggregate types in 18NT: higher levels were observed in biogenic aggregates sampled from both layers. In 6NT, biogenic aggregates had higher HUMC in the 0.00-0.05 m soil layer.

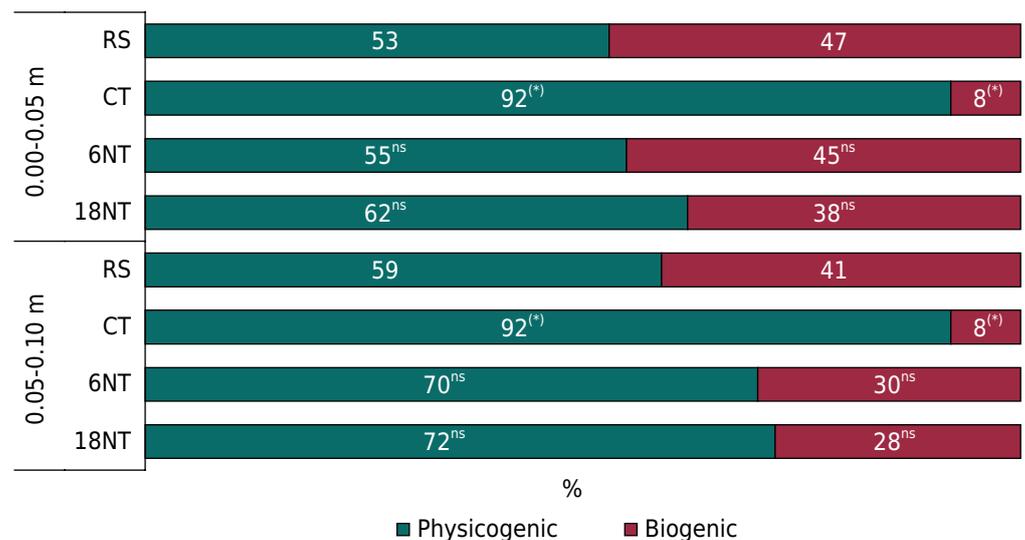


Figure 3. Distribution of physicogenic and biogenic aggregates in 0.00-0.05 and 0.05-0.10 m soil layers under different management systems in the Cerrado region of Uberaba, Minas Gerais, Brazil. An asterisk (*) indicates a significant difference from the reference site (Dunnett's test, $p < 0.05$). ^{ns}: not significant; RS: reference site, a well-preserved fragment of the Brazilian Cerrado; CT: 20-year conventional tillage site; 6NT: 6-year no-till site; 18NT: 18-year no-till site.

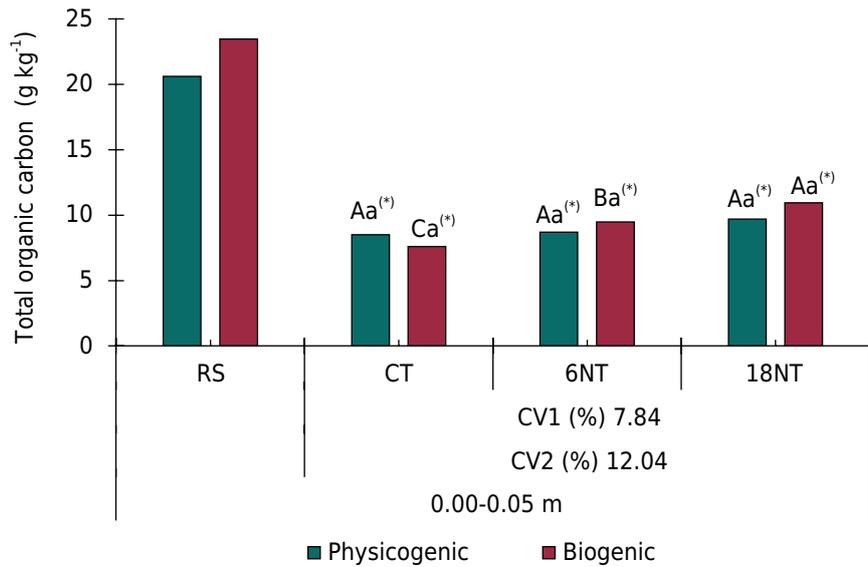


Figure 4. Total organic carbon content in physicogenic and biogenic aggregates in the 0.00-0.05 m soil layer under different management systems in the Cerrado region of Uberaba, Minas Gerais, Brazil. Different uppercase and lowercase letters indicate significant differences between sites and aggregate types, respectively, by Tukey's test ($p < 0.05$). An asterisk (*) indicates a significant difference from the reference site (Dunnett's test, $p < 0.05$). ns: not significant; RS: reference site, a well-preserved fragment of the Brazilian Cerrado; CT: 20-year conventional tillage; 6NT: 6-year no-till; 18NT: 18-year no-till; CV₁: coefficient of variation between aggregate types; CV₂: coefficient of variation between sites.

