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Aggregate formation and soil organic matter under different vegetation types in Atlantic Forest from Southeastern Brazil

Formação de agregados e matéria orgânica do solo sob diferentes tipos de vegetação na Floresta Atlântica do Sudeste do Brasil

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Abstract

Changes in soil use and management can affect the soil aggregation, including aggregate formation by biogenic and physicogenic processes. The aim of this study was to analyze physical and biological influences on the genesis of soil aggregates in areas with different vegetations in the Atlantic Forest, as well as to compare physical and chemical attributes of the aggregates formed in different ways. Undeformed soil samples were collected from a depth of 0-10 cm from second-growth forests at different successional stages and a pasture area. To identify the pathways of aggregation we used morphological patterns proposed by Bullock et al. (1985), and established three clusters: physicogenic, biogenic, and intermediates. The aggregates were analyzed for stability, exchangeable cations, distribution of total organic carbon (TOC), and oxidizable fractions of total organic carbon. In all areas evaluated, the percentage of physicogenic aggregates was higher than that of biogenic and intermediate aggregates. The biogenic aggregates with the highest mean weight diameter (MWD) and geometric mean diameter (GMD) were recorded for samples from the second-growth forest at an advanced stage of succession (SFAS) and from the mixed managed pasture (MMP) sites (MWD: 4.520 mm and 4.896 mm; GMD: 3.678 mm and 4.479 mm, respectively). The biogenic aggregates presented higher levels of K and P compared to the other morphological types in all areas studied, with higher P levels in the SFAS area. The TOC content was also higher in the biogenic aggregates in all study areas, with 22.33 g kg^{-1} in SFAS, 25.60 g kg^{-1} in the site with second-growth forest at the middle stage (SFMS) of succession, 24.74 g kg^{-1} in the site with second-growth forest at the initial stage (SFIS) of succession, and 20.28 g kg^{-1} in MMP. The highest content of the fractions F1 (6.93 g kg^{-1}) and F2 (7.43 g kg^{-1}) were found in the biogenic class compared to the intermediate and physicogenic aggregates. The biological aggregation process was the most efficient process in terms of soil structural stability and carbon sequestration, and biogenic aggregates may be considered indicators of soil quality.

Key words: Aggregation. Atlantic Forest. Organic carbon. Oxidizable fractions.

Resumo

Mudanças no uso e manejo do solo podem afetar os processos de agregação, incluindo a formação de agregados por processos biogênicos e fisiogênicos. O objetivo deste estudo foi analisar a gênese de agregados por diferentes vias de formação, bem como atributos físicos e químicos dos agregados formados por essas vias em áreas com diferentes coberturas vegetais. Foram coletadas amostras de

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solo indeformadas na camada de 0-10 cm em áreas de floresta secundária com diferentes estádios sucessionais e uma área de pastagem. Para identificar as vias de agregação foram usados padrões morfológicos propostos por Bullock et al. (1985) e estabeleceu-se três grupos: fisiogênicos, biogênicas e intermediários. Os agregados foram analisados quanto à estabilidade em água, cátions trocáveis, teor de carbono orgânico total (COT) e frações oxidáveis do carbono orgânico total. Em todas as áreas avaliadas a porcentagem de agregados fisiogênicos foi maior do que a de agregados biogênicos e intermediários. Os agregados biogênicos foram encontrados em quantidade menor, com as maiores médias de Diâmetro Médio Ponderado (4.520 milímetros e 4.896 milímetros) e Diâmetro Médio Geométrico (3.678 milímetros e 4.479 milímetros) nas áreas de Floresta Secundária Estádio Avançado (FSEA) e Pasto Misto Manejado (PMM). Os agregados biogênicos apresentaram níveis mais elevados de K e P entre as classes morfológicas em todas as áreas estudadas, com os níveis de fósforo mais elevados na área de FSEA. O conteúdo COT também foi maior nos agregados biogênicos em todas as áreas de estudo, com 22.33 g kg^{-1} na FSEA, 25.60 g kg^{-1} na Floresta Secundária Estadio Médio (FSEM), 24.74 g kg^{-1} na Floresta Secundária Estadio Inicial (FSEI) e 20.28 g kg^{-1} em PMM. O maior teor de frações F1 (6.93 g kg^{-1}) e F2 (7.43 g kg^{-1}) foram encontrados na classe biogênica em comparação com agregados intermediários e fisiogênicos. O processo de agregação biológica é provavelmente o processo mais eficiente em termos de estabilidade estrutural do solo e sequestro de carbono e os agregados biogênicos podem ser considerados indicadores da qualidade do solo.

