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Biogenic and physicogenic aggregates as indicators of quality in soils with sandy texture in areas of organic agriculture

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ABSTRACT: Sandy texture soils have a great expression in agricultural areas worldwide. In the Baixada Fluminense, soils with a sandy texture on the surface horizons are striking, and a good part of these areas is destined for producing vegetables using conventional cultivation methods. The sandy texture is one of the great challenges for agriculture due to the low water retention capacity provided to the soil, the rapid decomposition of organic matter, and the intense loss of nutrients by leaching. In these areas, the action of erosive processes is sometimes observed, whether water or wind erosion. The practices carried out in conventional agriculture can accentuate these processes. This study aimed to evaluate the influence of different soil management systems, with different vegetation covers, on the pathways of aggregate formation, the nutrient contents contained therein, and the organic matter fractions, with the objective of using these properties as indicators of soil quality. The study was carried out in an organic production unit, with no-till system (NT) and conventional system (CT), three vegetal covers were evaluated, namely; seed cocktail 1 (C1) (Crotalaria (*Crotalaria juncea*) (20 kg ha^{-1}), Jack Bean (*Canavalia ensiformis*) (150 kg ha^{-1}) and millet (*Pennisetum glaucum*) (60 kg ha^{-1})), and seed cocktail 2 (C2) (with 50 % of the amount of seeds used in C1), and spontaneous plants (S. P). Undisturbed samples were collected at the layers of 0.00-0.05 and 0.05-0.10 m, and, from these samples, aggregates with a diameter between 9.7 and 8.0 mm were classified according to the formation route (Biogenic or Physicogenic). From these, the chemical properties were quantified (pH, Ca^{2+}, Mg^{2+}, Al^{3+}, P, Na^{+}, K^{+}), and also the carbon fractions (total organic carbon – TOC, mineral-associated organic carbon – MAOC), particulate organic carbon – POC, and free light fraction carbon – LFC). Based on the results, it was verified that the percentage of biogenic aggregates was higher than the physicogenic one in the layer of 0.00-0.05 m, not being verified influences of the vegetal coverage or the management system. Chemical properties did not differ significantly between training pathways. The CT, for the most part, was the system in which the highest values of chemical properties were observed, and in general, the C2 and S.P coatings were the ones that provided the greatest improvements for chemical properties and carbon content.

Keywords: technical land classification, rock fragments, effective soil depth, water deficit.

INTRODUCTION

Agricultural production is crucial for the development and maintenance of society as a whole. However, to achieve maximum productivity without needing to advance over new areas, it is necessary to develop management techniques that improve cultivated soils. In the state of Rio de Janeiro, southeast Brazil, one of the main obstacles to increased productivity is the sandy texture of most part of soils, which are observed in the superficial horizons. Sandy textured soils represent approximately 900 million hectares worldwide (Yost et al., 2019). According to Donagemma et al. (2016), more than 8 % of the Brazilian soils have a sandy texture in their arable layer, a significant percentage.

The challenges associated with managing these soils are related to their lower water retention capacity, rapid decomposition of organic matter, and loss of nutrients by leaching, as well as its susceptibility to erosion processes (water and wind). To achieve higher productivity levels in these soils, a set of practices should be adopted, emphasizing those that contribute to increasing soil organic matter (SOM) content.

Among the management practices that can be used to promote improvements in these sandy texture soils, the no-till farming system (NT) can be highlighted, which promotes the improvement of physical, chemical and biological soil properties, also acting to mitigate the effects caused by greenhouse gas emissions, and when implemented and managed thoroughly, is ecologically sustainable (Silva et al., 2022). In contrast, the conventional system (CS), due to the intensive soil disturbance, the conventional system (CS) results in a lower SOM retention than NT (Dewi et al., 2022).

In association with NT, it can be implemented organic farming, which does not use chemical inputs, mostly used for fertilization and pest and disease control, adopting only organic inputs, bringing many benefits to the soil, such as reducing the rate of mineralization of organic matter, reducing nutrient loss also by leaching, increasing the diversity of macro and micro fauna, culminating in improved soil physical properties, such as soil aggregation (van Rijssel et al., 2022).

Organic matter is fundamental for the evaluation of soil quality, which is considered the largest carbon reservoir on the planet, and much of it is in SOM, and one of the ways to preserve this fraction in the soil is done by the physical protection that aggregates provide, with the occlusion of SOM (Rossi et al., 2023). Furthermore, soil aggregation is an important indicator of the quality of edaphic properties (Oliveira-Silva et al., 2020). Soil structure has great importance in maintaining water, nutrients, and oxygen to the roots, besides providing conditions of mechanical resistance favorable to root growth (Beutler et al., 2001; Pereira et al., 2010; Schiavo et al., 2011; Bell and Moore, 2012; Aziz et al., 2013; Loss et al., 2014).

Aggregates can be classified according to their morphological patterns and/or formation pathways. They can be classified as physicogenic, which are formed from physical and chemical soil processes, and biogenic, which are formed from the action of biological agents (Bullock et al., 1985; Pulleman et al., 2005; Pereira et al., 2021). The root system of the mulches affects soil aggregation differently among plants, however, it is not yet deeply known how this differentiation occurs among plants (York et al., 2016).

The use of the morphological parameter, the distinction of aggregates by formation pathways as indicators of soil quality, has shown positive results, in which it is possible to observe differences in nutrient content and especially carbon and its fractions in the different formation pathways, these positive results mostly associated with aggregates of biogenic origin (Loss et al., 2017; Lima et al., 2020; Rossi et al., 2023). A recent study in grazing and grain production areas in sandy-textured superficial layers, Pinto et al. (2022) found that biogenic aggregation provided a higher concentration of labile organic carbon; and contributed to elevated macroaggregate stability and glomalin-related soil protein contents.

Considering the importance of these indicators, FAO published an official document entitled "Protocol for the assessment of Sustainable Soil Management" (FAO-ITPS, 2020), which highlights soil organic carbon as an indicator that reflects the chemical, physical and biological state of the soil, which responds to change through the implementation of sustainable soil management (SSM) practices. It directly relates to other soil properties, such as nutrient availability; structure and aggregation; porosity; water holding capacity; and the presence of macro, meso, and microfauna.

Due to the relevance of the role of soil aggregation, and how important conservation systems are in promoting the improvement of soil properties, this study aims to use aggregates formed by different pathways (biogenic and physicogenic), as indicators of soil quality in areas of organic agriculture using the no-till farming system, in sandy textured soils in the arable layer, in the Rio de Janeiro lowlands.

MATERIALS AND METHODS

Study area

The study area is located in Sítio do Sol, in the municipality of Seropédica, Rio de Janeiro, southeast Brazil, whose geographic coordinates are 22° 49' 20.3" S and 43° 44' 19.4" W (Figure 1). According to Köppen's classification system, the climate is tropical Aw, with dry winters and rainy summers, and an average annual temperature of around 23.5 °C. The average annual precipitation reaches around 1,200 mm. The native vegetation of the region is classified as a subcaducifolia tropical forest (Loss et al., 2011).

