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Soil organic matter in biogenic, intermediate and physicogenic aggregates under agroecological management

Matéria orgânica do solo em agregados biogênicos, intermediários e fisiogênicos sob manejo agroecológico

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ABSTRACT - Agroecological management can favor the improvement of soil attributes, especially soil organic matter (SOM) and soil aggregation. The objective of the study was to quantify the carbon contents of the humic and oxidizable fractions of SOM of aggregates from different origins from agroecological management systems. Five experimental areas located in the Integrated Agroecological Production System were evaluated: AFS – Agroforestry System; C-SUN – Coffee in full sun; C-SHA – Shaded coffee; AL-FLE – Cultivation in alleys of *Flemingia macrophylla* with green beans; and NT – No-tillage. The aggregates were separated, identified, and classified as to their origin or formation pathways into biogenic, intermediate, and physicogenic. The carbon contents of the humic fractions fulvic acid (C-FAF), humic acid (C-HAF) and humin (C-HUMF); and oxidizable fractions (F1 and F2, labile; and F3 and F4, recalcitrant) of SOM were determined. The greatest variations in the carbon values of the humic fractions were observed in the aggregates of the AFS, C-SUN and C-SHA systems. In relation to C-HUMF, the highest contents of this fraction were quantified in the biogenic and intermediate aggregates of the C-SUN, C-SHA and AL-FLE systems. The carbon contents of the oxidizable fractions of SOM showed variability between the management systems, mainly for the F1, F2 and F3 fractions in the aggregates under C-SUN and C-SHA. The C-SUN system showed a higher proportion of more humified and recalcitrant fractions of SOM when compared to the C-SHA system. The management practices maids in the agroecological systems of C-SHA, C-SUN and AFS promoted improvements in soil quality.

Keywords: Aggregate formation pathways. Compartmentalization of organic carbon. Soil quality.

RESUMO - O manejo agroecológico pode favorecer a melhoraria dos atributos do solo, com destaque para a matéria orgânica do solo (MOS) e agregação do solo. O objetivo do estudo foi quantificar os teores de carbono das frações húmicas e oxidáveis da MOS de agregados de diferentes origens de sistemas de manejo agroecológico. Foram avaliadas cinco áreas experimentais localizadas no Sistema Integrado de Produção Agroecológica: SAF – Sistema agroflorestal; C-SOL – Café em pleno sol; C-SOM – Café sombreado; AL-FLE – Cultivo em aleias de flemíngia com vagem; e PD – Plantio direto. Os agregados foram separados, identificados e classificados quanto à sua origem ou vias de formação em biogênicos, intermediários e fisiogênicos. Nestes, foram determinados os teores de carbono das frações ácido fúlvico (C-FAF), ácido húmico (C-FAH) e humina (C-FHUM); e das frações oxidáveis (F1 e F2, frações lábeis; e F3 e F4, frações recalcitrantes). As maiores variações nos valores de carbono das frações húmicas foram verificadas nos agregados sob SAF, C-SOL e C-SOM. Em relação ao C-FHUM, nos agregados biogênicos e intermediários de C-SOL, C-SOM e AL-FLE foram quantificados os maiores teores dessa fração. Os teores de carbono das frações oxidáveis apresentaram variabilidade entre os sistemas de manejo, principalmente para as frações F1, F2 e F3 nos agregados sob C-SOL e C-SOM. No sistema de C-SOL verifica-se maior proporção de frações mais humificadas e recalcitrantes da MOS em comparação à C-SOM. As práticas de manejo empregadas nos sistemas agroecológicos de C-SOM, C-SOL e SAF proporcionaram melhorias na qualidade do solo.

Palavras-Chave: Vias de formação de agregados. Compartimentalização do carbono orgânico. Qualidade do solo.

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INTRODUCTION

Soil organic matter (SOM) plays a fundamental role in soil quality assessment, being pointed out as the key indicator and the largest reservoir of organic carbon of the earth's surface, with approximately 58% carbon in the total composition of the soil organic material (MACHADO, 2005). Among its definitions, SOM can be considered as the most complex, dynamic, heterogeneous and reactive component of the soil (STEVENSON, 1994). Due to its heterogeneity, it has clusters of organic compounds with different degrees of complexity, structural diversity and lability.

From a physical point of view, these organic compounds in the soil can be protected against microbial decomposition, with carbon occlusion in aggregates, or chemically protected by their interactions with soil minerals and cations, thus hindering microbial oxidation (SIQUEIRA NETO et al., 2010). In order to study the various compartments of SOM, numerous fractionation techniques have been used to quantify organic carbon, in its different fractions, in the different types of soil aggregates (LOSS et al., 2010, 2017; SILVA NETO et al., 2016).

Soil aggregates can be morphologically classified as physicogenic (formed by physical and chemical processes), biogenic (formed by the action of biological agents) (BULLOCK; FEDOROFF; JONGERIUS, 1985) and intermediate to these two types (PULLEMAN et al., 2005). The differentiation between the types of aggregates is performed based on their genesis or pathways of formation from morphological characteristics (BULLOCK; FEDOROFF; JONGERIUS, 1985; PULLEMAN et al., 2005; BATISTA et al., 2013).