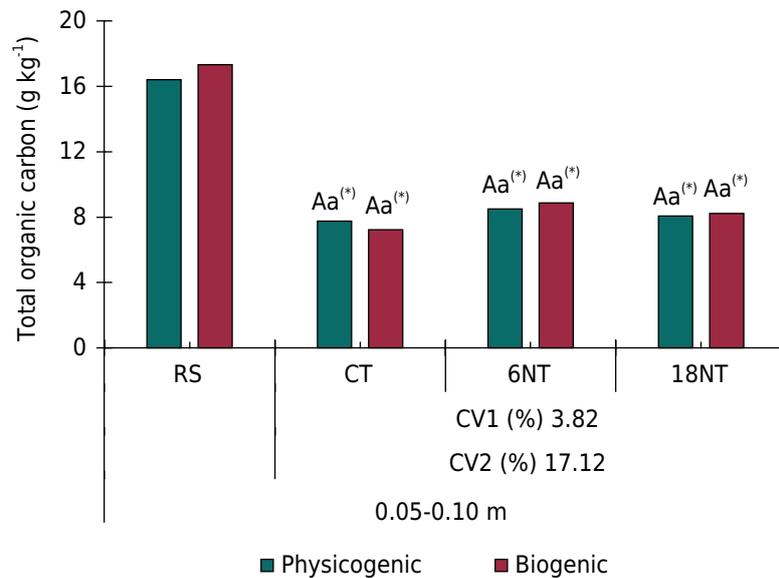


Figure 5. Total organic carbon content in physicogenic and biogenic aggregates in the 0.05-0.10 m soil layer under different management systems in the Cerrado region of Uberaba, Minas Gerais, Brazil. Different uppercase and lowercase letters indicate significant differences between sites and aggregate types, respectively, by Tukey's test ($p < 0.05$). An asterisk (*) indicates a significant difference from the reference site (Dunnett's test, $p < 0.05$). ns: not significant; RS: reference site, a well-preserved fragment of the Brazilian Cerrado; CT: 20-year conventional tillage; 6NT: 6-year no-till; 18NT: 18-year no-till; CV₁: coefficient of variation between aggregate types; CV₂: coefficient of variation between sites.

Organic carbon in physical SOM fractions

The variation in organic carbon in physical SOM fractions of soil aggregates was more pronounced between aggregate types than between management systems. The greatest variations were observed for FLFC in both layers (Table 2). The POC content was higher in physicogenic aggregates from 6NT than in physicogenic aggregates from CT in the

Table 1. Distribution of organic carbon in humic fractions of physicogenic (Phy) and biogenic (Bio) aggregates from 0.00-0.05 and 0.05-0.10 m depth soils under different management systems in the Cerrado region of Uberaba, Minas Gerais, Brazil

Site	FAC		HAC		HUMC	
	Phy	Bio	Phy	Bio	Phy	Bio
g kg^{-1}						
0.00-0.05 m soil layer						
CT	1.23 ^{NS ns}	1.43 ^{NS ns}	1.90 ^{NS ns}	1.63 ^{B ns}	3.53 ^{NS ns}	4.33 ^{NS ns}
6NT	1.49 ^{NS ns}	1.51 ^{NS ns}	2.13 ^{NS ns}	2.43 ^{A ns}	3.57 ^{NS b}	4.57 ^{NS a}
18NT	1.60 ^{NS ns}	1.71 ^{NS ns}	2.48 ^{NS ns}	2.49 ^{A ns}	4.02 ^{NS b}	5.36 ^{NS a}
CV ₁ (%)	18.8		16.5		17.0	
CV ₂ (%)	23.9		20.5		16.2	
RS	4.28	4.59	2.71	3.81	9.94	10.66
0.05-0.10 m soil layer						
CT	1.37 ^{NS ns}	1.30 ^{NS ns}	1.27 ^{NS ns}	1.47 ^{NS ns}	3.22 ^{NS ns}	3.80 ^{NS ns}
6NT	1.60 ^{NS ns}	1.61 ^{NS ns}	2.05 ^{NS ns}	2.04 ^{NS ns}	3.10 ^{NS ns}	3.80 ^{NS ns}
18NT	1.70 ^{NS ns}	1.43 ^{NS ns}	1.95 ^{NS ns}	2.16 ^{NS ns}	3.33 ^{NS b}	4.44 ^{NS a}
CV ₁ (%)	16.3		18.4		15.2	
CV ₂ (%)	23.7		28.8		25.7	
RS	3.39	3.73	1.97	2.97	6.94	7.65

Means within columns followed by different uppercase letters and means within rows followed by different lowercase letters do not differ significantly at $p < 0.05$ by Tukey's test. NS: differences between sites are not significant; ns: differences between aggregate types are not significant; RS: reference site, a well-preserved fragment of the Brazilian Cerrado; CT: 20-year conventional tillage; 6NT: 6-year no-till; 18NT: 18-year no-till; FAC: fulvic acid carbon; HAC: humic acid carbon; HUMC: humin carbon; CV₁: coefficient of variation between aggregate types; CV₂: coefficient of variation between sites. Humic fractions were extracted according to a method adapted by Benites et al., 2003. Determination of carbon of the humic fractions was carried out according to Yeomans and Bremner (1988).

0.00-0.05 m layer (Table 2). Physicogenic aggregates from 18NT had a similar POC content to those collected from CT and 6NT. Differences were observed between aggregate types. Biogenic aggregates from CT and 18NT had higher POC levels than physicogenic aggregates in both layers (Table 2).

Mineral-associated organic carbon content was higher in biogenic aggregates from 6NT and 18NT than from CT (Table 2). However, in comparing aggregate formation pathways, we observed that MAOC content was higher in physicogenic than in biogenic aggregates from CT (Table 2).

Free light fraction carbon content was higher in biogenic aggregates from CT than those from other sites at the layer of 0.00-0.05 m (Table 2). For all sites, FLFC content was higher in biogenic aggregates than in physicogenic aggregates in both layers (Table 2), similar to the observed for POC (Table 2).

PCA

We carried out the PCA of aggregate proportion, TOC content, and SOM fraction carbon of 0.00-0.05 (Figure 6) and 0.05-0.10 m soil layers (Figure 7) under different management systems. Two principal components (PCs) explained together approximately 53 and 61 % of the variance in soil parameters in the 0.00-0.05 and 0.05-0.10 m layers, respectively. Three groups were formed in PCA biplots, with 6NT and 18NT plotted far from CT along PC1 (main axis), in agreement with the high variance explained by PC1 (almost 43 and 36 % in figures 6 and 7, respectively). The 6NT was plotted far from 18NTS along PC2, which explained approximately 18 and 17 % of the dataset variance for samples taken from the first and second layers, respectively.