Palavras-chave: Agregação. Floresta atlântica. Carbono orgânico. Frações oxidáveis.

Introduction

Changes in soil use and management lead to enormous losses of organic carbon in agricultural areas all over the world, and may have negative effects on soil structure and fertility (BOSSUYT et al., 2004). In tropical environments within the Atlantic Forest, there is a predominance of highly weathered soils, and soil organic matter (SOM) plays an important role in soil fertility (MORAES et al., 2002). Conservative agricultural practices may increase agricultural productivity and transform the soil into a sink of atmospheric CO_2. However, in order to define those practices, we need a better understanding of management effects on SOM-dynamics and its interactions with soil structure.

Soil aggregates work as structural units that control SOM-dynamics and nutrient cycling. Therefore, soil aggregates are very important for the maintenance of porosity and aeration of the soil, plant and microbial population growth, water infiltration, and in determining the intensity and control of erosion (CHEVALLIER et al., 2004). Because of their important role, several studies have investigated the origin and dynamics of soil aggregates (SIX et al., 2004; BRONICK; LAL, 2005; DE GRYZE et al., 2006).

Aggregates in the soil may be formed as a result of physical forces in the process of wetting and drying, compression by roots, and organo-mineral interactions (TISDAL; OADES, 1982). These aggregates are denominated physicogenic, i.e., formed by physical and chemical actions and by the addition of organic matter (PULLEMAN et al., 2005). Another formation process of soil aggregates is the biogenic way, through which aggregates are formed by excrements produced by animals and plant roots. This formation process is faster than the first (MELLO et al., 2008; BATISTA et al., 2013).

SOM contributes directly to the formation and stabilization of aggregates, as the large amount of organic radicals of the supramolecular structures, with different composition and patterns, is able to interact with the surface of minerals through different functional mechanisms (BAYER; MIELNICZUK, 2008). Further, for the biogenic process, the diversity and amount of soil flora and fauna are important to improve aggregation, as the activity of the edaphic fauna is important in the formation of organo-mineral complexes and in aggregation.

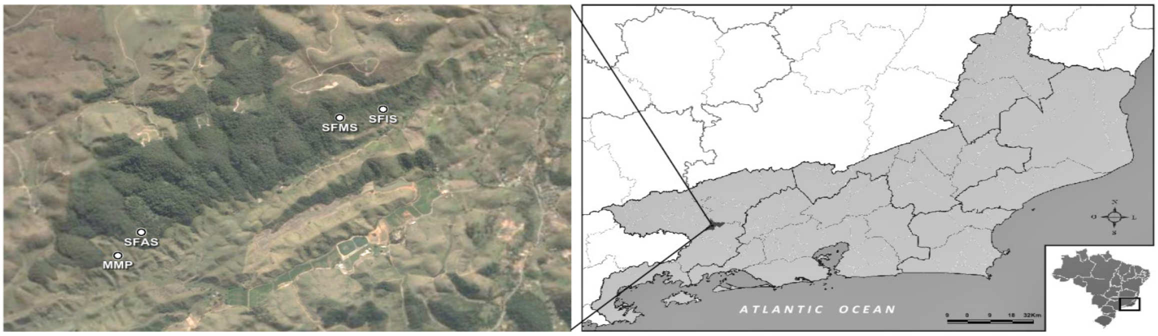
Previous studies show evidence that a marked loss of organic matter is accompanied by the consumption of fractions with higher lability, and the biological activity in the soil is closely associated with mineralization and humification of organic matter (CORREIA, 2002). By studying oxidizable fractions, it is possible to quantify the different degrees of oxidation of SOM, through increasing concentrations of sulfuric acid, and by analyzing the impact of management on compartments of organic matter. According to Chan (2001), the oxidizable fractions of total organic carbon (TOC) denoted as F1, F2, F3, and F4, correspond, respectively, to the concentrations of 3, 6, 9, and 12 mol L^{-1} of sulfuric acid. According to these authors, the fractions F1 and F2 are associated with the formation of macroaggregates and nutrient availability, and the fraction F1 has the highest lability in the soil, and is highly correlated with the free light fraction of SOM (MAIA et al., 2007). The fractions F3 and F4 are related to compounds with higher chemical stability, originated from the decomposition and humification of the SOM (STEVENSON, 1994).