Studies involving the different morphological types of aggregates and their potential use as soil quality indicators have found differences in the contents of total organic carbon and its fractions, especially those formed by soil biological agents (macrofauna and roots, mainly) (LOSS et al., 2014; SILVA NETO et al., 2016; ROSSI et al., 2016; FERNANDES et al., 2017; LOSS et al., 2017; PINTO et al., 2018; MELO et al., 2019; FERREIRA et al., 2020; LIMA et al., 2020). Among these fractions of organic carbon, the humic and oxidizable fractions of SOM stand out.

Chemical fractionation of SOM is used to quantify the carbon contents in the different humic fractions of the soil, based on the principle of differential solubility of organic compounds, and obtain the fractions fulvic acids, humic acids and humin (BENITES; MADARI; MACHADO, 2003). The sum of these fractions represents, in general, more than 80% of the total carbon of the soil and they are differentiated by color, molecular mass, functional groups (carboxylic, phenolic etc.) and degree of polymerization (aliphaticity, aromaticity and condensation) (STEVENSON, 1994).

The oxidizable organic carbon (CHAN; BOWMAN; OATES, 2001) can be divided into four fractions (F1, F2, F3 and F4) that have different degrees of recalcitrance. Fractions F1 and F2 are associated with nutrient availability and soil aggregation (CHAN; BOWMAN; OATES, 2001), and F1 is the most labile fraction and is correlated with the free light fraction of SOM (LOSS et al., 2013). Fractions F3 and F4 are related to compounds of greater chemical stability and molar mass, derived from the decomposition and humification of SOM (STEVENSON, 1994; RANGEL et al., 2008).

Agroecological management can positively influence edaphic attributes. In this context, information on the aggregation and contents of organic carbon and its fractions, mainly of the soil surface layer, can help elucidate the dynamics of SOM in areas under agroecological agriculture, as these are relatively simple quality indicators and are sensitive to the impacts of natural or anthropic processes. From the above, the study aimed to quantify the organic carbon contents of the humic and oxidizable fractions of SOM of different morphological types of aggregates from agroecological management systems.

MATERIAL AND METHODS

The study was carried out in the area of the Integrated Agroecological Production System (SIPA), called "Fazendinha Agroecológica do Km 47" (ALMEIDA et al., 1999). The area is located at Embrapa Agrobiology, in the municipality of Seropédica, RJ, Brazil, with the following coordinates: 22°45' S and 43°41' W, at an altitude of 33 meters, and the climate of the region is classified as type Aw (NEVES et al., 2005). The soil was classified as *Argissolo Vermelho-Amarelo* (Ultisol) according to Santos et al. (2018), showing sandy texture in the surface layer and being located in an area with gently undulating relief, routinely cultivated with vegetable and fruit crops.

Five experimental areas under different agroecological management systems were evaluated, namely: ***i)*** AFS – Agroforestry system with 10 years of implementation, cultivated with banana (*Musa sapientum*), jussara palm (*Euterpe edulis*), cocoa (*Theobroma cacao*), papaya (*Carica papaya*), guapuruvu (*Schizolobium parahyba*), achiote (*Bixa orellana*) and açaí palm (*Euterpe oleracea*); ***ii)*** C-SUN – Coffee (*Coffea canephora*) cultivated in full sun, with 15 years of implementation; ***iii)*** C-SHA – Coffee (*Coffea canephora*) shaded by gliricidia (*Gliricidia sepium*), with 15 years of cultivation; ***iv)*** AL-FLE – Cultivation in alleys of *Flemingia macrophylla* with green beans (*Phaseolus vulgaris*), with 10 years of implementation; and ***v)*** NT – No-tillage, with maize (*Zea mays*)/eggplant (*Solanum melongena*), with 6 years of cultivation.

Coffee areas annually receive fertilization in the hole with bokashi (organic fertilizer of plant and/or animal origin, subjected to a controlled fermentation process), and the NT area receives fertilization in the sowing furrow at the time of planting, with corral manure (doses required for supplying 50 to 100 kg ha^{-1} of N) and poultry litter as top-dressing (doses between 100 and 200 kg ha^{-1} of N). The areas are all close to each other and under the same topographic conditions.

Sampling was carried out in May 2014 and, in each sampling area, four pseudo-replicates (undisturbed samples – lumps) were collected in the 0–0.05 m layer, by opening soil pits transverse to the sowing rows. After collection, the samples were air-dried and subsequently sieved, using a set of sieves of 9.7 and 8.0 mm mesh, selecting only aggregates retained within this range. These were taken to the laboratory, examined under magnifying glass and separated by hand into morphological fractions, identifying three classes of aggregates (biogenic, intermediate and physicogenic) using a method adapted by Pulleman et al. (2005) from the morphological patterns established by Bullock, Fedoroff and Jongerius (1985) and validated by other authors (BATISTA et al., 2013; LOSS et al., 2014, 2017).