The soil of the experimental area was classified as Ultisol (*Argissolo Amarelo*), with medium texture (sandy loam and sandy loam) (Santos et al., 2018). The experimental area has approximately 1400 m^2 and has been cultivated with organic farming since the year 2000, but soil preparation was conventional until the year 2018, from this year began a study with cultivation by the no-till system (NT), alternating between the cultures of okra (*Abelmoschus esculentus*) and cabbage (*Brassica oleracea*), currently the experimental area has five years of driving.

Experimental design

In the experimental area, when the soil was collected, the crop cultivated in all plots was okra (Abelmoschus esculentus). Between plants and rows, the spacing is 0.5 × 1.0 m, with drip irrigation located on the plant. The experimental design was divided into 2 × 3 factorial plots, with two planting systems [Conventional System (CT) and No-Tillage System (NT)] and three types of cover crops: cocktail 1 (C1), cocktail 2 (C2) and spontaneous plants (S.P). The plots measure 24 × 6 m, and the subplots 6 × 4 m.

The mulches used in the plots were: cocktail 1 (C1) - 100 % of the number of seeds recommended for single cultivation of the species that compose the cocktail [Crotalaria (*Crotalaria juncea*) (20 kg ha^{-1}), Jack Bean (*Canavalia ensiformis*) (150 kg ha^{-1}) and Millet (*Pennisetum glaucum*) (60 kg ha^{-1})]; Cocktail 2 (C2) - Using 50 % of the number of seeds recommended for single cultivation of each species that make up the cocktail [Crotalaria

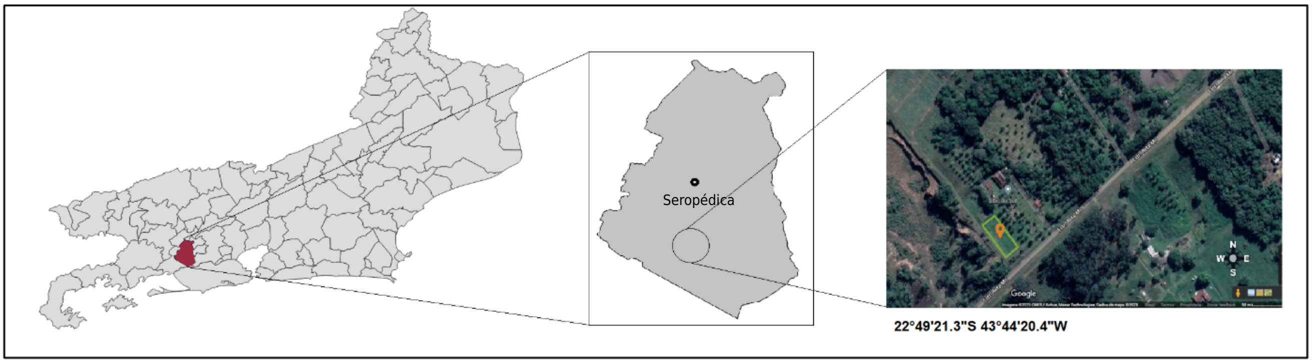

Figure 1. Experimental area, Sítio do Sol, Seropédica - RJ. Source: Google Earth.

(*Crotalaria juncea*) (10 kg ha^{-1}), JackBean (*Canavalia ensiformis*) (750 kg ha^{-1}) and Millet (*Pennisetum glaucum*) (30 kg ha^{-1})] and spontaneous plants (S.P) (Figure 2).

The vegetation covers were implemented together with the crop, both in the NT and CT, chemical products were not used for desiccation, and this cover was cut with a cutter, the cut material after the end of the cycle was kept in the cut place to maintain the straw in the NT. In the CT, this material was incorporated with a rotary fill.

Collecting aggregates

A soil sample in the parallelepiped form, measuring 0.05 × 0.10 × 0.10 m (height, width, and length) was randomly collected from each plot, at depths of 0.00-0.05 and 0.05-0.10 m, with the aid of a straight shovel, to preserve the soil structure (Figure 3), totaling 36 samples collected.

Samples were added to previously identified packaging and packed in plastic boxes for transport, organized in such a way as not to destroy soil structures, and finally transported from the experimental area to the place where the analyzes were carried out, in the laboratory. These samples are not placed to dry on site, being removed from the packaging and deposited on sheets of paper, in a naturally ventilated environment for seven days.

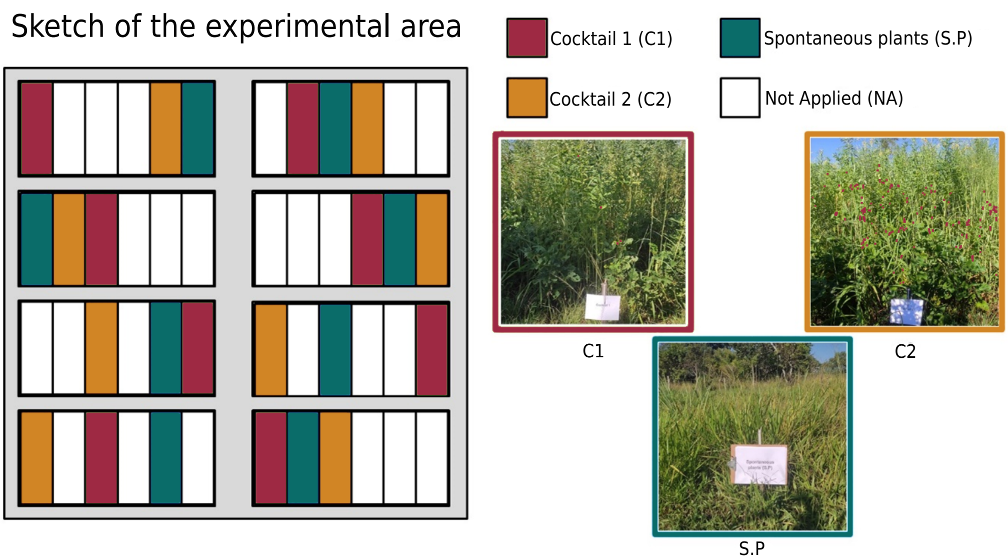

Figure 2. Representation of the crops covers used for the study, and their experimental design, for the different crops covers, under sandy textured soils, in southeastern Brazil.