Table 2. Distribution of organic carbon in physical fractions of physicogenic (Phy) and biogenic (Bio) aggregates from 0.00-0.05 and 0.05-0.10 m soil layers under different management systems in the Cerrado region of Uberaba, Minas Gerais, Brazil

Site	POC		MAOC		FLFC	
	Phy	Bio	Phy	Bio	Phy	Bio
g kg^{-1}						
0.00-0.05 m soil layer						
CT	1.40 ^{B b}	2.59 ^{NS a}	7.09 ^{NS a}	4.50 ^{B b}	0.52 ^{NS b}	1.86 ^{A a}
6NT	2.13 ^{A ns}	2.62 ^{NS ns}	6.58 ^{NS ns}	7.11 ^{A ns}	0.45 ^{NS b}	0.71 ^{B a}
18NT	1.93 ^{AB b}	2.98 ^{NS a}	7.89 ^{NS ns}	8.19 ^{A ns}	0.45 ^{NS b}	0.79 ^{B a}
CV ₁ (%)	17.3		11.2		32.0	
CV ₂ (%)	21.3		14.8		29.8	
RS	3.44	6.58	17.51	17.96	1.05	1.46
0.05-0.10 m soil layer						
CT	1.38 ^{NS b}	2.50 ^{NS a}	6.06 ^{NS a}	4.18 ^{C b}	0.51 ^{NS b}	0.77 ^{NS a}
6NT	1.85 ^{NS ns}	2.14 ^{NS ns}	6.64 ^{NS ns}	6.72 ^{A ns}	0.41 ^{NS b}	0.65 ^{NS a}
18NT	1.71 ^{NS b}	2.58 ^{NS a}	6.28 ^{NS ns}	5.69 ^{B ns}	0.44 ^{NS b}	0.68 ^{NS a}
CV ₁ (%)	19.8		6.6		17.8	
CV ₂ (%)	21.6		12.8		30.6	
RS	1.57	2.55	13.93	14.43	0.76	0.81

Means within columns followed by different uppercase letters and means within rows followed by different lowercase letters do not differ significantly at $p < 0.05$ by Tukey's test. NS: differences between sites are not significant; ns: differences between aggregate types are not significant; RS: reference site, a well-preserved fragment of the Brazilian Cerrado; CT: 20-year conventional tillage; 6NT: 6-year no-till site; 18NT: 18-year no-till; POC: particulate organic carbon; MAOC: mineral-associated organic carbon; FLFC: free light fraction carbon; CV₁: coefficient of variation between aggregate types; CV₂: coefficient of variation between sites. Particle size according to Cambardella and Elliot (1992). Density fractionation according to Sohi et al. (2001). Carbon of the physical fractions was carried out according to Yeomans and Bremner (1988).