Differentiation was made through morphological patterns, obeying the following criteria: biogenic aggregates - those in which it is possible to visualize rounded forms, caused by the intestinal tract of individuals of the soil macrofauna, especially Oligochaeta (earthworms) and/or those in which it is possible to visualize the presence and activity of roots; physicogenic aggregates - those that showed angular forms resulting from the interaction between carbon, clay, cations and soil wetting and drying cycles; and intermediate aggregates - characterized by having indefinite forms, possibly being biogenic ones that lost their rounded shape due to aging or physicogenic ones associated with a small coprolite (BATISTA et al., 2013) (Figure 1).

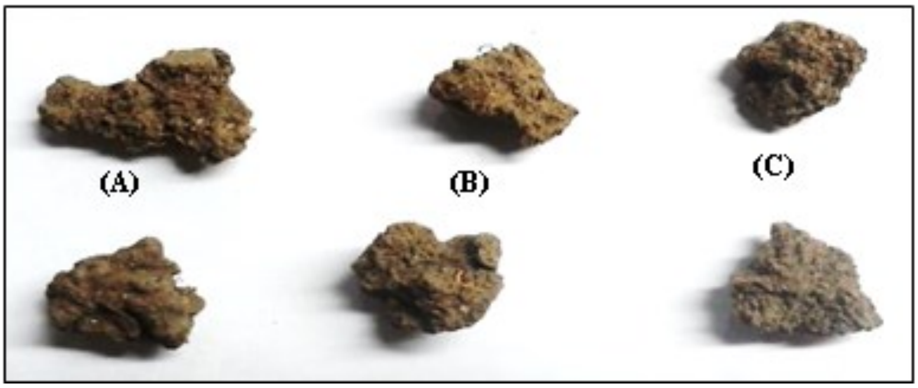


Figure 1. Classification of the origin of the aggregates by observation in magnifying glass. Biogenic aggregates (A); Intermediate aggregates (B) and Physicogenic aggregates (C).

The relative contribution (in percentage) of the different classes of aggregates in the sampled areas is shown in Table 1, and Table 2 shows the characterization data of the chemical attributes associated with fertility. After identification, the aggregates were crushed and passed through a 2.00-mm-mesh sieve, thus obtaining the air-dried fine earth fraction (ADFE) (TEIXEIRA et al., 2017) for organic matter analysis. From the ADFE of the aggregates, the analyses of chemical fractionation of humic substances and fractionation of organic carbon by oxidation degrees were performed.

Humic substances (HS) were obtained by extraction and separation according to the differential solubility of organic matter in basic or acidic medium (fulvic and humic acids) and the residue (humin) (BENITES; MADARI; MACHADO, 2003). The organic carbon contents in each of the humic fractions, fulvic acids (C-FAF), humic acids (C-HAF) and humin (C-HUMF), were determined according to Yeomans and Bremner (1988). From the results obtained, the percentages represented by each humic fraction in the total organic carbon (TOC; extracted from ROSSI et al., 2016) were calculated: 1) Percentage of the fulvic acid fraction: %CFA = ((C-FAF/TOC)*100); 2) Percentage of the humic acid fraction: %CHA = ((C-HAF/TOC)*100); 3) Percentage of the humin fraction: %CHUM = ((C-HUMF/TOC)*100); 4) Percentage of the sum of the humic substances: %CHS = (%CFA+%CHA+%CHUM); and 5) Percentage of the non-humified carbon fraction: %CNH = (100 - %CHS).

Organic carbon fractionation based on the degree of oxidation was carried out according to Chan, Bowman and Oates (2001). Four fractions were quantified: Fraction 1 (F1): C oxidized by $K_2Cr_2O_7$ in acidic medium with 3 mol L^{-1} of H_2SO_4; Fraction 2 (F2): difference between C oxidized by $K_2Cr_2O_7$ in acidic medium with 6 and 3 mol L^{-1} of H_2SO_4; Fraction 3 (F3): difference between C oxidized by $K_2Cr_2O_7$ in acidic medium with 9 and 6 mol L^{-1} of H_2SO_4; and Fraction 4 (F4): difference between C oxidized by $K_2Cr_2O_7$ in acidic medium with 12 and 9 mol L^{-1} of H_2SO_4.

Table 1. Distribution, in percentage, of biogenic, intermediate and physicogenic aggregates in areas under different agroecological management systems, Seropédica, RJ, Brazil.

Management system	Aggregates (%)		
	Biogenic	Intermediate	Physicogenic
AFS	26	42	22
C-SUN	30	40	30
C-SHA	34	38	28
AL-FLE	34	36	30
NT	25	40	35

AFS – Agroforestry system; C-SUN – Coffee cultivated in full sun; C-SHA – Coffee shaded by gliricidia; AL-FLE – Cultivation in alleys of *Flemingia macrophylla* with green beans; and NT – No-tillage with maize and eggplant.
Source: Rossi et al. (2016).

Table 2. Chemical characterization and total organic carbon of biogenic, intermediate and physicogenic aggregates in agroecological management systems, Seropédica, RJ, Brazil.