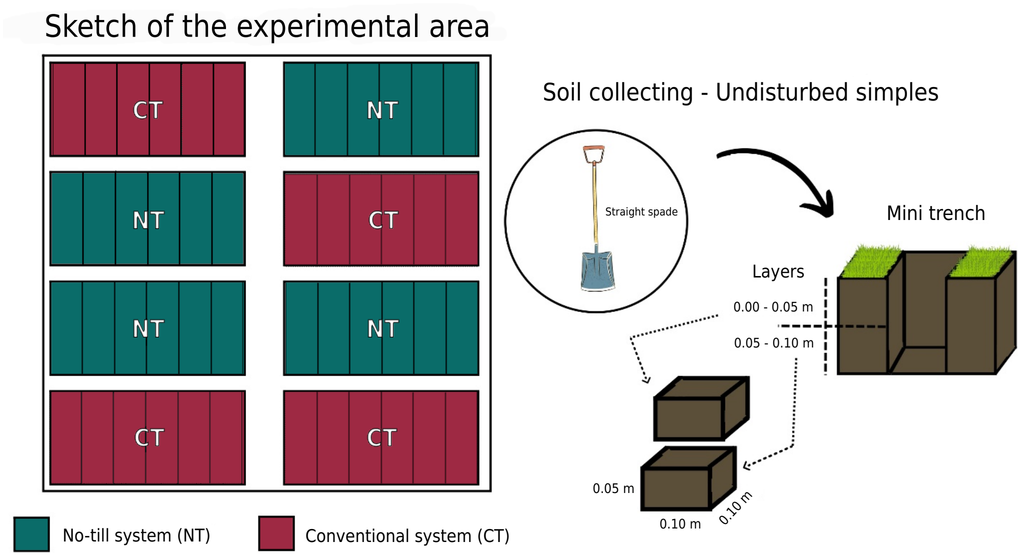

Figure 3. Form of undisturbed soil collection for the study of soil aggregation at the layers of 0.00-0.05 and 0.05-0.10 m, and its experimental design, for different soil cultivation systems, under sandy texture, in southeastern Brazil.

Aggregate analysis

Pathways of formation

After drying, the material was fragmented into clumps on the weak lines, obtaining aggregates of different sizes, subsequently passed through a set of sieves with meshes of 9.7 and 8.0 mm, using the aggregates that were retained in the sieve of 8.0 mm. The aggregates were examined with a magnifying glass, separated manually, and classified according to their origin by a method adapted (Pulleman et al., 2005), and validated by Pereira et al. (2021), this one based on the morphological patterns established by Bullock et al. (1985).

The separation of aggregates followed the following criteria: biogenic aggregates - those in which it is possible to visualize rounded shapes, provided by the intestinal tract of soil macrofauna individuals, mainly Oligochaeta (earthworms) or those in which it is possible to visualize the presence and activity of roots (Figure 4). Physicogenic aggregates were defined as those in which angular forms resulting from the interaction between carbon, clay, cations, and soil wetting and drying cycles are observed (Figure 4). After separating the aggregates, the percentage and relative contribution in the mass of each type of aggregate were determined.

Chemical analyses

After the classification and quantification of the soil aggregates, the samples were crushed and passed through a 2.0 mm mesh sieve, thus obtaining the fine air-dried soil fraction (FASF) for the soil fertility and organic matter analyses. The samples were analyzed for pH(H_2O) at a 1:2.5 ratio (soil:water); exchangeable Ca^{2+}, Mg^{2+}, and Al^{3+} contents extracted with KCl 1 mol L^{-1}, analyzed by titulometry; P, Na^+, and K^+ extracted by the Mehlich-1 method and analyzed by colorimetry (P) and flame photometry (K^+ and Na^+) and H+Al extracted with KCl 1 mol L^{-1} analyzed by titration (Teixeira et al., 2017). Total organic carbon (TOC) was determined according to Yeomans and Bremner (1988).

The fraction of particulate organic carbon (POC) was also determined from the samples of the aggregates, through the granulometric fractionation of the soil organic matter (Cambardella and Elliott, 1993). Which consists of using 20 g of FASF and 60 mL of sodium hexametaphosphate solution (5 g L^{-1}), the sample is carefully homogenized with the dispersing solution until the material is detached from the bottom to increase

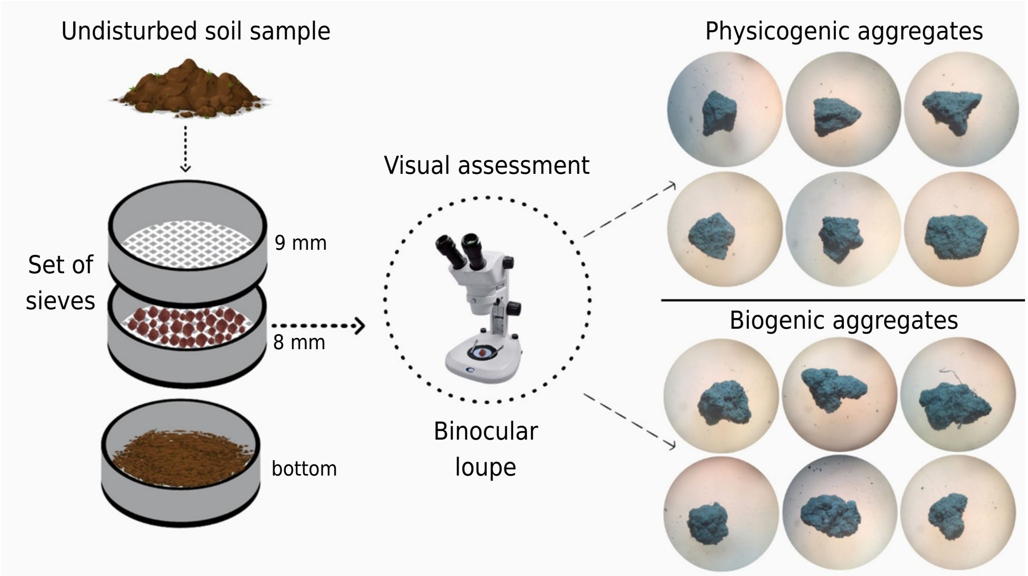

Figure 4. Schematic model of aggregate separation and classification, and the representation of the distinction between biogenic and physicogenic aggregates from undisturbed soil samples under sandy texture from southeastern Brazil.

the surface in contact with the solution. Subsequently, this material is placed under stirring for 15 h in a horizontal shaker, at 160 rpm. The obtained suspension was passed through a 53 µm sieve with the aid of a jet of water. The material retained on the sieve, consisting of particulate organic carbon (POC) that is the size of the sand fraction, was dried in an oven at 60 °C. Then, the material was macerated, and the total organic carbon (TOC) was determined according to Yeomans and Bremner (1988). The organic carbon associated with the silt and clay mineral fractions (MAOC) was obtained by the difference between TOC and POC.

The light fractions were extracted from the soil using a sodium iodide (NaI) solution at a density of 1.80 g cm^{-3} (± 0.02). For this, 5 g of the FASF sample was weighed into 50 mL centrifuge flasks and 35 mL of NaI was added. Next, the samples were centrifuged at 18,000 rpm for 15 min at a temperature of 18 °C to promote sedimentation of the soil mineral particles. The supernatant organic fraction present in the solution (free light fraction) was aspirated together with the NaI solution and immediately separated by vacuum filtration (Sterifil Aseptic System, 47 mm – Millipore) with previously weighed glass fiber filters (47 mm diameter; 2 microns – Whatman type GF/A) (Pinheiro et al., 2004).

The collected fraction was washed with distilled water to remove excess of NaI from the sample and filter. The organic fraction, together with the filter, was subsequently dried at 65 °C, weighed, and macerated, and the carbon was further analyzed according to Yeomans and Bremner (1988).

Statistical analysis

The data were submitted to normality and homogeneity analyses, with the Shapiro-Wilk and Bartlett tests, respectively. The means were compared using the Tukey test at a 5 % significance level. The layers were analyzed separately since no interaction was observed between them. For the variables that did not meet the statistical assumptions, the non-parametric Kruskal-Wallis test was applied at a 5 % significance level.