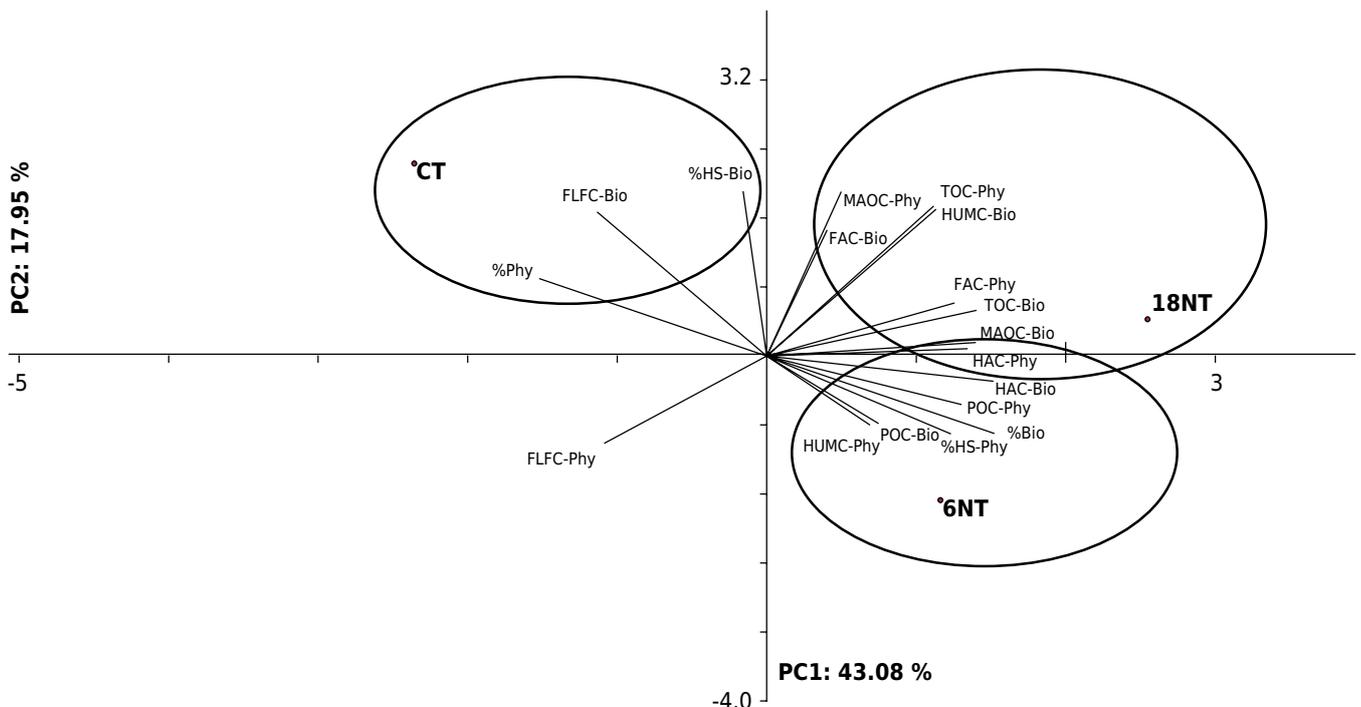


Figure 6. Principal component analysis of total organic carbon and chemical and physical fractions of soil organic matter in physicogenic (Phy) and biogenic (Bio) aggregates from 0.00-0.05 m soil layer under different management systems in the Cerrado region of Uberaba, Minas Gerais, Brazil. CT: 20-year conventional tillage; 6NT: 6-year no-till; 18NT: 18-year no-till; TOC: total organic carbon; FAC: fulvic acid carbon; HAC: humic acid carbon; HUMC: humin carbon; %HS: percentage of humic substances; POC: particulate organic carbon; MAOC: mineral-associated organic carbon; FLFC: free light fraction carbon; %Phy: percentage of physicogenic aggregates; %Bio: percentage of biogenic aggregates.

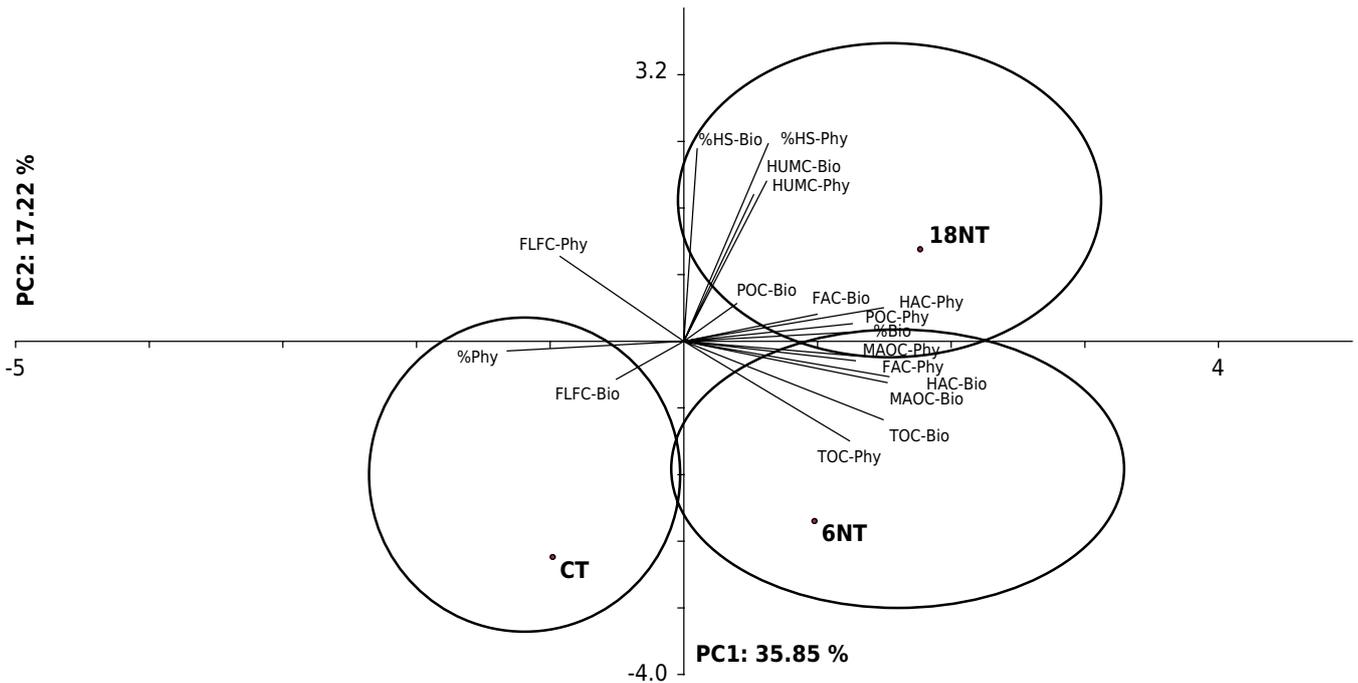


Figure 7. Principal component analysis of total organic carbon and chemical and physical fractions of soil organic matter in physicogenic (Phy) and biogenic (Bio) aggregates from 0.05-0.10 m soil layer under different management systems in the Cerrado region of Uberaba, Minas Gerais, Brazil. CT: 20-year conventional tillage; 6NT: 6-year no-till; 18NT: 18-year no-till; TOC: total organic carbon; FAC: fulvic acid carbon; HAC: humic acid carbon; HUMC: humin carbon; %HS: percentage of humic substances; POC: particulate organic carbon; MAOC: mineral-associated organic carbon; FLFC: free light fraction carbon; %Phy: percentage of physicogenic aggregates; %Bio: percentage of biogenic aggregates.

The variables that most contributed to the formation of PC1 (positive correlations with this axis >0.7) and separation between no-tillage and conventional tillage systems, in 0.00-0.05 m layer, were %Bio, TOC-Bio, FAC-Phy, HAC-Phy, HAC-Bio, %HS-Phy, POC-Phy, and MAOC-Bio (Figure 6); while, in the 0.05-0.10 m layer, the %Bio, TOC-Bio, HAC-Phy, HAC-Bio, and MAOC-Bio variables stood out (Figure 7). In both layers, these variables were more strongly associated with 6NT and 18NT management systems (Figures 6 and 7). On the other hand, the CT, located along PC1, in the opposite direction to no-tillage systems, was associated with physicogenic aggregate proportion (%Phy), FLFC in biogenic aggregates (Figures 6 and 7), and percentage of humic substances in biogenic aggregates (Figure 6).