Systems	pH	TOC	Ca^{2+}	Mg^{2+}	Al^{3+}	H+Al	S	T	K^+	P
	H_2O	g kg^{-1}	------------------------------$cmol_c$ dm^{-3}------------------------------						-----mg dm^{-3}-----	
					Biogenic					
AFS	5.9	24.6	3.0	2.0	0.0	2.4	5.3	7.7	125	42
C-SUN	6.0	30.7	3.1	3.6	0.0	2.1	7.4	9.5	285	35
C-SHA	6.0	33.7	2.8	2.7	0.0	1.7	5.6	7.3	64	25
AL-FLE	5.3	22.0	1.6	1.2	0.0	1.5	2.9	4.4	44	35
NT	6.4	15.7	1.6	1.0	0.0	0.5	2.8	3.2	56	44
					Intermediate					
AFS	5.9	20.2	3.0	1.5	0.0	2.2	4.9	7.1	117	29
C-SUN	6.1	27.7	3.3	2.9	0.0	2.0	6.9	8.9	267	35
C-SHA	6.0	31.0	2.5	2.7	0.0	1.6	5.4	7.0	58	27
AL-FLE	5.3	17.2	1.5	1.6	0.0	1.5	3.1	4.6	37	39
NT	6.4	14.8	1.6	1.0	0.0	0.5	2.8	3.2	58	50
					Physicogenic					
AFS	5.9	24.5	2.6	2.8	0.0	2.4	4.7	7.0	106	36
C-SUN	6.2	22.7	3.5	2.3	0.0	1.8	6.4	8.1	234	46
C-SHA	6.0	29.7	2.5	2.2	0.0	1.3	4.8	6.1	54	27
AL-FLE	5.3	17.8	1.5	0.9	0.0	1.5	2.5	4.0	33	36
NT	6.4	13.9	1.5	1.1	0.0	0.4	2.7	3.2	54	39

AFS – Agroforestry system; C-SUN – Coffee cultivated in full sun; C-SHA – Coffee shaded by gliricidia; AL-FLE – Cultivation in alleys of *Flemingia macrophylla* with green beans; and NT – No-tillage with maize and eggplant.
Source: Rossi et al. (2016).

The design used in the study was completely randomized. The results of the humic and oxidizable fractions of SOM were analyzed for normality and homogeneity of the data by the Lilliefors and Cochran test and Bartlett test, respectively. The results were subjected to analysis of variance with application of F test, and the mean values, when significant, were compared to each other by the Scott-Knott test at 5% probability level using the ASSISTAT program (SILVA; AZEVEDO, 2002).

RESULTS AND DISCUSSION

The greatest variations in the carbon contents of the humic fractions of SOM were observed in the aggregates under AFS, C-SUN and C-SHA, mainly for fulvic acid (C-FAF) and humic acid (C-HAF) (Table 3).

The C-FAF and C-HAF fractions ranged from 1.37 to 3.65 g kg^{-1} and from 0.94 to 4.16 g kg^{-1}, respectively (Table 3). The highest values of C-FAF and C-HAF were found in AFS, C-SUN and C-SHA in the different types of aggregates evaluated. The lowest contents of the same fractions were verified in NT, regardless of the formation pathway evaluated. These results indicate that the aggregates of the AFS, C-SUN and C-SHA systems are accumulating more carbon in organic structures with different degrees of solubility and lability, which stand out in several processes in the soil, such as in the aggregation and cycling of nutrients.

In a study conducted in the same areas where the aggregate formation pathways and their chemical and physical attributes were evaluated, Rossi et al. (2016) found higher contents of TOC in aggregates under C-SHA, C-SUN and AFS in the 0–0.05 m layer, corroborating the results of C-FAF and C-HAF in the present study. These authors inferred that the carbon content of these humic fractions can increase in systems in which management favors the increment of TOC contents in the soil.

The lowest carbon contents in the NT area may be associated with the time of implementation of the system. The area has the shortest time of use (6 years) compared to the others, 10 years for AFS and AL-FLE and 15 years for C-SUN and C-SHA. The management, use and time of use promote several changes in soil properties, for instance in the structure and organic carbon content.

Studies conducted under different biome, relief and management conditions have shown changes in the carbon contents of the humic substances between the aggregate formation pathways, especially for the biogenic one (LOSS et al., 2014; FERNANDES et al., 2017; MELO et al., 2019; FERREIRA et al., 2020), which has been pointed out as a potential indicator in the evaluation of soil quality, precisely because of its greater sensitivity to different land use and management systems (PULLEMAN et al., 2005; LOSS et al., 2014; FERNANDES et al., 2017; MOURA et al., 2019).

Table 3. Organic carbon of the humic fractions of biogenic, intermediate and physicogenic aggregates in areas under different agroecological management systems, Seropédica, RJ, Brazil.

