Physical fractions of organic matter and mineralizable soil carbon in forest fragments of the Atlantic Forest

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ABSTRACT

This study determined the physical granulometric fractionation evaluated the mineralizable carbon within and around forest fragments of the Atlantic Forest biome located in the state of Paraná. Soil samples were collected at three three internal points of the fragments: the edge (E), the half radius (HR) and the center (CF); and one point in no-tillage system (NTS) areas around the fragments, in four replicates. The contents of total organic carbon (TOC), particulate fraction carbon (C-POM) and mineral fraction (C-MOM) were determined, and the %POM and %MOM and the stocks of POM (StockPOM) and MOM (StockMOM) were calculated, in addition to the indices: carbon stock index (CSI), lability (L), lability index (LI) and carbon management index (CMI), also evaluating CO_2 emission, daily and accumulated. The highest TOC levels were observed in the CF point. The highest C-POM contents were observed in the E and CF points of fragment 1, in the CF point of fragment 2, and the highest C-MOM contents were expressed in the CF points of both fragments. CMI showed a distinct pattern among the fragments. The NTS areas showed lower $C\text{-}CO_2$ emissions, with 39.8% and 28.3% less total emission compared to CF. The results of physical granulometric fractionation show the CF point favors the quality of SOM and the mineralizable carbon analysis indicated that the conversion of native areas into NTS compromises soil microbial activity.

Keywords: carbon management, environmental assessment, soil quality.

Frações físicas da matéria orgânica e carbono mineralizável do solo em fragmentos florestais da Mata Atlântica

RESUMO

O objetivo do presente trabalho foi determinar o fracionamento físico-granulométrico e avaliar o carbono mineralizável no interior e ao entorno de fragmentos florestais do bioma Mata Atlântica localizados no estado do Paraná. As amostras de solo foram coletas em três de três pontos internos dos fragmentos: borda (BO), metade do raio (MR) e centro (CF) e um ponto

em áreas de sistema plantio direto (SPD) no entorno dos fragmentos, em quatro repetições. Foram determinados os teores de carbono orgânico total (COT), carbono da fração particulada (C-MOP) e da fração mineral (C-MOM), sendo calculados as %MOP e %MOM e os estoques de MOP (Est. MOP) e de MOM (Est. MOM), além dos índices: índice de estoque de carbono (IEC), labilidade (L), índice de labilidade (IL) e índice de manejo de carbono (IMC), avaliando ainda a emissão de CO_2, diária e acumulada. Os maiores teores de COT foram observados no ponto CF. Os maiores teores de C-MOP foram observados nos pontos BO e CF do fragmento 1, no ponto CF do fragmento 2, e os maiores teores de C-MOM foram expressos no ponto CF de ambos os fragmentos. O IMC apresentou padrão distinto entre os fragmentos. As áreas de SPD apresentaram menor emissão de C-CO_2, com 39,8% e 28,3% menos emissão total em relação ao CF. Os resultados do fracionamento físico-granulométrico mostram o ponto CF favorece a qualidade da MOS e a análise de carbono mineralizável indicou que a conversão de áreas nativas em SPD compromete a atividade microbiana do solo.

Palavras-chave: avaliação ambiental, manejo de carbono, qualidade do solo.

1. INTRODUCTION

The effect of anthropization on the Brazilian Atlantic Forest biome has generated several impacts on the landscape in general, among them, the increase in forest fragmentation stands out (Warburton, 1997). Forest fragments were defined by Viana and Pinheiro (1998) as areas of natural vegetation interrupted by natural barriers (mountains, rivers, lakes, among others), or anthropic barriers (roads, agricultural activities, cities), which interfere with the flow of fauna, pollen and seed dispersal.

Forest fragmentation is a phenomenon distributed throughout large natural areas, shaping the landscape in general (Viana *et al*., 1997), restricting the survival of biodiversity to these areas, making the remaining fragments extremely important for the conservation biology (Warburton, 1997). The consequence of forest fragmentation is mainly reflected in the decrease, and even in the extinction of fauna (Pereira and Neves, 2007; Laurance and Vasconcelos, 2009) and flora (Souza *et al*., 2015). A major problem when thinking about forest fragments is the non-connectivity between them, which would allow greater survival of species due to the greater effectiveness of gene flow (Viana and Pinheiro, 1998).