In the Atlantic Forest, studies on the biological and structural quality of the soil are needed, as this biome is nationally important for its biodiversity and agricultural production. There are few studies with information about the genesis of the different types of aggregates, as well as the biological contribution (fauna and flora) to different aggregate formation processes (REATTO et al., 2009; VOLLAND-TUDURI, 2005). Studies on the genesis of the different types of aggregates not only advance the knowledge of the dynamics of these and associated processes, but also can help qualify these aggregates as indicators of soil quality. Hence, the objective of the present study was to analyze physical and biological influences on the genesis of soil aggregates in areas with different vegetation types in the Atlantic Forest, as well as to compare physical and chemical attributes of the aggregates formed by different processes.

Material and Methods

Location, climate, and soil in the study area

The present study was carried out in Pinheiral, located in the region of the Paraiba do Sul Valley, in the state of Rio de Janeiro, southeastern Brazil, between 22° 33’-22° 38’ S and 43° 57’-44° 05’ W (Figure 1). The region is located within the Atlantic Forest, and its original vegetation is known as submontane seasonal semi-deciduous forest (IBGE, 1992), which is characteristic of altitudes between 300 and 800 m above sea level. Climate in the area is identified as Cwa or temperate dry winter and rainy summer, and as Am or tropical rainy climate with dry winter, according to the Köppen climate classification system. The region has an annual rainfall around 1308 mm and an average annual temperature of 20.9 °C (OLIVEIRA, 1998). Soil texture is similar between the sites and shows the following composition of sand (53-2000 μm), silt (2-53 μm), and clay (<2 μm) in the upper 40-cm depth: in the SFAS, 52% sand, 18% silt, and 30% clay; in the SFMS, 56% sand, 17% silt, and 27% clay; in the SFIS, 57% sand, 17% silt, and 26% clay; and in the MMP, 58% sand, 16% silt, and 26% clay. Soil is classified as Cambissolo Háplico, according to the Brazilian Soil Classification System (SANTOS et al., 2013).



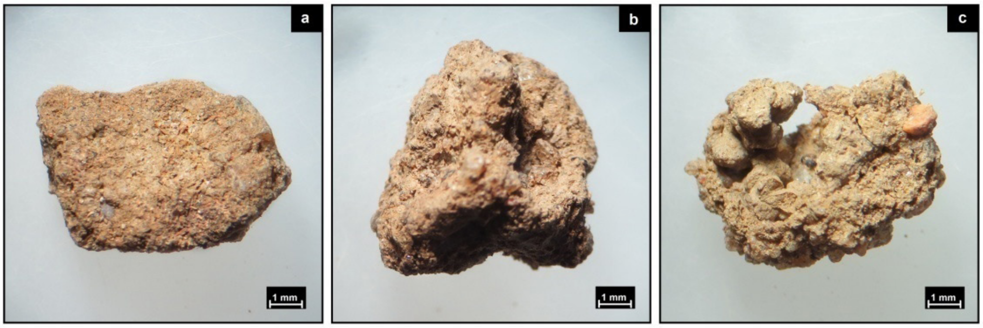
Source: Google Maps.

Sample collection and investigation of aggregate formation

Were selected four study units - (a) Second-growth forest at advanced stage (SFAS) of succession that is characterized by dense and very structured forests (CONAMA, 1996). It is the oldest fragment in the lower sub-basin, and in this study it was considered as the control area; (b) Second-growth forest at middle stage (SFMS) of succession where, until 1985, the area was managed under spontaneous pasture cover with initial '*capoeira*' training (typical vegetation). This has been kept under protection with typical successional development of the middle stage (CONAMA, 1996) and is characterized by a shrubby cover and often a more closed arboreal than the initial stage; (c) Second-growth forest at initial stage (SFIS) of succession which are located in an area adjacent to FSEM, and has little dense forest cover, featuring early stage succession characteristics (CONAMA, 1996). Until 1985, this area was used as a spontaneous pasture, managed with annual mowing and burning. From 1985, forest regeneration has been recorded; (d) The fourth site is an area of mixed managed pasture (MMP). This area has been used as a spontaneous pasture from 1950, and in the 1990s, *Brachiaria decumbens* was the dominant species recorded here. Thereafter, this area has been maintained through annual mowing and the practice of burning.