Systems	C-FAF	C-HAF	C-HUMF
	g kg^{-1}	g kg^{-1}	g kg^{-1}
	Biogenic Aggregates		
AFS	3.57 a	3.33 a	12.03 b
C-SUN	3.62 a	4.16 a	13.83 a
C-SHA	3.61 a	3.51 a	15.18 a
AL-FLE	2.49 b	2.09 b	14.15 a
NT	1.38 c	1.15 c	11.80 b
CV (%)	13.7	20.2	18.0
	Intermediate Aggregates		
AFS	2.91 a	2.92 a	11.48 b
C-SUN	3.20 a	3.63 a	13.45 a
C-SHA	3.11 a	2.96 a	13.63 a
AL-FLE	2.50 a	2.19 a	13.38 a
NT	1.37 b	0.94 b	10.58 b
CV (%)	17.0	22.0	20.7
	Physicogenic Aggregates		
AFS	3.15 a	2.73 a	13.65 ns
C-SUN	3.65 a	3.17 a	12.60
C-SHA	3.13 a	3.16 a	12.15
AL-FLE	2.34 b	2.09 b	13.35
NT	1.52 c	1.11 c	10.00
CV (%)	14.9	23.8	19.6

Means followed by the same lowercase letter in the column do not differ from each other by the Scott-Knott test at 5% probability level. ^{ns} not significant by the Scott-Knott test ($p<0.05$). AFS – Agroforestry system; C-SUN - Coffee cultivated in full sun; C-SHA – Shaded coffee; AL-FLE – Cultivation in alleys; and NT – No-tillage; C-FAF: Carbon of the fulvic acid fraction; C-HAF: Carbon of the humic acid fraction; C-HUMF: Carbon of the humin fraction; and CV: Coefficient of variation.

When evaluating the chemical attributes of the soil and the physical and chemical fractions of the organic matter of biogenic and physicogenic aggregates in conventional tillage (CT) and no-tillage (NT) systems, pasture and secondary forest, Loss et al. (2014) observed that biogenic aggregates provide a more favorable environment for the formation of humic substances. The authors attribute this pattern to the action of factors such as soil fauna (macro and microfauna) and root system, which are mainly related to the formation of biogenic aggregates.

When evaluating the different aggregate formation pathways in NT areas with different times of implementation and forest in two seasons in Guaíra (PR), Ferreira et al. (2020) observed higher contents of C-FAF and C-HAF in biogenic aggregates compared to intermediate and physicogenic ones for the two sampling times.

The highest values of C-FAF and C-HAF quantified in aggregates under AFS, C-SUN and C-SHA can be explained by the higher contents of TOC and the better environmental conditions promoted by biological activity. The longer time of use with legumes and organic fertilization may have increased the intensity of the humification process, thus contributing to the formation of humic substances with a higher degree of condensation, such as humic acids, in these aggregates (STEVENSON, 1994). According to Ferreira et al. (2020), the fulvic acid and humic acid fractions are the most important compartments of the humic fractions of SOM in terms of reactivity and occurrence in ecosystems, precisely because they have lower molecular weight and greater capacity for cation exchange.

It is worth pointing out that in biogenic and physicogenic aggregates, for C-HAF and C-FAF, it was possible to observe greater variations (differences) between the evaluated areas compared to intermediate aggregates, which showed few variations between the sampled areas (Table 3). This pattern indicates that biogenic and physicogenic aggregates should be preferred for evaluating the humic fractions of SOM over intermediate aggregates.