With the forest fragmentation of Brazilian biomes, the species are exposed to physical and biotic changes, causing the so-called "edge effect" in the fragments. This effect occurs near the edge of the fragment, where there is greater sensitivity to external agents, making more noticeable the various forms of changes, such as vegetation variation, with changes in edaphic attributes over time, due to several regional factors (Malchow *et al*., 2017).

Changes in edaphic attributes in forest fragments as a function of the edge effect are not yet well defined, and may differ from one region to another (Primack and Rodrigues, 2001). Thus, there is no defined pattern for the exact point at which microclimatic, vegetation and soil changes on the edge effect can be noticeable by entering the forest fragment, as it depends on numerous factors (Kapos, 1989).

Barros and Fearnside (2016), studying carbon stock (C) on the edges of forest fragments in the Amazon biome, reported an increase in soil C stock in the first meters entering the fragments, when compared to areas of 300 meters within these fragments. However, studies that present the effects that fragmentation and edge effect can cause in C and in the edaphic characteristics of Brazilian biomes are still incipient in the literature (Ozório *et al*., 2019).

Soil organic matter (SOM) studies based on C contents are sensitive in identifying changes in soil management and mainly in vegetation modifications (Souza *et al*., 2019; Ferreira *et al*., 2020). The fact that the C content is immediately changed when the vegetation is modified occurs by the change in the input of SOM by the deposition of dry mass (Lal, 2018; Assunção

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et al., 2019).

Another way to evaluate the edaphic quality and possible changes caused by the management and alteration of natural vegetation is the fractionation of SOM, mainly due to its high diversity in oxidation state, chemical composition, size, lability and recalcitrance (Rangel and Silva, 2007). Thus, physical granulometric fractionation of SOM, which quantifies labile and recalcitrant fractions, is an important environmental assessment tool (Rosset *et al.*, 2019b). In addition to the forms of fractionation, the evaluation of soil mineralizable carbon is another variable that contributes to evaluate soil biological quality (Borges *et al.*, 2016; Rosset *et al.*, 2019a), through the emission of CO_2, product of the activity of microorganisms that decompose SOM (Rosset *et al.*, 2019b).

Thus, studies evaluating soil quality with analytical techniques that are sensitive in identifying changes in soil and vegetation management are of great scientific importance and are also important for the conservation of existing forest fragments. The hypothesis of the work is that the interior of the forest fragments present quantity and quality of the MOS, as they do not suffer from a possible edge effect. Therefore, this study determined the labile and recalcitrant fractions of carbon through physical granulometric fractionation, and evaluated the mineralizable carbon within forest fragments and in areas managed around forest fragments of the Atlantic Forest biome.