In each study unit, we delimited a 20 m × 20 m plot, located at the upper third of the hill. We dug six trenches in different vegetation cover, collecting a sample of soil per study unit, formed from three samples collected at a depth of 0-10 cm. We obtained in total, 36 soil samples. After collection, the samples were sieved in the field and we identified as aggregates those with size between 8.0 and 9.7 mm. To determine relative mass contribution, 100 g of aggregate was weighed for each replicate and area. As proposed by Bullock et al. (1985), the aggregates were observed under a magnifying glass and manually separated into physicogenic and biogenic according to their morphological patterns. Biogenic aggregates, produced by soil and/or root-associated microorganisms, were round. Physicogenic aggregates, formed by wetting and drying cycles, showed angular or prism shapes (VELASQUEZ et al., 2007; JOUQUET et al., 2009), and those with indefinite shape were classified as intermediate aggregates. Figure 2 shows examples of the physicogenic, intermediate and biogenic aggregates.

Figure 2. Examples showing the typical morphology of physicogenic (a), intermediate (b), and biogenic (c), aggregates.



Sample analyses

Aggregate stability

The aggregate stability represented by mean weight diameter (MWD) and the geometric mean diameter (GMD) were carried out according to the methodology described by Brazilian Corporation of Agricultural Research (EMBRAPA). Samples were pre-sieved using an 8 and 4 mm sieve. Soil aggregates retained on the 4 mm sieve were separated by wet sieving (KEMPER; CHEPIL, 1965). The samples (25 g) were pre-wetted with an atomizer. Aggregates were then sieved for 15 min (at 35 rpm), using five sieves of 2, 1, 0.5, 0.25, and 0.105 mm mesh. The material retained on each sieve was removed and oven dried at 105 °C for 24 h. After recording aggregate weights in each size fraction for each soil sample, the aggregate indices were calculated according to the following formulas:

$$MWD = \sum x_i w_i$$

where, w_i is the proportion of each size class (i) with respect to the total sample and x_i is the mean diameter in that size class (mm).

The geometric mean diameter was calculated as follows:

$$GMD = \exp\{(\sum w_i \ln x_i)/(\sum w_i)\}$$

where, w_i is the weight (in g) of the aggregates of each size class and $\ln x_i$ is the natural logarithm of the mean diameter of that size class.

Characterization of aggregate exchange complex

For chemical analysis, physicogenic and biogenic aggregates were crumbled and sieved through a 2.0 mm mesh. This sample was used in the following analyses. The pH , calcium (Ca^{2+}), magnesium (Mg^{2+}), aluminum (Al^{3+}), potassium (K^+), sodium (Na^+), hydrogen + aluminum ($H^+ + Al^{3+}$), and phosphorus (P) were determined according to the Brazilian Agricultural Research Corporation (EMBRAPA, 2011). The pH in H_2O was determined by potentiometer, using a 1:2.5 (v/v) soil solution. Exchangeable cations Ca^{2+}, Mg^{2+} and Al^{3+} were extracted with 1 M KCl, and potential soil acidity (H + Al) was determined using a solution of 0.5 M calcium acetate, at pH 7.0. P, Na^+ and K^+ were extracted with 0.0125 mol L^{-1} H_2SO_4 solution + 0.05 M HCl. Contents of Ca^{2+} and Mg^{2+} were determined by titration with 0.0125 mol L^{-1} EDTA solution, Na^+ and K^+ by flame photometry, P by colorimetry, and Al^{3+} and H + Al by titration with 0.025 M NaOH.