DISCUSSION

The proportion of physicogenic and biogenic aggregates observed in soil samples (Figure 3) agrees with the results of Pulleman et al. (2005) and Loss et al. (2014). The process by which aggregates are formed is related to the management practices adopted, as aggregates are sensitive to changes in the soil environment and result in changes in aggregate formation pathways (Pulleman et al., 2005). In the Cerrado, Batista et al. (2013a) observed in the dry season higher percentage values of intermediate aggregates, followed by physicogenic and lower biogenic percentage in areas under integrated crop-livestock and Cerrado vegetation. In the state of Santa Catarina, Mergen Junior et al. (2019b) assessed the proportion of aggregate formation pathways in soil under no-till receiving pig slurry and composted pig manure and found that the addition of pig waste increased biogenic aggregate formation. According to the authors, application of organic amendment, slurry treatment, and lack of tillage provided favorable physical and chemical conditions to soil fauna, the major agents responsible for the formation of biogenic aggregates (Batista et al., 2013a).

Contrary to the observed in the present study, Schultz et al. (2019) assessed forest and grass vegetation's influence on aggregate formation in Acrisols (*Argissolo Vermelho Amarelo*), and observed a predominance of biogenic over physicogenic aggregates in the area of forest. The authors concluded that the combination of organic matter input and tree shading improved soil fauna activity, contributing to biogenic aggregate formation and stability.

The results showed that soil management has a determining effect on the formation process of aggregates. Under adequate soil use and management practices, maintenance or increase in the SOM content (plants aerial part and root systems) may occur and favor the population of edaphic micro and macroorganisms development in the rhizosphere, and contribute to the formation of the biogenic aggregates (Bronick and Lal, 2005; Lima et al., 2020).

Conservationist systems tend to reduce the percentage differences between physicogenic and biogenic aggregates. Such results may explain the similarity between the aggregates of the areas under conservationist management in comparison to the RS area (reference area) (Dunnett's test, $p < 0.05$; Figure 3). In soils under native vegetation, a greater action of biological agents (macrofauna and flora) occurs because of the stability of the environment. In a secondary forest area in southeastern Brazil, Lima et al. (2020) observed termite nest in the soil, which probably contributed to the formation of the aggregates from the biogenic pathway. In a study involving individuals from the edaphic fauna and aggregates genesis, Batista et al. (2013a) observed that the Cerrado vegetation area was important in distinguishing the characteristics of the different types of aggregates because it is a native environment.

Regarding the TOC results of the present study, previous research has shown that TOC content differs greatly between physicogenic and biogenic aggregates and is usually higher in the latter. Loss et al. (2014), Silva Neto et al. (2016), Loss et al. (2017), and Melo et al. (2019) found that the TOC content of biogenic aggregates was 56, 24, 22, and 21 % higher than that of physicogenic, respectively. The enrichment of carbon in biogenic structures indicates selective feeding of organic material by soil organisms, increasing the carbon content in these aggregates (Pulleman et al., 2005; Batista, 2015).

The highest TOC content in biogenic aggregates from sites under NT in the first layer when comparing the systems indicates a greater accumulation and maintenance of soil carbon in biogenic structures (Figure 4). Such results can probably be related to the higher biological activity on the surface layer. No-till systems generally enhance carbon deposition and preservation in soil compared with conventional tillage systems, which expose SOM previously protected inside the aggregate (physical protection) to microbial processes and enzymatic reactions (Lal et al., 2003). Conservation practices adopted in no-till systems contribute to soil moisture maintenance and prevent the direct exposure of soil to sunlight, thereby decreasing soil temperatures and, consequently, SOM mineralization rates (Loss et al., 2009; 2014). As evidenced by the present study results, biogenic aggregates contribute greatly to the preservation of TOC in agricultural sites.

As shown in figures 4 and 5, TOC content was significantly higher in RS than in managed sites (Dunnett's test, $p < 0.05$), in agreement with the results of Batista (2015), in which a similar pattern was verified when comparing treatments to the area of native vegetation. The author justifies the results of TOC as a reflection of the management adopted in the experimental areas under conventional soil management practices for more than 20 years before the implementation of the NT.

No significant differences in FAC were observed between sites (Table 1). The fulvic acid fraction is highly soluble and labile; therefore, its formation and decomposition rates are higher than those of other SOM fractions (Fontana et al., 2006). The HAC results indicate that biogenic aggregates from 6NT and 18NT accumulated more recalcitrant

forms of carbon than biogenic aggregates from CT. Such results demonstrate the negative effects of soil tillage, which fragmenting aggregates into smaller units, exposing the organic matter previously chemically protected from mineralization (Loss et al., 2014). The higher HAC contents in biogenic aggregates from no-till sites can be explained by the favorable environmental conditions for biological activity. As a result, humification is intensified, increasing the degree of humification of humic substances, such as humic acid, in biogenic aggregates (Stevenson, 1994).

The HUMC contents of physicogenic and biogenic aggregates found in the current study are in line with those reported by Loss et al. (2014) and Ventura et al. (2018). For these authors, these data are directly related to the edaphic fauna action and the root system factors, which are mainly related to the formation of the biogenic aggregates, which occurs in greater intensity in the superficial layers due to the plant residues and minimal soil revolving. In investigating Atlantic Forest fragments at different stages of regeneration, Fernandes et al. (2017) observed that biogenic aggregates had higher HUMC levels than physicogenic and intermediate aggregates. The results were attributed to soil macrofauna, especially earthworms, which play a major role in the biogeochemical cycling of nutrients in soil (Jouquet et al., 2009) and positively influence the ecology of humification (Fernandes et al., 2017). Such effects explain the higher HUMC content in biogenic aggregates from no-till sites (Table 1) and show that biological aggregation favors SOM fractions (cementing action) during its genesis process.