For the variables that satisfied the normality assumptions, a multivariate analysis was performed on principal components to better explain these as a function of the different management systems evaluated. The data analyses were performed in R Core Team software (2017).

RESULTS

Formation pathways

A significantly higher percentage of biogenic aggregates than physicogenic ones was observed at the layer of 0.00-0.05 m (Figure 5a), while no significant difference was observed for the 0.05-0.10 m soil layer (Figure 5b). For the 0.00-0.05 m soil layer, values ranging from 64 and 35 % were observed for biogenic and physicogenic aggregates, respectively. While for the layer of 0.05-0.10 m, the values ranged between 58 and 41 %, for biogenic and physicogenic aggregates, respectively.

Chemical properties of aggregates

In general, the different management systems showed low availability of nutrients in the aggregates (Table 1). The pH values in all treatments (cover crops) were higher than 5.8, especially in the areas covered with S.P, which had higher pH values when compared to the other treatments. No differences were observed between the cover crops. In agreement with the pattern observed for pH values, the aluminum content was equal to zero in all areas.

As for the Ca^{2+} contents, the results varied from 0.30 to 1.10 and 0.25 to 1.60 $cmol_c\ kg^{-1}$, at the layers of 0.00-0.05 and 0.05-0.10 m, respectively, with no significant difference observed between the systems and the formation pathways. For Mg^{2+}, the values varied from 1.10 to 2.35 and 0.95 to 2.50 $cmol_c\ kg^{-1}$, at the layers of 0.00-0.05 and 0.05-0.10 m, respectively.

The K^+ content varied from 0.16 to 0.81 and 0.08 to 0.52 $cmol_c\ kg^{-1}$, at the layers of 0.00-0.05 and 0.05-0.10 m, respectively, with no significant difference between the systems and formation pathways. The Na^+ contents varied from 0.09 to 0.15 $cmol_c\ kg^{-1}$ and 0.03 to 0.11 $cmol_c\ kg^{-1}$, at the layers of 0.00-0.05 and 0.05-0.10 m, respectively, with the same pattern observed for K^+, absence of significant difference between types of cover and types of aggregates.

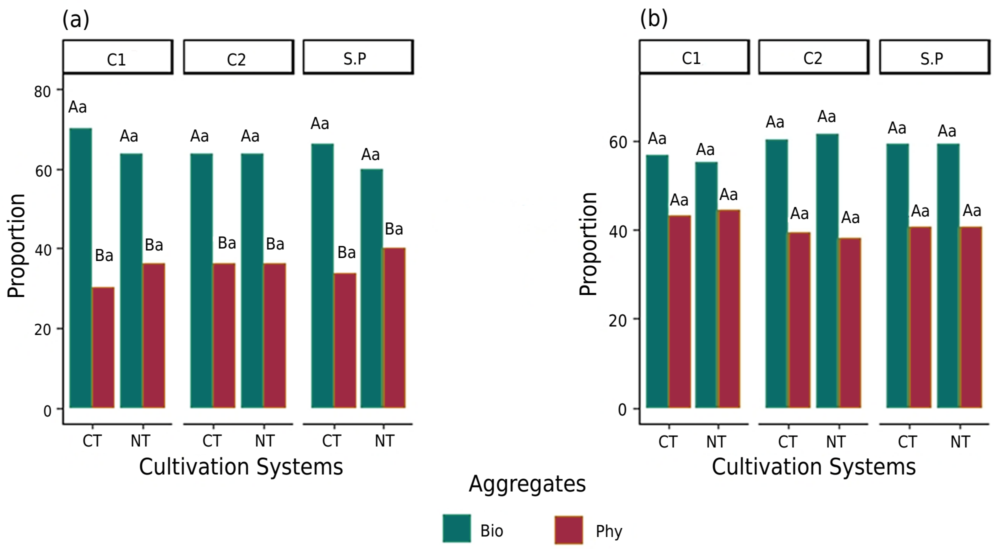

Figure 5. Percentage of biogenic (Bio) and physicogenic (Phy) aggregates of areas under different cultivation systems in sandy-textured soils, southeastern Brazil. (a) 0.00-0.05 m and (b) 0.05-0.10 m layers. Measurement corresponds to 100 g of soil aggregates of size 9.7–8.0 mm before separation between biogenic and physicogenic. Averages followed by equal letters, upper case for pathways formations and lower case for cultivation systems, do not differ by Tukey's test, at 5 % probability. NT: no-tillage system; CT: conventional tillage; Cocktail 1 (C1): 100 % of the number of seeds recommended for each species that compose the cocktail [Crotalaria (*Crotalaria juncea*) (20 kg ha^{-1}), Jack Bean (*Canavalia ensiformis*) (150 kg ha^{-1}) and Millet (*Pennisetum glaucum*) (60 kg ha^{-1})]; Cocktail 2 (C2): 50 % of the recommended seed amount for each species composing the cocktail [Crotalaria (*Crotalaria juncea*) (10 kg ha^{-1}), Jack Bean (*Canavalia ensiformis*) (75 kg ha^{-1}) and Millet (*Pennisetum glaucum*) (30 kg ha^{-1}); and spontaneous plants (S. P].

The values of P varied from 0.51 to 6.94 and 0.23 to 5.51 mg kg^{-1} at the layers of 0.00-0.05 and 0.05-0.10 m, respectively. In both layers, a significant difference was observed between the tillage systems, with the values verified for CT being higher than NT. No differences were observed between covers and formation pathways.

The H+Al contents were low, ranging from 2.10 to 3.60 and 1.80 to 3.60 $cmol_c$ kg^{-1}, at the layers of 0.00-0.05 and 0.05-0.10 m, respectively (Table 1), with no significant difference being observed at the layer of 0.05-0.10 m, between cover crops and formation pathways, while for the depth of 0.00-0.05 m, in the CT area, significantly lower values were observed.

As for the values of SB, these varied from 2.12 to 3.70 and 1.73 to 3.46 $cmol_c$ kg^{-1}, at the layers of 0.00-0.05 and 0.05-0.10 m, respectively; at the layer of 0.00-0.05 m, a significant difference was observed between the preparation systems, with the highest values verified in the area of CT, with no difference between the mulches and the ways of formation.

The T values, ranging from 5.03 to 6.50 and 4.65 to 6.24 $cmol_c$ kg^{-1}, at the layers of 0.00-0.05 and 0.05-0.10 m, respectively; in the layer of 0.05-0.10 m was observed a significant difference between the preparation systems, being the highest values verified in NT. As for the V% value, it ranged from 38 to 60 % and 32 to 64 %, at the layers of 0.00-0.05 and 0.05-0.10 m, respectively; in the laryer of 0.00-0.05 m, it was observed a significant difference in the productivity between the preparation systems, the highest values was determined in CT.

About layer, there is variation between the 0.00-0.05 and 0.05-0.10 m layers for some of the evaluated properties, namely: Ca^{2+}, P and SB, T, and V%. At the layer of 0.00-0.05 m, the areas with CT were those that presented the best values for the chemical properties, differing significantly from the NT areas (Table 1). It can be observed, in general, that the cover that provided better soil fertility conditions was the one with S.P (Table 1).