Carbon and Oxidizable organic carbon fraction in the aggregates

The total organic carbon (TOC) of the aggregates was quantified by wet oxidation of the organic matter, using a potassium dichromate solution in an acid medium, with an external heat source (YEOMANS; BREMNER, 1988). Partitioning of oxidizable carbon was performed by decreasing the oxidation degree (lability) according to Chan (2001). In an adaptation of the Walkley-Black method, four oxidizable fractions were analyzed: very easily oxidizable (F1), easily oxidizable (F2), moderately oxidizable (F3), and resistant (F4). The four quantified fractions corresponded to carbon oxidation with $K_2Cr_2O_7$ were acidified with the following concentrations of H_2SO_4: 3 mol L^{-1} (F1), 3-6 mol L^{-1} (F2), 6-9 mol L^{-1} (F3), and 9-12 mol L^{-1} (F4).

Statistical analyses

After confirming normality with the Lilliefors test and homoscedasticity using the Cochran and Bartlett tests, results were analyzed. The F-test ($P < 0.05$) was applied to determine the significance of the main effects obtained from ANOVA. For variables that were significant, we separated the treatment means using the Bonferroni test at 5%.

Results and Discussion

In all the areas that we evaluated, the percentage of physicogenic aggregates was larger than intermediate and biogenic aggregates (Table 1). The lower expression of biogenic class suggests a greater sensitivity of the formation of biogenic aggregates to changes in vegetation cover. These results are in accordance with the study of Loss et al. (2014) who reported that physicogenic aggregates were more abundant than biogenic and intermediate aggregates in south-west Paraná State, Brazil. We found the highest percentage of biogenic aggregates (28.77%) in the MMP area. This was probably because of the high density and continual renewal of pasture root system that contributes to increased activity of soil fauna, which are precursors of biogenic aggregates (MENEZES et al., 2009). According to Pasini et al. (2000), cultivated pastures can increase the biomass and population of soil fauna groups, especially Oligochaeta.

Table 1. Percentage of each aggregate type found in different vegetation types and their average [(1)] (%), Mean weight diameter (MWD), and the geometric mean diameter (GMD).

Attributes	Formation process	Study areas [(2)*]			
		SFAS	SFMS	SFIS	MMP
%	Phys	40.70 Aa	41.28 Aa	36.29 Bb	42.19 Aa
	Int	32.26 Cb	36.68 Bb	40.28 Aa	28.20 Db
	Bio	26.78 Ac	24.23 Bc	23.07 Bc	28.77 Ab
MWD (mm)	Phys	4.123 Bb	4.876 Aa	4.990 Aa	4.828 Ab
	Int	4.391 Bb	4.910 Aa	4.950 Aa	4.853 Ab
	Bio	4.520 Ca	4.897 Ba	4.967 Aa	4.896 Ba
GMD (mm)	Phys	3.133 Cb	4.593 ABa	4.832 Aa	4.328 Bb
	Int	3.591 Cb	4.567 Ba	4.841 Aa	4.396 Bb
	Bio	3.678 Ca	4.585 ABa	4.817 Aa	4.479 Ba

[1] Approximate average of six repetitions.

[2] Average of four repetitions.

SFAS: Second-growth Forest at Advanced Stage; SFMS: Second-growth Forest at Middle Stage; SFIS: Second-growth Forest at Initial Stage; MMP: Mixed Managed Pasture; Phys: physicogenic; Int: intermediate; Bio: biogenic.

* Within a row, means followed by the same uppercase letter are not significantly different between systems for each aggregate type, and within a column, means followed by the same lowercase letter are not significantly different between aggregate types in the same system in Bonferroni *t*-test (least square distance at P = 0.05).

In SFAS areas and MMP, the biogenic aggregates showed the highest values of MWD (4.520 mm and 4.896 mm, respectively) and GMD (3.678 mm and 4.479 mm, respectively) with a significant difference when comparing the aggregation paths. Consequently, these aggregates were less likely to lose cations due to erosion and lixiviation. This could be related to the highest value for total bases found in this areas (Table 2). In a study on the physical and chemical attributes of soil aggregates, Silva Neto et al. (2010) related higher stability of biogenic aggregates to higher proportions of clay, cations, and organic matter. According to Blanchart et al. (2004), biogenic aggregates are highly stable and assure resistance to degradation, be it by water, wind, or mechanic erosion.