The higher levels of POC in physicogenic aggregates from 6NT than those from CT in the 0.00-0.05 m layer (Table 2) are a reflection of the deposition, accumulation, and maintenance of leaf litter in the soil in the initial stage of transition from till to no-till (5-10 years). These results highlight the importance SOM input, either via leaf litter deposition or root fragmentation, for POC content. The POC was more sensitive to management practices than TOC in a crop-livestock farming system (Batista et al., 2013b). Thus, according to the authors, POC can be used to monitor changes in SOM quality arising from soil management practices.

The POC content was higher in biogenic than in physicogenic aggregates from CT and 18NT (Table 2). Such results indicate that more labile (available) substances predominate in biogenic aggregates compared with physicogenic aggregates (Loss et al., 2014). As previously discussed, these effects can be attributed to the activity of soil fauna and plant root systems, particularly in no-till sites (Loss et al., 2014; Mergen Junior et al., 2019a). Other authors observed similar results (Pulleman et al., 2005; Loss et al., 2014; Batista, 2015; Rossi et al., 2016; Schultz et al., 2019). The POC is one of the most labile fractions of organic matter and is highly sensitive to soil disturbances; it can be easily mineralized in soil under conventional tillage (Rossi et al., 2016). As shown by our results, biogenic aggregates can protect POC, whether in conventional tillage or no-till systems.

Biogenic aggregates from no-till sites (6NT and 18NT) had higher MAOC levels than those from CT in both soil layers (Table 2), which can be attributed to the ability of biogenic aggregates to protect and stabilize the more labile fractions of SOM, such as POC, especially in soil conservation systems. The higher MAOC content observed in physicogenic aggregates than in biogenic aggregates from CT disagrees with the results of Pulleman et al. (2005), Loss et al. (2014), Batista (2015), Rossi et al. (2016), and Schultz et al. (2019). The authors found that biogenic aggregates had higher MAOC levels than physicogenic aggregates. The results of the present study may be explained by the formation of SOM physical fractions.

For high levels of MAOC to occur, POC decomposition rates must be high, allowing organic carbon to associate with silt and, particularly, clay fractions (Figueiredo et al., 2010). However, MAOC is not always a good indicator of the effects of management practices because of its high stability; changes in MAOC content may take years to occur (Carmo et al., 2012) due to its high stability.

Biogenic aggregates from CT were enriched with FLFC compared with biogenic aggregates from no-till sites (6NT and 18NT) (Table 2). These data suggest that stored FLFC was cycled more quickly in biogenic aggregates from CT than in those from conservation systems. The higher light fraction values in conventional areas may be due to the greater SOM transformation in no-till areas, increasing the participation of the most recalcitrant forms.

Regarding comparisons between aggregate formation pathways, FLFC content had a similar pattern to POC (Table 2). Overall, it can be inferred that biological activity (roots and macrofauna) increased carbon accumulation in the more labile fractions of SOM. The free light fraction of SOM has a similar composition to highly labile plant materials, whose stabilization is related to the organic molecule's intrinsic recalcitrance (Conceição et al., 2008). Among the more labile fractions of SOM, POC and FLFC stand out as potential SOM quality indicators because of their sensitivity to changes in soil management. Such results may be related to the role of aggregates in carbon sequestration. Biogenic aggregates store more labile forms of carbon, whereas physicogenic aggregates store more recalcitrant forms (Pinto et al., 2018).

The PCA revealed that TOC, most of the physical and chemical fractions of SOM, and biogenic aggregate proportions were associated with no-till sites (Figures 6 and 7). This pattern may be associated with the greater input of crop residues on the soil surface, which, associated with the minimal revolving of this layer, favors a lower decomposition rate and better environment conditions for edaphic fauna. Thus, higher levels of organic matter, TOC, and SOM fractions are observed in the 0.00-0.10 m layer. Such conditions are ideal for the activity of biological agents responsible for the formation of biogenic aggregates, as shown in figures 6 and 7, and in the applied statistical tests.

The association of physicogenic aggregate proportion, percentage of humic substances in biogenic aggregates, and FLFC in biogenic aggregates with CT (Figures 6 and 7) may be related to the inherent characteristics of the management system. The CT favors physicogenic rather than biogenic aggregate formation pathways. The results suggest that the major organic carbon fractions that favor or remain in biogenic aggregates from CT are either stabilized in humic substances or depend on organic molecules' recalcitrance (light free SOM fraction).

CONCLUSIONS

The practices adopted in the conservation management system favored biogenic aggregation in the Cerrado region, which can be proven through the study of the fractions of soil organic matter contained in these aggregates. The biogenic aggregation changed the SOM (soil organic matter) dynamics.

More labile SOM fractions were detected in biogenic aggregates (particulate organic carbon and free light fraction carbon). These aggregates were more efficient in reducing SOM decomposition rates and increasing soil carbon content.

There was a clear distinction between conventional and conservationist management systems. Highlighting the attributes humic acid carbon of physicogenic aggregates and total organic carbon, humic acid carbon and mineral-associated organic carbon of biogenic aggregates in the layer of 0.00-0.10 m.