For the 0.05-0.10 m layer, T, P, and pH were the only properties that differed statistically. The results obtained suggest less influence of management and mulches on soil chemical properties. In this, a significant difference was observed between the vegetative covers and the chemical properties between the classes of aggregates.

Soil organic carbon

The values of total organic carbon (TOC) varied from 11.18 to 33.88 and 6.90 to 37.66 g kg^{-1}, at the layers of 0.00-0.05 and 0.05-0.10 m, respectively, with no significant differences between the types of aggregates, vegetation cover, and soil preparation system in any of the areas (Figures 6a and 6e). As for the contents of POC, the contents varied from 4.13 to 14.24 and 1.21 to 18.66 g kg^{-1}, at the layers of 0.00-0.05 and 0.05-0.10 m, respectively, with no significant differences being observed (Figures 7a and 7b).

For mineral-associated organic carbon (MAOC), the values were between 0.66 to 26.46 and 0.40 to 30.97 g kg^{-1} at the layers of 0.00-0.05 and 0.05-0.10 m, respectively, and no significance was observed (Figures 7c and 7d). For the LFC values, ranging from 0.19 to 1.73 and 0.04 to 0.87 g kg^{-1}, at the layers of 0.00-0.05 and 0.05-0.10 m, respectively, no significant differences were observed (Figures 7e and 7f). The levels of MAOC were higher compared to particulate organic carbon (POC) in all management systems, regardless of aggregate type, vegetation cover, and depth (Figure 4).

Table 1. Chemical properties of aggregates in the different systems

System	Cover	Via	pH(H_2O)	Ca^{2+}	Mg^{2+}	H+Al	SB	Value T	P	V
				cmol$_c$ kg^{-1}					mg kg^{-1}	%
0.00-0.05 m soil layer										
NT	C1	Bio	5.88 Ba[1]	1.80 Ba	0.65 Aa	3.07 Aa	2.92 Ba	5.98 Aa	3.20 Ba	48 Ba
	C2		5.88 Ba	1.63 Ba	0.78 Aa	3.17 Aa	3.00 Ba	6.17 Aa	2.48 Ba	48 Ba
	S.P		6.21 Ba	1.63 Ba	0.83 Aa	2.70 Aa	2.92 Ba	5.62 Aa	2.57 Ba	52 Ba
CT	C1	Bio	6.24 Aa	1.55 Aa	0.70 Aa	2.67 Ba	2.82 Aa	5.49 Aa	2.86 Aa	51 Aa
	C2		6.19 Aa	1.50 Aa	1.02 Aa	2.83 Ba	2.96 Aa	5.79 Aa	3.17 Aa	51 Aa
	S.P		6.76 Aa	1.75 Aa	0.90 Aa	2.27 Ba	3.02 Aa	5.29 Aa	5.13 Aa	57 Aa
NT	C1	Phy	5.82 Ba	1.69 Ba	0.70 Aa	2.97 Aa	2.84 Ba	5.81 Aa	2.74 Ba	49 Ba
	C2		5.82 Ba	1.58 Ba	0.78 Aa	3.17 Aa	2.89 Ba	6.06 Aa	2.35 Ba	47 Ba
	S.P		6.15 Ba	1.67 Ba	0.77 Aa	2.83 Aa	2.89 Ba	5.73 Aa	2.15 Ba	50 Ba
CT	C1	Phy	6.28 Aa	1.65 Aa	0.62 Aa	2.60 Ba	2.86 Aa	5.46 Aa	2.63 Aa	52 Aa
	C2		6.24 Aa	1.70 Aa	0.70 Aa	2.70 Ba	2.80 Aa	5.50 Aa	2.73 Aa	50 Aa
	S.P		6.54 Aa	1.67 Aa	1.02 Aa	2.30 Ba	3.10 Aa	5.40 Aa	4.96 Aa	57 Aa
0.05-0.10 m										
NT	C1	Bio	5.86 Ba	1.36 Aa	0.68 Aa	2.80 Aa	2.30 Aa	5.10 Aa	1.49 Ba	45 Aa
	C2		5.70 Ba	1.67 Aa	0.53 Aa	3.23 Aa	2.44 Aa	5.67 Aa	0.94 Ba	43 Aa
	S.P		6.03 Ba	1.53 Aa	0.70 Aa	2.90 Aa	2.52 Aa	5.42 Aa	1.08 Ba	46 Aa
CT	C1	Bio	6.08 Aa	1.40 Aa	0.88 Aa	2.60 Aa	2.55 Aa	5.15 Ba	1.42 Aa	49 Aa
	C2		5.99 Aa	1.70 Aa	0.82 Aa	2.80 Aa	2.85 Aa	5.65 Ba	1.83 Aa	50 Aa
	S.P		6.73 Aa	1.78 Aa	1.05 Aa	2.03 Aa	3.11 Aa	5.14 Ba	3.12 Aa	60 Aa
NT	C1	Phy	5.91 Ba	1.62 Aa	0.58 Aa	2.73 Aa	2.47 Aa	5.20 Aa	1.34 Ba	47 Aa
	C2		5.82 Ba	1.47 Aa	0.58 Aa	3.13 Aa	2.29 Aa	5.42 Aa	0.90 Ba	42 Aa
	S.P		6.10 Ba	1.52 Aa	0.65 Aa	2.80 Aa	2.44 Aa	5.24 Aa	1.00 Ba	46 Aa
CT	C1	Phy	6.09 Aa	1.63 Aa	0.80 Aa	2.70 Aa	2.83 Aa	5.53 Ba	1.36 Aa	51 Aa
	C2		6.10 Aa	1.58 Aa	0.80 Aa	2.67 Aa	2.58 Aa	5.25 Ba	1.60 Aa	49 Aa
	S.P		6.78 Aa	1.75 Aa	0.92 Aa	2.00 Aa	2.90 Aa	4.90 Ba	3.19 Aa	59 Aa

[1] Averages followed by equal letters, upper case for cropping systems, and lower case for formation pathways, do not differ by the Tukey test, at 5 % probability. NT: no-tillage system; CT: conventional tillage; Phy: physicogenic; Bio: Biogenic; Cocktail 1 (C1): 100 % of the number of seeds recommended for each species that compose the cocktail [Crotalaria (*Crotalaria juncea*) (20 kg ha^{-1}), JackBean (*Canavalia ensiformis*) (150 kg ha^{-1}) and Millet (*Pennisetum glaucum*) (60 kg ha^{-1})]; Cocktail 2 (C2): 50 % of the recommended seed amount for each species composing the cocktail [Crotalaria (Crotalaria (*Crotalaria juncea*) (10 kg ha^{-1}), JackBean (*Canavalia ensiformis*) (75 kg ha^{-1}) and Millet (*Pennisetum glaucum*) (30 kg ha^{-1})]; and spontaneous plants (S. P).