In the SFAS, we found the lowest MWD and GMD values compared to the other forest successional stages (SFIS and SFMS). In addition to the effects associated with the regeneration of native vegetation under natural conditions, the content of soil organic matter is more stable because of the intensive addition of litter resulting in conditions that influence an increase in the microbial biomass and activity (BAYER; MIELNICZUK, 2008; VIEIRA et al., 2008; RIBEIRO et al., 2009). In SFAS area, we recorded a higher percentage of biogenic aggregates and intermediaries, which highlights the efficiency of biological pathways in the formation of soil aggregates, and indicates that these results are inversely proportional to values of MWD and GMD. These values possibly also reflected changes associated with the quantity and quality of vegetation residues available to soil biota and this was most evident especially in biogenic and intermediary aggregates. The conversion process from pasture to forest contributes to the input of organic matter from rhizodeposition of the grasses previously present (MENEZES, 2008). Well-managed pastures can lead to the increase in aggregate stability and provide physical protection against the fast decomposition of the SOM. However, these roots work as temporary agents of aggregation that do not persist unless they are continuously replaced (PULLEMAN et al., 2004).

The average values of the chemical attributes of aggregates in different formation process are shown in Table 2. The pH values did not differ between aggregate types in the study areas. In the SFAS area, we found the lowest pH values, which are related to the highest Al^{3+} content. This was in contrast to our observations in the MMP, where, we report the lowest values in potential soil acidity (H + Al). These results can be explained by the constant renovation of the root system of grasses in MMP area, which positively contributes to nutrient cycling and acts in the aluminum complexation through the organic matter that they add to the system in the MMP area. The low pH values observed in the SFAS can be attributed to the immobilization of nutrients in the large-sized plant biomass that predominates in this system, similar to the pattern observed for the lower values of nutrients and higher values of aluminum.

Among the three morphological types, the biogenic aggregates presented higher levels of K and P in all areas studied, with the P levels in the area of SFAS showing significant difference in relation to the other study areas. Higher values of these elements can result from their release by the fragmentation of nutrient-rich organic materials by the soil macrofauna. Silva Neto et al. (2010) and Batista et al. (2013) found higher P levels in biogenic aggregates derived from earthworm castings and associated with root activity. The dynamics of these elements in biogenic aggregates differs not only by its higher content, but also due to pH, which affects the availability of these elements (NOGUERA et al., 2010). In the SFAS, we observed lower Ca and Mg content compared to the MMP, which can be attributed to the immobilization of these elements in plant biomass. Consequently, a lower cycling, in particular of structural elements such as Ca, can be expected in the short term. No differences were found between aggregate types for the other nutrients in the study areas.

Table 2. Average values [(1)] of nutrient content, sum of bases (S value), cation exchange capacity in the soil (T value), and base saturation (V value) of fraction from different origins in the study areas.

Area [(2)]	Ca			Mg			Na			K			Al			P		
	cmol$_c$ kg^{-1}															mg kg^{-1}		
	F	I	B	F	I	B	F	I	B	F	I	B	F	I	B	F	I	B
SFAS	1.5 Ba	1.7 Ba	1.8 Ba	1.8 Ba	2.0 Ba	2.0 Ba	0.03 Aa	0.03 Aa	0.03 Aa	0.07 Cc	0.11 Cb	0.19 Ca	0.6 Aa	0.7 Aa	0.8 Aa	1.2 Ab	1.4 Ab	3.7 Aa
SFMS	2.8 Aa	2.9 Aa	3.1 Aa	2.4 Ba	2.4 Ba	2.4 Ba	0.04 Aa	0.04 Aa	0.05 Aa	0.21 Ac	0.36 Ab	0.59 Aa	0.3 Ba	0.3 Ba	0.3 Ba	0.9 Bb	1.0 Bb	2.7 Ba
SFIS	2.7 Aa	3.2 Aa	3.2 Aa	2.6 Ba	2.7 Aa	2.2 Ba	0.03 Aa	0.04 Aa	0.04 Aa	0.11 Bc	0.21 Bb	0.46 Ba	0.3 Ba	0.3 Ba	0.3 Ba	0.7 Bb	1.2 Ab	2.7 Ba
MMP	2.8 Aa	2.9 Aa	3.2 Aa	3.7 Aa	3.3 Aa	3.3 Aa	0.04 Aa	0.04 Aa	0.05 Aa	0.27 Ac	0.42 Ab	0.52 Aa	0.2 Ba	0.2 Ba	0.2 Ba	0.5 Bb	1.0 Ab	2.2 Ba