2. MATERIAL AND METHODS

2.1. Location, Climate, Soil and History of Study Areas

Soil samples were collected from two forest fragments located in the municipality of Terra Roxa, western Paraná state, Brazil (Figure 1, Table 1). The vegetation of the two fragments is of Atlantic Forest – Semideciduous Seasonal Forest (Campos and Silveira Filho, 2010), the two fragments are rectangular, with a proximity of 50 m from one another.
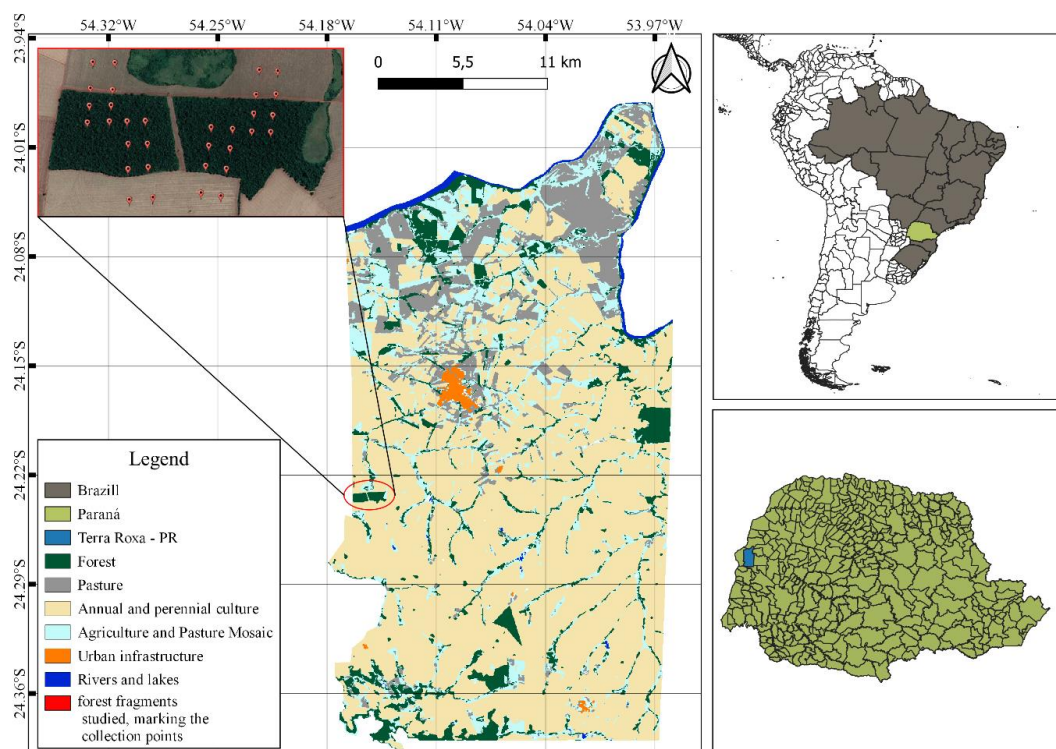

Figure 1. Location map with the main land-use activities, assessed fragments and sampling points, in which each sampled point represents a repetition, in the municipality of Terra Roxa - PR.

Table 1. Descriptions of the areas of the forest fragments evaluated.

Evaluated fragments	Description
Fragment 1	60.4 ha; 337 m altitude, 24º14'05,56" South (S) and 54º09'30,63" West (W).
Fragment 2	69.1 ha; 338 m altitude, 24º14'04,37" South (S) and 54º08'51,89" West (W).

The climate of the area is subtropical (Cfa), according to Köppen classification (Caviglione *et al.*, 2000). According to the detailed survey of soils of Paraná state (Bhering *et al.*, 2007), the study areas are under typical Eutrophic Red Latosol (Santos *et al.*, 2018), very clayey texture (58.0, 249.8, 692.2 g kg^{-1} of sand, silt and clay, respectively in Fragment 1, and 57.6, 242.4, 701.0 g kg^{-1} of sand, silt and clay, respectively in Fragment 2) (Santos *et al.*, 2018), and the chemical characterization of the studied points is presented in Table 2.

Table 2. Chemical characterization of the studied points in Fragments 1 and 2 and in the surrounding NTS areas.

Determinations	Points E, HR and CF of Fragment 1	Points E, HR and CF of Fragment 2	NTS around Fragment 1	NTS around Fragment 2
pH (CaCl$_2$ 0.01M)	4.8	4.7	5.1	5.1
P (mg/dm^3)	8.1	4.1	10.8	30.1
K (cmol$_c$/dm^3)	0.5	0.6	0.4	0.5
Ca (cmol$_c$/dm^3)	1.4	1.2	2.9	3.0
Mg (cmol$_c$/dm^3)	1.1	0.8	1.4	2.0
Al (cmol$_c$/dm^3)	0.1	0.1	0.1	0.1
H+Al (cmol$_c$/dm^3)	5.0	2.2	3.2	3.5
SB	3.0	2.6	4.7	5.5
C.E.C (pH 7.0)	8.0	4.8	7.9	9.0
V%	37.7	54.1	59.4	61.0

Laboratory: NUTRISOLO, Ivinhema, MS. Chemical characterization - Calcium Chloride (pH); Mehlich (P and K); KCl 1N (Ca, Mg and Al); Calcium Acetate pH 7.0 (H + Al). SB: Sum of bases, C.E.C: Cation exchange capacity, V%: Base saturation.