Principal Component Analysis

A PCA was performed, with the attributes proportion of aggregates, TOC content, POC, MAOC, LFC, and chemical properties (pH, value T, and V%), in the aggregates in the layers of 0.00-0.05 m (Figure 8) and 0.05-0.10 m (Figure 9) under different management systems (CT and NT). For the two PCA carried out, the principal components (PCs) together explained approximately 77 and 67 % of the variance of the parameters analyzed in the soil at the 0.00-0.05 and 0.05-0.10 m layers, respectively. At both layers (Figures 8 and 9), a separation is observed between the CT and NT management systems by the Y axis.

The variables that most contributed to the formation of PC1 (upper positive correlation on this axis >0.3) at the layer of 0.00-0.05 m (Figure 8) were V_F, pH_B, V_B, and pH_F, being these variables more associated with CT, and S.P cover, by their location in the same quadrant in the PCA. It can be observed that most of the variables are more correlated to CT, being the following attributes associated with NT: POC (B), T value (F and B), and LFC (F), being all these attributes more related to C2 cover, what can be verified by the positioning in the same quadrant in the PCA.

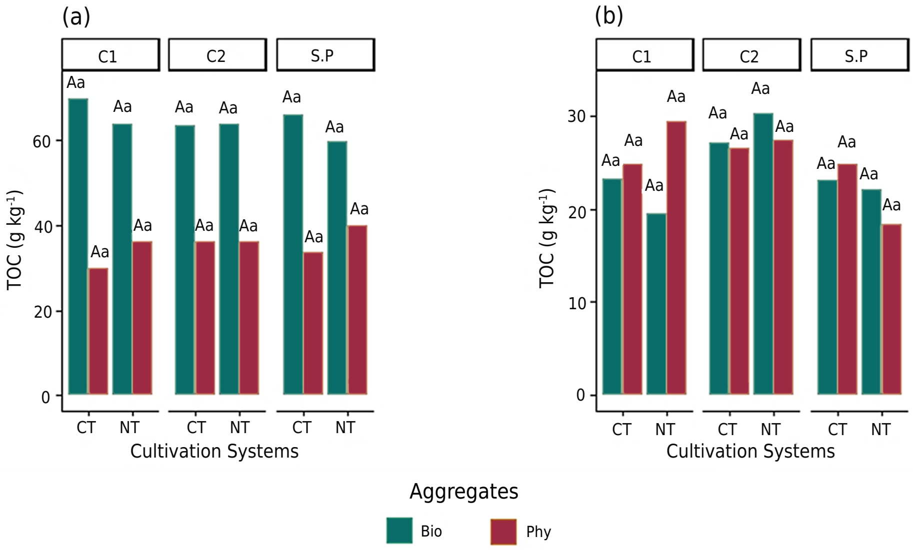

Figure 6. Values of total organic carbon (TOC) of biogenic (Bio) and physicogenic (Phy) aggregates of areas under different cultivation systems in sandy-textured soils, southeastern Brazil. (a) 0.00-0.05 m and (b) 0.05-0.10 m layers. Averages followed by equal letters, upper case for pathways formations and lower case for cultivation systems, do not differ by Tukey's test, at 5 % probability. NT: No-till System; CT: Conventional Tillage System; Cocktail 1 (C1): 100 % of the number of seeds recommended for each species that compose the cocktail [Crotalaria (*Crotalaria juncea*) (20 kg ha^{-1}), Jack Bean (*Canavalia ensiformis*) (150 kg ha^{-1}) and Millet (*Pennisetum glaucum*) (60 kg ha^{-1})]; Cocktail 2 (C2): 50 % of the recommended seed amount for each species composing the cocktail [Crotalaria (*Crotalaria juncea*) (10 kg ha^{-1}), Jack Bean (*Canavalia ensiformis*) (75 kg ha^{-1}) and Millet (*Pennisetum glaucum*) (30 kg ha^{-1})]; spontaneous plants (S. P); TOC: Total Organic Carbon; POC: Particulate Organic Carbon; MAOC: Mineral-Associated Organic Carbon; and LFC: free light fraction organic carbon.

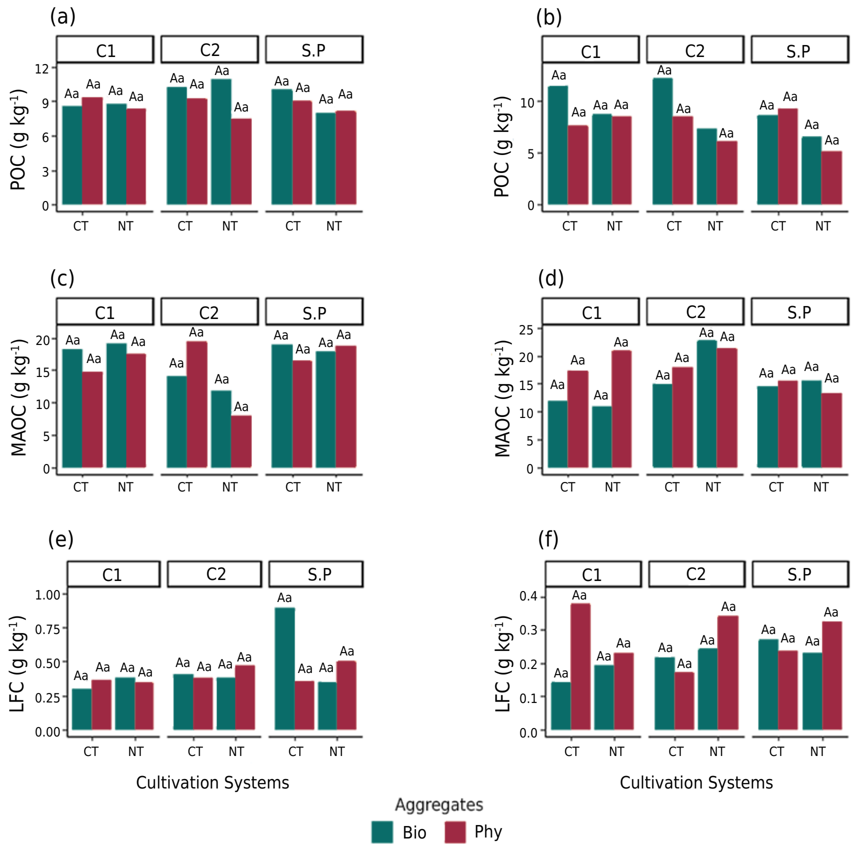

Figure 7. Soil organic matter fractions of biogenic (Bio) and physicogenic (Phy) aggregates of areas under different cultivation systems in sandy-textured soils, southeastern of Brazil. (a, c, and e) 0.00–0.05 m, and (b, d, and f) 0.05-0.10 m layers. Averages followed by equal letters, upper case for pathways formations and lower case for cultivation systems, do not differ by Tukey's test, at 5 % probability. NT: No-till System; CT: Conventional Tillage System; Cocktail 1 (C1): 100 % of the number of seeds recommended for each species that compose the cocktail [Crotalaria (*Crotalaria juncea*) (20 kg ha^{-1}), Jack Bean (*Canavalia ensiformis*) (150 kg ha^{-1}) and Millet (*Pennisetum glaucum*) (60 kg ha^{-1})]; Cocktail 2 (C2): 50 % of the recommended seed amount for each species composing the cocktail [Crotalaria (*Crotalaria juncea*) (10 kg ha^{-1}), Jack Bean (*Canavalia ensiformis*) (75 kg ha^{-1}) and Millet (*Pennisetum glaucum*) (30 kg ha^{-1})]; SP: spontaneous plants. POC: Particulate organic carbon; MAOC: Mineral associated organic carbon; and LFC: Free light fraction organic carbon.