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REFERENCES

- Andrade AT, Torres JLR, Paes JMV, Teixeira CM, Conde ABT. Desafios do sistema de plantio direto no Cerrado. *Infor Agropec*. 2018;39:19-26.
- Batista I. Relação entre macrofauna, agregação e atributos edáficos em sequência de culturas sob plantio direto [tese]. Botucatu: Universidade Estadual Paulista; 2015.
- Batista I, Correia MEF, Pereira MG, Bieluczyk W, Schiavo JA, Mello NA. Caracterização dos agregados em solos sob cultivo no Cerrado, MS. *Semina*. 2013a;34:1535-48. <https://doi.org/10.5433/1679-0359.2013v34n4p1535>
- Batista I, Pereira MG, Correia MEF, Bieluczyk W, Schiavo JA, Rows JRC. Teores e estoque de carbono em frações lábeis e recalcitrantes da matéria orgânica do solo sob integração lavoura-pecuária no bioma Cerrado. *Semina*. 2013b;34:3377-88. <https://doi.org/10.5433/1679-0359.2013v34n6Supl1p3377>
- Benites VM, Madari B, Machado PLOA. Extração e fracionamento quantitativo de substâncias húmicas do solo: um procedimento simplificado de baixo custo. Rio de Janeiro: Embrapa Solos; 2003.
- Bronick CJ, Lal R. Soil structure and management: a review. *Geoderma*. 2005;124:3-22. <https://doi.org/10.1016/j.geoderma.2004.03.005>
- Bullock P, Federoff N, Jongerius A, Stoops G, Tursina T. Handbook for soil thin section description. Wolverhampton: Waine Research; 1985.

- Cambardella CA, Elliott ET. Methods for physical separation and characterization of soil organic matter fractions. *Geoderma*. 1993;56:449-57. <https://doi.org/10.2136/sssaj1992.03615995005600030017x>
- Carmo FF, Figueiredo CC, Ramos MLG, Vivaldi LJ, Araújo LG. Frações granulométricas da matéria orgânica em Latossolo sob plantio direto com gramíneas. *Biosci J*. 2012;28:420-31.
- Conceição PC, Boeni M, Dieckow J, Bayer C, Mielniczuk J. Fracionamento densimétrico com politungstato de sódio no estudo da proteção física da matéria orgânica em solos. *Rev Bras Cienc Solo*. 2008;32:541-9. <https://doi.org/10.1590/S0100-06832008000200009>
- Denardin JE, Kochhann RA, Faganello A, Denardin ND, Wiethölter S. Diretrizes do sistema plantio direto no contexto da agricultura conservacionista. *Passo Fundo: Embrapa Trigo*; 2012.
- Fernandes JCF, Pereira MG, Silva Neto EC, Correa Neto TA. Characterization of biogenic, intermediate and physicogenic soil aggregates of areas in the Brazilian Atlantic Forest. *Caatinga*. 2017;30:59-67. <https://doi.org/10.1590/1983-21252017v30n107rc>
- Ferreira EB, Cavalcanti PP, Nogueira DA. *ExpDes.pt: Experimental Designs package (Portuguese)*. R package version 1.1.2. Vienna: R Development Core Team; 2013.
- Figueiredo CC, Resck DVS, Carneiro MAC. Labile and stable fractions of soil organic matter under management systems and native Cerrado. *Rev Bras Cienc Solo*. 2010;34:907-16. <https://doi.org/10.1590/S0100-06832010000300032>
- Fontana A, Pereira MG, Loss A, Cunha TJF, Salton JC. Atributos de fertilidade e frações húmicas de um Latossolo Vermelho no Cerrado. *Pesq Agropec Bras*. 2006;41:847-53. <https://doi.org/10.1590/S0100-204X2006000500018>
- Herlihy M, Mccarthy J. Association of soil test phosphorus with phosphorus fractions and adsorption characteristics. *Nutr Cycl Agroecosys*. 2006;75:79-90. <https://doi.org/10.1007/s10705-006-9013-2>
- Jouquet P, Zangerle A, Rumpel C, Brunet D, Bottinelli N, Tran Duc T. Relevance and limitations of biogenic and physicogenic classification: a comparison of approaches for differentiating the origin of soil aggregates. *Eur J Soil Sci*. 2009;60:1117-25. <https://doi.org/10.1111/j.1365-2389.2009.01168.x>
- Lal R, Follet RF, Kimble JM. Achieving soil carbon sequestration in the United States. A challenge to policy makers. *Soil Sci*. 2003;168:827-45. <https://doi.org/10.1097/01.ss.0000106407.84926.6b>
- Lima SS, Pereira MG, Silva Neto EC, Fernandes DAC, Aquino AM. Biogenic and physicogenic aggregates under different crops with black oat in Nova Friburgo, Brazil. *Caatinga*. 2020;33:299-309. <https://doi.org/10.1590/1983-21252020v33n203rc>
- Loss A, Lourenzi CR, Dos Santos E, Mergen CA, Benedet L, Pereira MG, Piccolo MC, Brunetto G, Lovato PE, Comin JJ. Carbon, nitrogen and natural abundance of ^{13}C and ^{15}N in biogenic and physicogenic aggregates in a soil with 10 years of pig manure application. *Soil Till Res*. 2017;166:52-8. <https://doi.org/10.1016/j.still.2016.10.007>
- Loss A, Pereira MG, Costa EL, Beutler SJ. Soil fertility, physical and chemical organic matter fractions, natural ^{13}C and ^{15}N abundance in biogenic and physicogenic aggregates in areas under different land use systems. *Soil Res*. 2014;52:685-97. <https://doi.org/10.1071/SR14045>
- Loss A, Pereira MG, Perin A, Coutinho FS, Anjos LHC. Particulate organic matter in soil under different management systems in the Brazilian Cerrado. *Soil Res*. 2013;50:685-93. <https://doi.org/10.1071/SR12196>
- Loss A, Pereira MG, Schultz N, Anjos LHC, Silva EMR. Carbono e frações granulométricas da matéria orgânica do solo sob sistemas de produção orgânica. *Cienc Rural*. 2009;39:1067-72. <https://doi.org/10.1590/S0103-84782009005000036>
- Melo TR, Pereira MG, Barbosa GMC, Silva Neto EC, Andrello AC, Filho JT. Biogenic aggregation intensifies soil improvement caused by manures. *Soil Till Res*. 2019;190:186-93. <https://doi.org/10.1016/j.still.2018.12.017>
- Mergen Junior CA, Loss A, Santos Junior E, Ferreira GW, Comin JJ, Lovato PE, Brunetto G. Atributos químicos em agregados biogênicos e fisiogênicos de solo submetido à aplicação com dejetos suínos. *Rev Bras Cienc Agrar*. 2019a;14:5620-7. <https://doi.org/10.5039/agraria.v14i1a5620>