Surrounding the two fragments, there are areas of agricultural cultivation under the no-tillage system (NTS) that total 76.1 ha. The fragments show no difference in management, where these remaining forest fragments were cleared in 1970 for the cultivation of mint for 10 years. From 1980, soybean/corn was cultivated in a conventional tillage system (CTS) until 2002, when the areas were converted to the NTS in the same succession system of CTS crops, which remains to date. However, in these two forest fragments, until 2000, there was forest management with removal of larger trees from the outermost areas, that is, until this year, anthropic actions existed within these fragments modifying their vegetation.

2.2. Soil sample collections

Soil collections were performed at four points, three points within the fragments and one point around them, in the NTS areas. The internal points correspond to the edge of the fragment (E), the central point between the edge and the center of the fragment, called half radius (HR), the center of the fragment (CF), and the point external to the fragments in the NTS areas surrounding the fragments. The layout of the points is described in Table 3.

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Table 3. Description of the collection points in the fragments and their distance from the edge of the fragments.

| | | Fragments (distance (m) from the edge) | |
| | | Fragments | |
Collection point	Description of the point	1	2
P. 1	Center of the fragment (CF)	310	310
P. 2	Half the radius of the fragment (HR)	155	155
P. 3	Edge of the fragment (E)	0	0
P. 4	Outside of the fragment (NTS)	310	310

For each collection point, 4 replicates were performed in a radius of 20 m². Samples of disturbed and undisturbed soils were collected in the interior, and in the NTS areas around the fragments. The undisturbed samples to evaluate soil density (Ds) were collected with the aid of a volumetric ring with volume of 48.86 cm^3. The disturbed samples were acquired with the aid of auger, by collecting three simple samples, in the layers of 0-0.05, 0.05-0.1 and 0.1-0.2 m. Some disturbed samples of the 0-0.05 m layer were immediately refrigerated for analysis of C-CO$_2$ (mineralizable carbon) evolution.

2.3. Analyses Performed

After collection, the disturbed samples were air-dried, disaggregated and passed through a 2 mm sieve to obtain thin air-dried soil (TADS). The total organic carbon (TOC) was determined by the oxidation of organic matter by potassium dichromate, in a sulfuric medium under heating, and titrated with ammoniacal ferrous sulfate (Yeomans and Bremner, 1988).

The physical granulometric fractionation of the SOM was performed following the methodology of Cambardella and Elliott (1992), in which 20 g of TADS, together with 60 ml of sodium hexametaphosphate (5 g L^{-1}) were placed in 250 ml Erlenmeyer, stirred for 16 hours on an agitating table at a speed of 150 rpm. After the stirring period, the samples were washed in a 53 μm sieve, and the material retained in the sieve consisted of particulate organic matter (POM), obtaining later, by the methodology of Yeomans and Bremner (1988), the carbon of particulate organic matter (C-POM) and, through the difference between TOC and C-POM, the carbon of mineral organic matter (C-MOM) was obtained.

After carbon determinations of the physical granulometric fractions of the SOM, indices were calculated to evaluate the quality of the SOM, which were; carbon stock index (CSI) (Equation 1), SOM lability (L) (Equation 2), lability index (LI) (Equation 3) and carbon management index (CMI) (Equation 4), calculated according to Blair *et al*. (1995).

$$CSI = \frac{TOC\ Treatment}{TOC\ Reference} \qquad (1)$$

$$L = \frac{C-POM}{C-MOM} \qquad (2)$$

$$LI = \frac{L\ Treatment}{L\ Reference} \qquad (3)$$

$$CMI = CSI \times LI \times 100 \qquad (4)$$

Where:

CSI = Carbon stock index;

TOC Treatment = Stock TOC (Mg ha^{-1}) in the evaluated management system;

TOC Reference = Stock TOC (Mg ha^{-1}) in the reference system; L = lability of SOM;

C-POM = Carbon of particulate organic matter;

C-MOM = Carbon of mineral organic matter;

LI = Lability index of the management system under analysis;

L Treatment = Lability of SOM in the management system under analysis;

L Reference = Lability of SOM in the reference system;

CMI = Carbon management index.