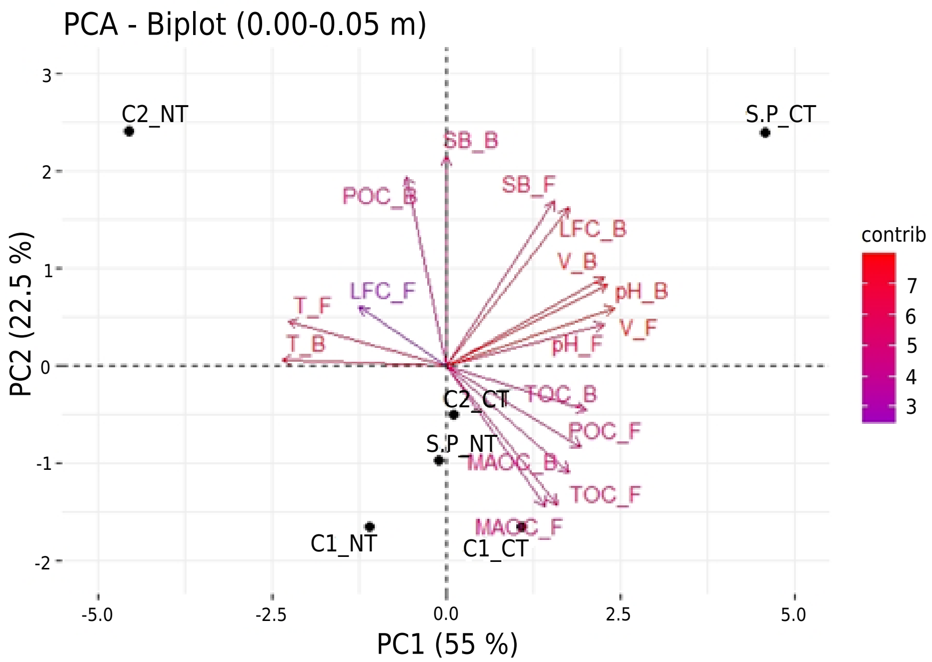

Figure 8. Principal component analysis (PCA) of soil chemical properties in biogenic (B) and physiogenic (F) aggregates, in different soil cultivation systems (NT and CT) and different vegetation covers (C1, C2, and S.P), at 0.00-0.05 m soil layer, in sandy soils of southeastern Brazil. Total organic carbon (TOC), particulate organic carbon (POC), mineral-associated organic carbon (MAOC), free light fraction organic carbon (LFC), base sum (SB), T-value (T), base saturation (V), spontaneous plants (S.P), No-till system (NT) and Conventional Tillage (CT).

For the layer of 0.05-0.10 m (Figure 9), the variables that most contributed to the formation of PC1 (upper positive correlation in this axis >0.3), were V_F, V_B, pH_B, pH_F, SB_F, and SB_B, being these variables associated with CT, and especially the S.P cover, which can be verified by their location in the same quadrant in the PCA. At this layer, it can be observed a greater number of properties correlated to the NT system, when compared to the layer of 0.00-0.05 m, with part of these properties associated with the C1 and S.P covers.

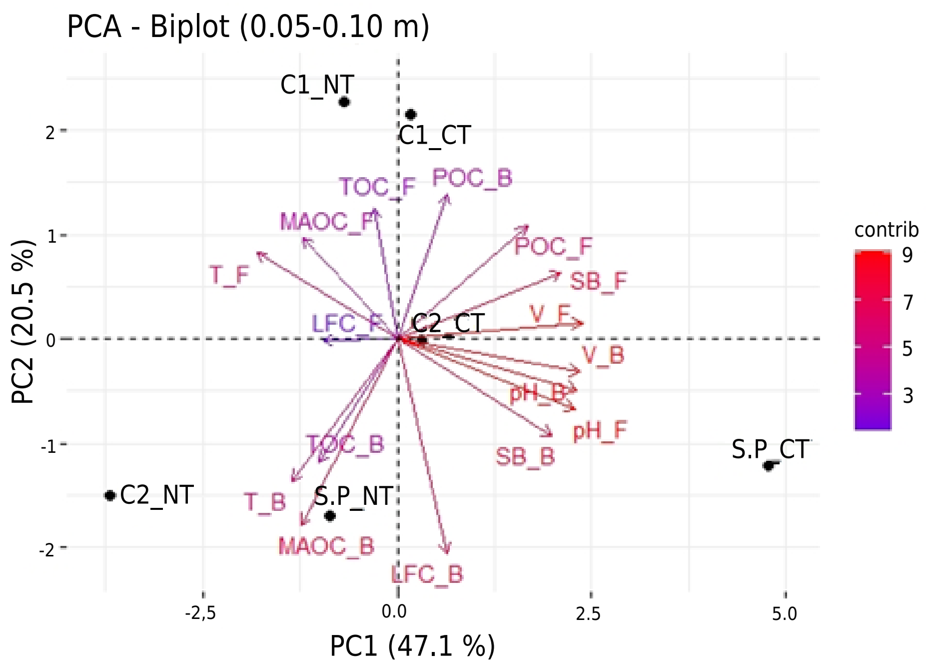

Figure 9. Principal component analysis (PCA) of soil chemical properties in biogenic (B) and physiogenic (F) aggregates, in different soil cultivation systems (NT and CT) and different vegetation covers (C1, C2, and S.P), at 0.05-0.10 m soil layer, in sandy soils of southeastern Brazil. Total organic carbon (TOC), particulate organic carbon (POC), mineral-associated organic carbon (MAOC), free light fraction organic carbon (LFC), base sum (SB), T-value (T), base saturation (V), spontaneous plants (S.P), No-till system (NT) and conventional tillage (CT).

DISCUSSION

Formation pathways

The cropping systems did not significantly influence the aggregate formation, and no significant difference was observed between the different vegetation covers in the relative proportion of the different aggregate types (Figure 5). The results observed in this study differ from those obtained by Mergen Júnior et al. (2015), in a study conducted in Braço do Norte - SC, with succession cultivation of oats and corn under NT, in which the authors observed a greater proportion of biogenic aggregates compared to physicogenic ones. In this study, there was a difference in the proportion of aggregates between the layers. At the 0.00-0.05 m soil layer, a higher percentage of biogenic aggregates was observed, whereas, at the 0.05-0.10 m layer, no differences were observed between the formation pathways.

In conservationist systems, it is expected to be a greater carbon stabilization, and, consequently, a greater formation and maintenance of biogenic aggregates (Brussaard et al., 2007). This pattern was not observed in this study, since the soil preparation systems (NT and CT) did not differ in the relative proportion of aggregates. A possible explanation for this pattern can be attributed to the sandy texture of the surface layer and the short time of implementation of the no-till farming system. According to Inagaki et al. (2016), it is in the transition phase (6 to 10 years after the implementation of the system) that the accumulation of straw and soil organic matter (SOM) begins.