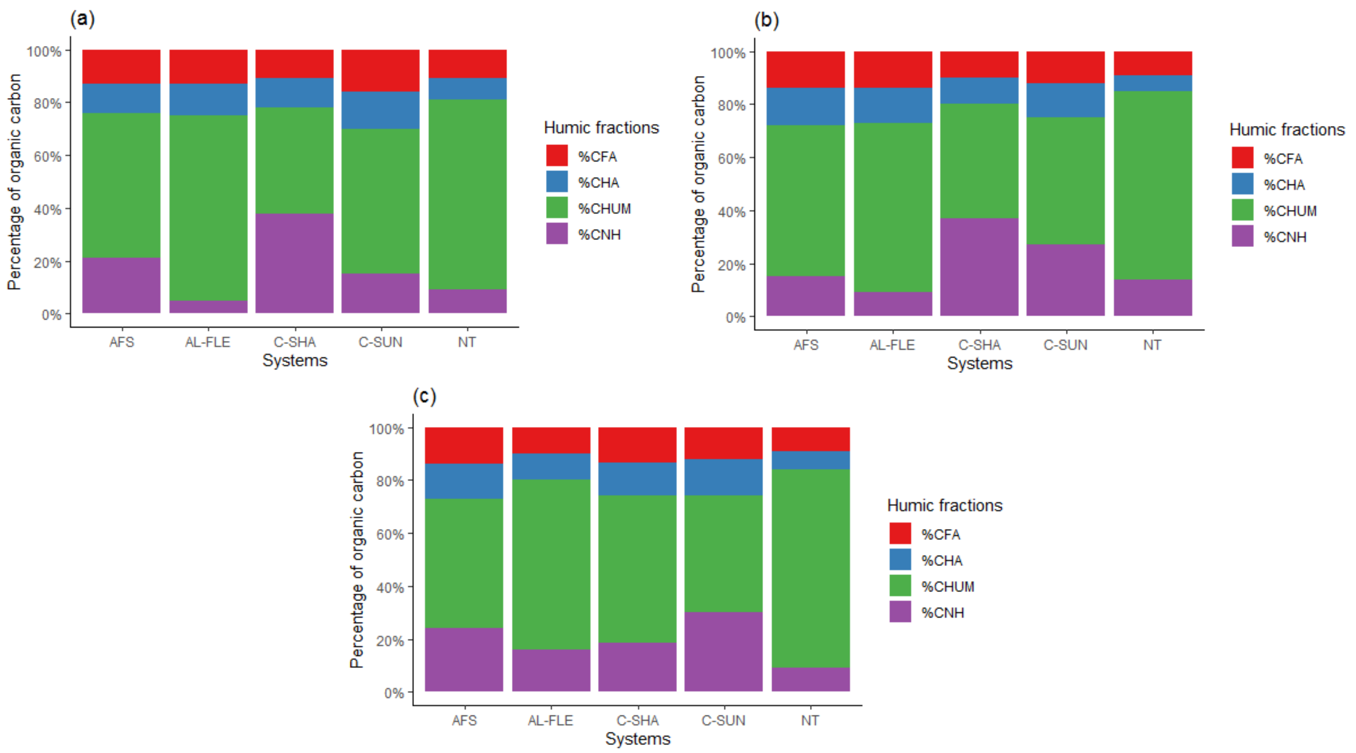
Regarding the organic carbon of the humin fraction (C-HUMF), the highest contents of this fraction were quantified in the biogenic and intermediate aggregates of C-SUN, C-SHA and AL-FLE, when compared to the other systems studied, ranging from 13.83 to 15.18 g kg^{-1} in biogenic and from 13.38 to 13.63 g kg^{-1} in intermediate (Table 3). In the same areas of the study, Rossi et al. (2016) found that the same aggregates under C-SUN and C-SHA, and AL-FLE, in sequence, had the highest values of mineral-associated organic carbon in the 0-0.05 m layer, which is similar to the results found for the humin fraction in the present study.

Also in these areas, Moura et al. (2019) found higher contents of organic phosphorus extracted with NaOH (Po-OH^-) in the 0–0.05 m layer in biogenic aggregates in C-SUN, C-SHA and AL-FLE, respectively. The authors suggest that these results may be related to the values of C-HUMF present in these aggregates, as the carbon of this fraction is more recalcitrant and is associated with the mineral matrix of the soil, so it can consequently adsorb and accumulate part of the soil P (ROSSET et al., 2016), increasing the concentrations of P in the fraction of lower lability.

When studying fragments of the Atlantic Forest in different stages of regeneration, Fernandes et al. (2017) observed higher contents of C-HUMF in biogenic aggregates compared to physicogenic and intermediate aggregates. The authors attributed these results to the presence of edaphic macrofauna, especially earthworms, since they act directly on biogeochemical cycling in soil (JOUQUET et al., 2006), positively affecting the ecology of the humification process (FERNANDES et al., 2017).

In biogenic, intermediate and physicogenic aggregates, Ferreira et al. (2020) quantified higher values of C-HUMF in the NT area with 23 years of use compared to NT areas with 7 and 14 years of use. These data reinforce that the longer the system implementation time, combined with practices such as organic fertilization and planting of legume crops, the higher the total carbon contents of the soil and of its humic fractions, such as C-HUMF.

In terms of percentage of the humic fractions of SOM, %CHUM represents the majority of TOC in the different types of aggregates in all evaluated systems (Figure 2), ranging from 49 to 75% of TOC in biogenic aggregates (Figure 2c), from 43 to 71% in intermediate aggregates (Figure 2b), and from 40 to 72% in physicogenic aggregates (Figure 2a). These results demonstrate the strong interaction of C-HUMF with the mineral fraction of the soil, since values between 40 and 75% of TOC in this fraction were observed in all evaluated systems (Figure 2). This effect may be related to the accumulation of organic compounds with high chemical stability and molecular weight resulting from the decomposition and humification of SOM (STEVENSON, 1994).



Physicogenic (a), intermediate (b) and biogenic (c) aggregates. AFS – Agroforestry system; C-SUN – Coffee cultivated in full sun; C-SHA – Shaded coffee; AL-FLE – Cultivation in alleys; NT – No-tillage; %CFA – Percentage of carbon of the fulvic acid fraction; %CHA – Percentage of carbon of the humic acid fraction; %CHUM – Percentage of carbon of the humin fraction; %CNH – Percentage of non-humified carbon; Bio – Biogenic aggregates; Int – Intermediate aggregates; and Phys – physicogenic aggregates.

Figure 2. Percentage of organic carbon of the humic fractions relative to the total organic carbon of aggregates in areas under different agroecological management systems, Seropédica, RJ, Brazil.

However, when analyzing the distribution of carbon in the three humic fractions of SOM and in the non-humified fraction (%CNH) (little decomposed), it was observed in general that the aggregates in AL-FLE and NT showed an increase in the proportion of carbon in the %CHUM fraction and reduction in %CNH compared to the other systems (Figure 2). Among the agroecological management systems studied, AL-FLE and NT are those in which there is annual mobilization of the soil surface layer, exposing more the SOM to mineralization. This fact may help explain the pattern of the results.