- Mergen Junior CA, Loss A, Santos Junior E, Giumbelli LD, Pinho D, Abreu L, Lourenzi CR, Comin JJ, Brunetto G. Caracterização física de agregados do solo submetido a 10 anos de aplicação de dejetos suínos. *Rev Cienc Agric*. 2019b;36:79-92.
- Pinto LASR, Mendonça OVT, Rossi CQ, Pereira MG, Barros FC. Evolución y acumulación de C-CO₂ en agregados biogénicos y fisiogénicos presentes en diferentes tipos de manejos agroecológicos. *Acta Agron*. 2018;67:494-500. <https://doi.org/10.15446/acag.v67n4.67923>
- Pulleman MM, Marinissen JCY. Physical protection of mineralizable C in aggregates from long-term pasture and arable soil. *Geoderma*. 2004;120:273-82. <https://doi.org/10.1016/j.geoderma.2003.09.009>
- Pulleman MM, Six J, Marinissen JCY, Jongmans AG. Earthworms and management affect organic matter incorporation and microaggregate formation in agricultural soils. *Appl Soil Ecol*. 2005;29:1-15. <https://doi.org/10.1016/j.apsoil.2004.10.003>
- R Development Core Team. R: A language and environment for statistical computing. R Foundation for Statistical Computing. Vienna, Austria; 2015. Available from: <http://www.R-project.org/>.
- Ribeiro AC, Guimarães PTG, Alvarez V VH. Recomendação para o uso de corretivos e fertilizantes em Minas Gerais - 5ª aproximação. Viçosa, MG. Comissão de Fertilidade do Solo do Estado de Minas Gerais; 1999.
- Rossi CQ, Pereira MG, Moura OVT, Almeida APC. Vias de formação, estabilidade e características químicas de agregados em solos sob sistemas de manejo agroecológico. *Pesq Agropec Bras*. 2016;51:1677-85. <https://doi.org/10.1590/s0100-204x2016000700068>
- Santos HG, Jacomine PKT, Anjos LHC, Oliveira VA, Lumbreiras JF, Coelho MR, Almeida JA, Araújo Filho JC, Oliveira JB, Cunha TJF. Sistema brasileiro de classificação de solos. 5. ed. rev. ampl. Brasília, DF: Embrapa; 2018.
- Schultz N, Pinto LASR, Lima SS, Ziviani MM, Assunção SA, Pereira MG. Agregação do solo e atributos químicos em áreas com diferentes coberturas vegetais. In: Tullio L. Características do solo e sua interação com as plantas 2 [e-book]. Ponta Grossa: Atena Editora; 2019. v. 2. p. 1-12. Available from: <https://www.atenaeditora.com.br/wp-content/uploads/2019/10/E-book- Caracteristicas-do-Solo-e-sua-Interacao-com-as-Plantas-2.pdf>.
- Silva Neto EC, Pereira MG, Fernandes JCF, Corrêa Neto TA. Aggregate formation and soil organic matter under different vegetation types in Atlantic Forest from Southeastern Brazil. *Semina*. 2016;37:3927-40. <https://doi.org/10.5433/1679-0359.2016v37n6p3927>
- Silva Neto LF, Silva IF, Inda AV, Nascimento PC, Bortolo L. Atributos físicos e químicos de agregados pedogênicos e de coprólitos de minhocas em diferentes classes de solos da Paraíba. *Cienc Agrot*. 2010;34:1365-71. <https://doi.org/10.1590/S1413-70542010000600002>
- Sohi SP, Mahieu N, Arah JRM, Powlson DS, Madari B, Gaunt JL. A procedure for isolating soil organic matter fractions suitable for modeling. *Soil Sci Soc Am J*. 2001;65:1121-8. <https://doi.org/10.2136/sssaj2001.6541121x>
- Soil Survey Staff. Keys to soil taxonomy. 10th ed. Washington, DC: United States Department of Agriculture, Natural Resources Conservation Service; 2006.
- Stevenson FJ. Humus chemistry: genesis, composition, reactions. 2nd ed. New York: John Wiley & Sons; 1994.
- Teixeira PC, Donagemma GK, Fontana A, Teixeira WG. Manual de métodos de análise de solo. 3. ed. rev e ampl. Brasília, DF: Embrapa; 2017.
- Ventura BS, Loss A, Giumbelli LD, Ferreira GW, Bueno AC, Lourenzi CR, Comin JJ, Brunetto G. Carbon, nitrogen and humic substances in biogenic and physicogenic aggregates of a soil with a 10-year history of successive applications of swine waste. *Trop Subtrop Agroec*. 2018;21:329-43.
- Yeomans JC, Bremner JM. A rapid and precise method for routine determination of organic carbon in soil. *Commun Soil Sci Plant Anal*. 1988;19:1467-76. <https://doi.org/10.1080/00103628809368027>