In a study conducted on agroecological systems, Rossi et al. (2016) found that management systems did not significantly affect the relative proportions of different aggregates. While Loss et al. (2017), in Braço do Norte - SC, evaluating the influence of the application of swine manure on the formation of aggregates, found that regardless of the type of management adopted, physicogenic aggregates always occur in greater proportions compared to biogenic ones, and this pattern was observed in the study up to 0.10 m depth.

The results obtained regarding the type of vegetation cover are in agreement with those observed by Silva Neto et al. (2012), in a study conducted in the sub-basin of the Cachimbal stream, in which the authors found no differences in the relative composition of biogenic and physicogenic aggregates between areas with different types of vegetation cover. In the Cerrado of Minas Gerais, Pinto et al. (2021), evaluating the origin of aggregates formed under different management systems, found that the conservationist systems favored the biogenic formation pathway, reducing the relative proportion between physicogenic and biogenic aggregates, and enabling amounts of biogenic aggregates similar to those found in more stable and balanced environments (Cerrado vegetation).

Chemical properties

The fertility of the soils in the study area can be considered low, which can be seen from the nutrient analysis. The results obtained are in agreement with those observed by Santos et al. (2017), in a study conducted at the Federal University of Mato Grosso do Sul in the Campus of Chapadão do Sul - MS, with different cropping systems, CT, NT, and cultivation of Eucalyptus, in which the chemical properties were higher in areas of CT compared to areas of NT, due to the incorporation of straw stubble in the soil.

However, according to Gregório and Silva, (2022), at the Epagri experimental station in Itajaí, with organic cultivation under different managements (CT and NT), NT provided improvements in the soil chemical properies, while CT with mineral fertilization caused soil acidification, results that are a function of the agricultural practices adopted.

It is notorious that conservationist systems decrease nutrient losses, because the use of cover crops promotes the accumulation and maintenance of nutrients, contributing to their permanence in the soil-plant system (Loss et al., 2017). Although the results show that the different vegetation covers do not directly affect the significant variations in the properties, according to Costa et al. (2019), in a study conducted at IF Baiano, Campus Teixeira de Freitas, in different systems, the vegetation cover and management influenced the chemical quality of soils.

Carbon in the soil

The absence of difference observed for TOC values may be associated in these environments with the use of cover crops, which promote improvements in soil properties, even with mechanical practices. Similar results were verified by Rossi et al. (2016) that observed no differences in TOC contents in systems with different cover crops. In contrast, some studies with aggregate formation pathways describe TOC contents in higher proportions in biogenic aggregates when compared to physicogenic aggregates (Fernandes et al., 2017; Loss et al., 2017). The no-till farming system's adoption time may be influencing the absence of differences between the areas and management systems. In the study area, the time of installation of the systems is approximately four years, which is within the adoption phase, since significant changes tend to occur slowly, but the consolidation phase is between 10 and 15 years (Anghinoni, 2007).

The higher contents of the MAOC fraction compared to the POC can be explained by the greater protection of organic matter, provided by clay and silt particles, which make the OM less susceptible to mineralization. A similar pattern to the one observed in this study was verified by different authors (Silva Neto et al., 2016; Batista et al., 2013; Loss et al., 2017) in studies with aggregates from different formation pathways, in areas with different management systems or vegetation cover.

For TOC, lower values were quantified at a depth of 0.00-0.05 m compared to a depth of 0.05-0.10 m (Figures 6a and 6b), this pattern may be associated with rapid mineralization in the upper layers due to the sandier texture (Costa et al., 2022). At the layer of 0.05-0.10 m, we observed higher TOC values due to the lower speed of decomposition, which occurs at this layer due to the decrease in biological activity.

Regarding the C2 cover area, a percentage increase in TOC was observed, which was not statistically confirmed, and is associated with the use of 50 % of the recommended number of seeds for each species of the cocktail (Figure 6), because the effect of the competition of plants for resources is lower when compared to the C1 area and spontaneous plants, providing better use of resources.

Principal Component Analysis

Through the PCA analysis, it is verified that the pH and V% are associated with the CT areas, with spontaneous plants cover, in both depths (Figures 8 and 9). This pattern may be related to the type of vegetation cover used, which can contribute to the modification of soil quality as a function of nutrient cycling (Favero et al., 2000). This result agrees with those observed by Espanhol et al. (2007), in an experiment in São Joaquim - SC, in an apple orchard, with different management of spontaneous plants. The authors verified an improvement in soil fertility, with an increase in the content of organic carbon, pH values in water, and reduction in aluminum saturation with the use of conventional management, with the revolving and incorporation of spontaneous plants.

As for the carbon fractions (TOC, POC, MAOC and LFC), a distinct pattern was observed among the layers, and in the 0.00-0.05 m layer (Figure 8), these fractions were associated with CT with the use of the C1 cover. While at the layer of 0.05-0.10 m (Figure 9), some fractions are associated with NT (TOC, MAOC, and LFC). The pattern observed for the 0.00-0.05 m soil layer differs from that observed by Loss et al. (2011), in which the authors evaluated an agroecological production area, with different preparation and cultivation systems, and found higher levels of carbon fractions in more conservationist systems, such as no-till, at both depths. At a layer of 0.05-0.10 m, the correlation between POC and the C1 cover demonstrates that this vegetation cover is acting in the formation of aggregates, and, consequently, this fraction is more protected in the aggregates. This pattern is in agreement with the study of Loss et al. (2011), which found higher values of POC associated with systems that use green manure.

CONCLUSION

Biogenic aggregates percentage was higher in the 0.00-0.05 m layer, in all areas regardless of the management system and vegetation cover evaluated. The chemical properties quantified in the different conditions did not differ significantly between the biogenic and physicogenic formation pathways.

The evaluation of the total organic carbon in the aggregates did not identify differences between the no-till system (NT) and conventional system (CT) areas and the biogenic and physiogenic formation pathways. The different management systems (NT and CT) positively impacted the chemical properties and the levels of carbon fractions in aggregates, with the highest values observed in CT. In general, C2 and S.P mulches provided the greatest improvements in chemical properties and carbon content, but not on formation pathways.

This study provides important information for further studies in similar environments to monitor the impacts of different management practices on sandy soils by means of efficient, economical and practical indicators.

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Investigation: Tiago Paula da Silva (equal) and Marcos Gervasio Pereira (equal).

Methodology: Hugo de Souza Fagundes (equal), Igor de Sousa Morais (equal), Marcos Gervasio Pereira (equal) and Tiago Paula da Silva (equal).

Project administration: Marcos Gervasio Pereira (lead).

Supervision: Marcos Gervasio Pereira (lead).

Writing – original draft: Everaldo Zonta (equal), Gilsonley Lopes dos Santos (equal), Luiz Alberto da Silva Rodrigues Pinto (equal), Marcos Gervasio Pereira (equal) and Tiago Paula da Silva (equal).

Writing – review & editing: Everaldo Zonta (equal), Gilsonley Lopes dos Santos (equal), Luiz Alberto da Silva Rodrigues Pinto (equal), Marcos Gervasio Pereira (equal) and Tiago Paula da Silva (equal).

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