For the calculations of carbon stock of particulate organic matter (StockC-POM) and carbon stock of mineral organic matter (StockC-MOM), the soil density of the undisturbed samples was determined according to Claessen (1997), and the stocks were calculated according to the equivalent mass method (Equation 5) (Reis *et al*., 2018; Signor *et al*., 2014).

$$\text{Equivalent mass method} = (\text{Sd of the evaluated treatment} \times \text{Corrected thickness} \times \text{Content} (C - POM, C - MOM)) / \text{Rated thickness} \tag{5}$$

Where:

Sd of the evaluated treatment = Soil density of the evaluated treatment;

Corrected thickness = Corrected soil thickness (Average treatment density / average reference density x evaluated thickness);

Content (C-POM, C-MOM) = Carbon content of particulate organic matter to result in MOP stock, and mineral organic matter to result in MOM stock, of the evaluated treatments;

Rated thickness = Soil thickness sampled.

The analysis of the mineralizable carbon emission ($C-CO_2$), was carried out following the methodology of Mendonça and Matos (2005). Thus, 50 g of soil were placed inside a plastic container of 3 L capacity, together with a glass container with 30 ml of 0.5 mol L^{-1} NaOH solution to capture the $C-CO_2$ emitted, and a flask with 30 ml of H_2O in order to maintain constant moisture. The plastic container was hermetically sealed. Each day of evaluation, 10 ml of $NaCl_2$ were removed from the glass container, and 10 ml of $BaCl_2$ 0.05 mol L^{-1} and 4 drops of phenolphthalein 1% were added, with subsequent titration with HCl 0.25 mol L^{-1}. After removing the 30 mL container of 0.5 mol L^{-1} NaOH solution, a new container with 30 mL was inserted for the next evaluation, leaving the plastic container open for 15 minutes to change the air before the next incubation. The titrations/evaluations were performed at 24-hour intervals in the first 7 days, 48 h between the 8th and 17th day, and 96 h between the 18th and 33rd day, as performed by Loss *et al*. (2013) and Rosset *et al*. (2019b).

The results obtained met the assumptions of normality and homogeneity of variance by means of the Shapiro-Wilk test and Bartlett's test. Subsequently, in a completely randomized design, the results were submitted to variance analysis with application of the F test, in isolation, evaluating each fragment individually, and the mean values compared by the Tukey test at 5% with the aid of the R Core Team program (2019).

3. RESULTS AND DISCUSSION

The forest fragments of the Atlantic Forest biome presented the highest levels of TOC in the CF points, differing from the other points within and around the fragments, reaching 63.2 g kg^{-1} and 60.9 g kg^{-1} in Fragments 1 and 2, respectively, in the 0-0.05 m layer in the CF points (Figure 2). In general, the lowest levels of TOC were observed in the areas of NTS around the fragments, with lower levels in the 0.10-0.20 m layer (Figure 2).

The E and HR points showed a decrease in TOC levels in the 0-0.05 m layer when compared to the CF point, with relative reductions of 46.1% and 28.9% for Point E, and 47.2%