Area [(2)]	pH			H+Al			S			T			V		
	(H$_2$O)			cmol$_c$ kg^{-1}									(%)		
	F	I	B	F	I	B	F	I	B	F	I	B	F	I	B
SFAS	4.39 Ca	4.43 Ca	4.41 Ca	6.33 Aa	6.43 Aa	6.43 Aa	3.39 Ca	3.84 Ba	4.04 Ba	9.73 Ba	10.27 Ba	10.45 Ba	35 Ba	37 Ba	38 Ba
SFMS	5.34 Ba	5.36 Ba	5.14 Aa	6.45 Aa	6.25 Aa	6.28 Aa	5.45 Ba	5.71 Aa	6.14 Ba	11.92 Aa	11.95 Aa	12.42 Aa	46 Aa	48 Aa	49 Aa
SFIS	5.38 Ba	5.31 Ba	4.98 Ba	6.70 Aa	6.78 Aa	6.75 Aa	5.44 Ba	6.15 Aa	5.97 Ba	12.14 Aa	12.93 Aa	12.65 Aa	45 Aa	48 Aa	47 Aa
MMP	5.75 Aa	5.78 Aa	5.34 Aa	5.70 Ba	5.43 Ba	5.10 Ba	6.81 Aa	6.66 Aa	7.07 Aa	12.51 Aa	12.09 Aa	12.17 Aa	54 Aa	55 Aa	58 Aa

Soil fertility in Rio de Janeiro state, Brazil, is considered high, according to the study of Freire et al. (2013), who obtained Ca + Mg > 6.10 $cmol_c$ dm^{-3} by the EMBRAPA method (EMBRAPA, 2011). However, the areas evaluated in the present study, especially the SFAS, showed low Ca + Mg levels in both aggregates. The only exception was the pasture area. The high Ca + Mg content in MMP area can be justified by the constant renewal of the root system of grasses working in cycling nutrients and complexation of exchangeable aluminum by soil organic matter (MENEZES, 2008). The highest concentrations of Ca + Mg in this area may also be associated with the release of nutrients in the ash generated by the burning of pasture management practice in this area.

The TOC content was also higher in the biogenic aggregates in all study areas (Table 3), with 22.33 g kg^{-1} in SFAS, 25.60 g kg^{-1} in SFMS, 24.74 g kg^{-1} in SFIS and 20.28 g kg^{-1} in MMP. Similar values were found by Bossuyt et al. (2005), who observed that the biogenic aggregates were enriched with 22% of organic carbon in comparison with soil physicogenic aggregates. Biogenic aggregates contribute more efficiently to the physical protection of the soil organic matter, reducing the decomposition rate and increasing the potential of carbon sequestration (SILVA NETO et al., 2010). Organic matter is considered one of the main agents favoring soil aggregation. Part of the aggregate size variation, and therefore, the aggregation indices in tropical soils can be attributed to variations in SOM (CASTRO FILHO, 1988).

Table 3. Average values (1) of total carbon and oxidizable fractions of organic carbon. Fractions correspond to the part of organic C oxidized by $K_2Cr_2O_7$ in acid solution with: F1, H_2SO_4 < 3 mol L^{-1}; F2, 3-6 mol L^{-1}; F3, 6-9 mol L^{-1}; and F4, 9-12 mol L^{-1}.

		SFAS	**SFMS**	**SFIS**	**MMP**
TOC	Ph	19.68 Bb	20.61 Ab	21.15 Ab	17.12 Bb
	I	20.55 Ab	21.21 Ab	20.92 Ab	19.01 Ab
	B	22.33 Aa	25.60 Aa	24.74 Aa	20.28 Aa
F1	Ph	4.92 Ab	3.55 Bb	3.67 Bb	5.05 Ab
	I	4.67 Ab	3.80 Bb	3.93 ABb	5.05 Ab
	B	6.93 Aa	4.80 Ba	4.55 Ba	7.43 Aa
F2	Ph	3.48 Aa	1.85 Ba	2.23 Aba	3.10 Aa
	I	4.10 Aa	2.10 Ba	2.35 Ba	3.48 Aa
	B	4.23 Aa	3.23 Ba	3.35 Ba	4.73 Aa
F3	Ph	3.85 Aa	2.10 Ba	2.50 Ba	2.88 ABa
	I	4.98 Aa	3.19 Ba	2.50 Ba	3.25 ABa
	B	5.35 Aa	3.73 Ba	3.37 Ba	4.38 Aa
F4	Ph	2.90 Aa	2.65 Aa	2.50 Aa	3.38 Aa
	I	3.03 Aa	2.15 Aa	2.75 Aa	3.51 Aa
	B	3.52 Aa	3.62 Aa	4.10 Aa	3.50 Aa