The organic carbon contents of the oxidizable fractions of SOM showed variability among the agroecological management systems, mainly for the F1, F2 and F3 fractions in the different formation pathways (Table 4). The highest contents were observed under C-SUN and C-SHA, AFS and AL-FLE, sequentially, and the lowest values in NT in biogenic aggregates. For physicogenic aggregates, the highest values were quantified in C-SHA, followed by the AFS and C-SUN systems and the lowest value in AL-FLE and NT.

Table 4. Organic carbon from the oxidizable fractions of biogenic, intermediate and physicogenic aggregates in areas under different agroecological management systems, Seropédica, RJ, Brazil.

Systems	F1	F2	F3	F4
	$g\ kg^{-1}$	$g\ kg^{-1}$	$g\ kg^{-1}$	$g\ kg^{-1}$
	Biogenic Aggregates			
AFS	5.66 b	7.51 a	7.16 b	5.25 ^{ns}
C-SUN	7.84 a	6.64 a	13.70 a	5.06
C-SHA	8.64 a	8.21 a	7.44 b	4.59
AL-FLE	4.55 b	8.91 a	3.79 c	4.75
NT	2.35 b	3.11 b	3.96 c	4.44
CV (%)	22.3	28.5	27.3	27.2
	Intermediate Aggregates			
AFS	3.68 b	7.01 a	8.03 a	3.74 ^{ns}
C-SUN	4.79 b	7.50 a	10.05 a	4.84
C-SHA	6.93 a	6.84 a	5.65 b	4.98
AL-FLE	4.78 b	3.68 b	3.41 b	5.38
NT	3.64 b	4.05 b	4.26 b	3.89
CV (%)	27.1	27.0	25.3	27.1
	Physicogenic Aggregates			
AFS	4.83 b	8.01 b	6.00 a	7.29 a
C-SUN	2.96 b	6.28 c	7.69 a	7.49 a
C-SHA	8.13 a	10.55 a	6.89 a	5.36 b
AL-FLE	5.10 b	3.71 d	4.57 b	5.74 b
NT	4.56 b	3.16 d	3.63 b	4.29 b
CV (%)	28.4	25.8	28.5	24.1

Means followed by the same lowercase letter in the column do not differ from each other by the Scott-Knott test at 5% probability level. ^{ns} not significant by the Scott-Knott test ($p<0.05$). F1 – C oxidized by $K_2Cr_2O_7$ in acidic medium with 3 mol L^{-1} of H_2SO_4; F2 – Difference between C oxidized by $K_2Cr_2O_7$ in acidic medium with 6 and 3 mol L^{-1} of H_2SO_4; F3 – Difference between C oxidized by $K_2Cr_2O_7$ in acidic medium with 9 and 6 mol L^{-1} of H_2SO_4; F4 – Difference between C oxidized by $K_2Cr_2O_7$ in acidic medium with 12 and 9 mol L^{-1} of H_2SO_4. AFS – Agroforestry system; C-SUN – Coffee cultivated in full sun; C-SHA – Shaded coffee; AL-FLE – Cultivation in alleys; NT – No-tillage; and CV – Coefficient of variation.

When studying the contents of carbon, light organic matter and oxidizable fractions of organic carbon under different organic production systems in the municipality of Seropédica, Loss et al. (2010) found the highest values of TOC in fig planting area, followed by the areas of agroforestry system, passion fruit, no-tillage and conventional tillage at the depth of 0–0.05 m. The authors attribute the results found to the use of mulch from the mown material of the grass vegetation (*Paspalum notatum*) of the fig area and also to the use of green manure with legumes in this area.

Regarding the oxidizable carbon for biogenic aggregates, the highest carbon contents of the F1 fraction were found in C-SHA and C-SUN. This greater accumulation of carbon in these systems compared to the others may be associated with the presence of spontaneous vegetation, composed predominantly of grasses between the rows of coffee, combined with the longer time of these systems (15 years) and the constant use of organic fertilization. For the F2 fraction, the lowest carbon contents were quantified in NT, in comparison to the others; in the F3 fraction the highest contents were found under C-SUN; and for the F4 fraction, no differences were found between the management systems.

Higher carbon contents in the F1 fraction tend to be found in areas where there is a recent input of organic matter via plant residues (CHAN; BOWMAN; OATES, 2001; RANGEL et al., 2008), and this increase is mainly related to the free light fraction of SOM. Rossi et al. (2016) quantified higher values of particulate organic carbon in biogenic and intermediate aggregates in areas of C-SUN, C-SHA and AL-FLE in the 0–0.05 m layer, corroborating the results observed for the F1 fraction in biogenic aggregates in the present study.