[1] Average of four repetitions.
[2] SFAS: Second-growth Forest at Advanced Stage; SFMS: Second-growth Forest at Middle Stage; SFIS: Second-growth Forest at Initial Stage; MMP: Mixed Managed Pasture; Ph: physicogenic; I: intermediate; B: biogenic.
* Within a row, means followed by the same uppercase letter are not significantly different between systems for each aggregate type, and within a column, means followed by the same lowercase letter are not significantly different between aggregate types in the same system in Bonferroni *t*-test (least square distance at P = 0.05).

The lower contents of total organic carbon (TOC) were observed in the areas of SFAS (19.68 g kg^{-1}) and MMP (17.12 g kg^{-1}). Menezes (2008) obtained similar results in an evaluation of the edaphic attributes of the same study areas. The author attributed the lower TOC content in SFAS, which contrasted with high values of leaf litter input, to an immobilization of a large part of the carbon in plant biomass above the soil, as this area has a more developed structure with larger trees than younger successional stages.

The different types of vegetation influenced the distribution pattern of the oxidizable carbon fractions among the aggregates formed by the different processes. The highest content of the fractions F1 (6.93 g kg^{-1}) and F2 (7.43 g kg^{-1}) were presented in the biogenic class in all areas studied (Table 3). We observed significant differences in these fractions between SFAS and MMP. The highest TOC content in the fractions F1 and F2 were found in area of SFAS which can be attributed to the fact that this environment is better structured, evidenced by floristic survey (MENEZES, 2008), offering the best soil conditions and microclimate for the activity of soil fauna.

Studies on soil organic carbon fractionation indicate that high carbon content in the fraction F1 tends to be found in those areas where there is organic matter input via plant residues (CHAN, 2001; RANGEL et al., 2008). In the pasture area, the high carbon content can result from the root system of grasses, which adds organic matter with higher lability to the soil, and, therefore, provides food source for edaphic macrofauna, such as the oligochaetes. A larger root growth of the herbaceous vegetation may have favored the increase in the fractions F1 and F2 in these areas, in detriment of the fractions F3 and F4.

The fractions F1 and F2 showed higher lability in the soil, whereas the fractions F3 and F4 were considered more recalcitrant. Hence, a balance in the carbon content of these fractions would be desirable to create a balance between nutrient availability and soil structuring (afforded by F1 and F2) and physical and chemical protection (afforded by F3 and F4). The biogenic aggregation showed a more homogeneous distribution of carbon (TOC) in each oxidizable fraction, which suggests that these aggregates are more efficient in terms of soil structural stability and carbon sequestration (Table 3). This pattern shows that biogenic aggregates have both organic matter with higher lability in the soil (F1) and a more recalcitrant organic matter (F4).

The fraction F4 was not very sensitive to changes in the environment, and did not show difference in content among areas and aggregation processes, which confirms that it is a very stable SOM compartment. The difference between the TOC and the sum of the labile fractions may be related to non-labile fraction. The fractions F3 and F4 are related to compounds with higher chemical stability and molar mass, originated from the decomposition and humification of SOM (STEVENSON, 1994).

Conclusions

The biogenic aggregates showed enrichment in organic carbon, potassium, and phosphorus, which indicates, better chemical and physical conditions, and suggests that the biological formation process is important for the maintenance of soil balance. The dynamics of exchangeable cations is sensitive to changes in vegetation and among aggregation processes, as the vegetation directly influences nutrient concentration and availability.

Morphological separation helped us detect a significant difference in physical attributes and organic carbon. The compartmentalization of organic carbon can be used for the assessment of management quality; the most sensitive compartments in the assessment of oxidizable fractions were the fractions F1 and F2. The biological aggregation process was the most efficient process in terms of soil structural stability and carbon sequestration, and biogenic aggregates may be considered indicators of soil quality.

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