In a study conducted with different agroecological management systems in the municipality of Seropédica (RJ), aiming to evaluate the mineralizable carbon of biogenic and physicogenic aggregates, Pinto et al. (2018) observed that the NT system under agroecological management had higher accumulation of C-CO_2 among the systems evaluated in biogenic aggregates and the lowest accumulation in physicogenic aggregates. The authors attributed these results to the nature of the carbon stored in each type of aggregate, as the carbon stored in physicogenic aggregates is more recalcitrant when compared to the labile carbon stored in aggregates formed by the biogenic pathway. The data reported by Pinto et al. (2018) do not corroborate those found in the present study for the F1 fraction in biogenic aggregates.

In the intermediate aggregates in C-SHA, the highest carbon contents were found in the F1 and F2 fractions. For the F3 fraction, the highest values were observed under AFS, C-SUN and C-SHA. The F4 fraction showed no difference between the systems. For physicogenic aggregates, the highest carbon values were found in the F1, F2 and F3 fractions in C-SHA and in the F4 fraction in the AFS and C-SUN systems. The oxidizable fractions of SOM, F1 and F2, have greater lability in the soil, while the F3 and F4 fractions are considered more recalcitrant. According to Silva Neto et al. (2016), the ideal in the edaphic environment would be the balance in carbon content in these fractions, creating a condition of stability between nutrient availability and soil aggregation (promoted by F1 and F2) and the physical and chemical protection of carbon in the soil (promoted by F3 and F4).

In the state of Paraná, Loss et al. (2014) in areas under CT, NT, pasture and secondary forest, observed differences in the carbon contents of the oxidizable fractions both between the evaluated areas and between the formation pathways, with biogenic aggregation standing out. The results found by Loss et al. (2014) showed that these aggregates are more sensitive to the management system adopted.

When analyzing the aggregate formation pathways in areas with different types of plant cover in the Atlantic Forest, Silva Neto et al. (2016) observed that the different types of vegetation influenced the distribution pattern of the carbon of oxidizable fractions of SOM between biogenic, intermediate and physicogenic aggregates. For the authors, biogenic aggregation showed a more homogeneous distribution of carbon in each oxidizable fraction, suggesting that this class of aggregates is more efficient in terms of soil structural stability and carbon sequestration.

When evaluating the oxidizable fractions of organic carbon in different organic production systems, Loss et al. (2010) observed the highest proportions of carbon in the F1 and F4 fractions in all evaluated systems. The authors concluded that a more homogeneous distribution of carbon of each oxidizable fraction relative to TOC was observed in the eggplant/maize NT, with higher proportions in the fractions F1 (24%; 0–0.05 m layer) and F4 (29%; 0–0.05 m layer). This pattern demonstrates that the NT system has organic matter of greater lability in the soil (F1) and also more recalcitrant organic matter (F4).

When studying oxidizable fractions in alley systems, Guareschi and Pereira (2013) observed the highest carbon contents in the F1 fraction when compared to F2, F3 and F4. For the F1 fraction, the highest carbon contribution was observed in the maize cultivation area with *Flemingia macrophylla* alley system with pruning at 1.2 m height. The authors attribute these data to the greater input of plant residues, which is contributing to the increase in the content of light organic matter.

In the areas of NT and AL-FLE, a similar pattern was observed for the carbon of the F2 and F3 fractions in all types of aggregates, in general with lower carbon contents of the intermediate fractions (F2 and F3) compared to the more labile fraction (F1) and more recalcitrant fraction (F4) (Table 4). These results are corroborated by the pattern shown in Figure 2, with higher proportion of C-HUMF quantified in the areas of AL-FLE and NT. That is, the management of these areas is not yet favoring an input of plant material to increase the labile fraction (F1), which may result from the time of use of these areas combined with the annual mobilization of the soil surface layer, thus favoring the mineralization of the labile fraction of SOM.

On the other hand, it is possible to observe differences between the areas of C-SUN and C-SHA, with higher carbon contents of F1 in C-SHA for intermediate and physicogenic aggregates. For biogenic aggregates, no differences were found between the carbon contents of F1 for C-SUN and C-SHA. This result may be due to higher soil moisture content in the C-SHA area, which can favor the wetting and drying cycles, increasing the formation of physicogenic aggregates and the consequent protection of carbon in these aggregates.

For the carbon of the F3 and F4 fractions, the C-SUN area stands out with higher contents compared to C-SHA for biogenic and intermediate (F3) and physicogenic (F4) aggregates. Possibly, the higher soil temperature in this area (C-SUN) is causing a higher rate of decomposition and humification of SOM, influencing the formation of more stable fractions, such as F3 and F4. These results are corroborated by the higher proportion of humified carbon in the C-SUN area compared to C-SHA, where a lower proportion is observed (Figure 2).

CONCLUSION

For biogenic aggregates, there was an increase in the organic carbon contents of the humic and oxidable fractions of soil organic matter, especially in aggregates formed under the C-SHA, C-SUN and AFS systems.

In the C-SUN system area, a higher proportion of more humified and more recalcitrant fractions of soil organic matter was observed. However, the C-SHA system had more labile fractions and a higher proportion of non-humified carbon.

The management practices involved in the agroecological systems of C-SHA, C-SUN and AFS promoted improvements in soil quality.

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