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and 34.4% for Point HR, of Fragments 1 and 2, respectively. The NTS areas showed the greatest reductions in TOC levels when compared to the CF point, with 53.1 and 47.4% reduction, in the 0-0.05 m layer of Fragments 1 and 2, respectively (Figure 2).
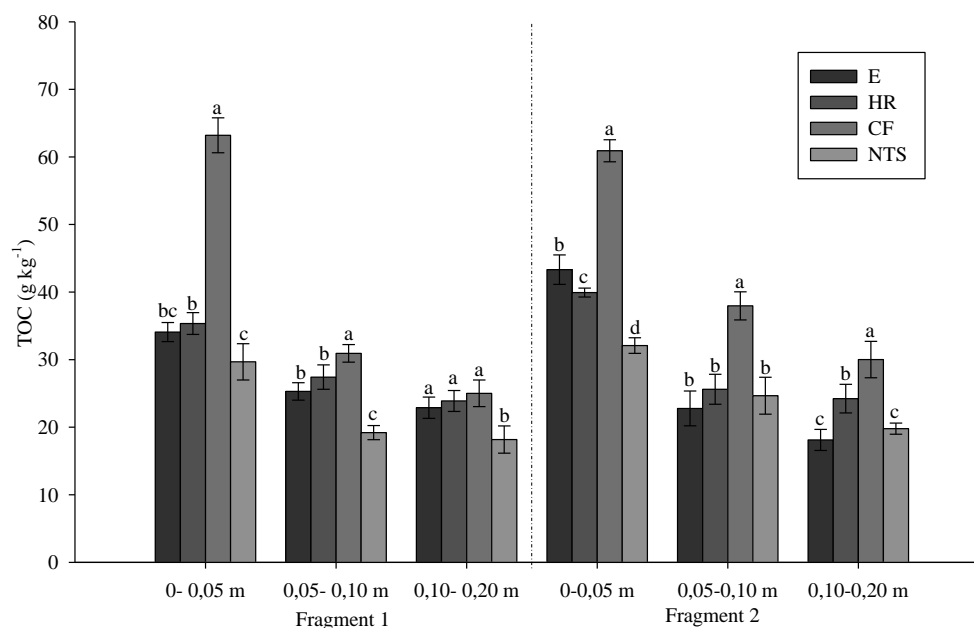

Figure 2. Total organic carbon (TOC) from the different collection points within and around fragments 1 and 2. Means followed by the same letter in the layer, for each fragment, do not differ statistically by the Tukey test (5%). E: Fragment edge; HR: Half radius; CF: Center of the fragment; NTS: No-tillage system. Dashes on the bars represent the standard deviation of the data.

The higher levels of TOC in the CF point compared to E and HR is mainly due to the greater isolation of this point in relation to the external factors, indicating that the points near the edge suffer greater influence of fragmentation, mainly due to the higher incidence of light and microclimatic changes in these areas (Laurance *et al.*, 1998). The highest contents presented by the internal points of the fragments compared to the NTS area is due to the greater contribution of litter in the most different forms (leaves, branches, fruits and thin roots), that is, a greater heterogeneity in the carbon/nitrogen ratio (C/N) (Matos *et al.*, 2017), which maintains the flow of TOC and increases carbon stocks in these areas (Rosset *et al.*, 2014; Freitas *et al.*, 2018; Assunção *et al.*, 2019).

On the other hand, the conversion of native areas into NTS ends up reducing the soil TOC, which, with the revolving, exposes the SOM to the oxidation process, increasing the emission of carbon dioxide (CO_2) into the atmosphere (Reinsch *et al.*, 2018). These results corroborate those presented by Rosset *et al.* (2014; 2016; 2019b), Assunção *et al.* (2019) and Pereira and Neves (2007), who obtained higher levels of TOC in native forest areas, compared to areas of NTS with up to 22 years of conduction, in the same area, with the same type of soil and vegetation.

The highest levels of C-POM in the 0-0.05 m layer were found in E and CF points in Fragment 1, 13.2 and 12.1 g kg⁻¹, respectively, and CF in Fragment 2, 19.5 g kg⁻¹, differing from the other points (Table 4). The Points E, HR and CF do not undergo anthropic alterations, therefore presenting a higher conservation status, with constant deposition of organic material on the soil surface (Malchow *et al.*, 2017), in addition to presenting greater diversity of plant species, different decomposition times and C/N ratio (Nascimento and Laurance, 2006), which favors the diversity of SOM, and consequent accumulation of particulate matter.

Table 4. Carbon of particulate organic matter (C-POM) and mineral (C-MOM), percentage of carbon of particulate organic matter (POM) and mineral (MOM), carbon stock of particulate organic matter (StockPOM) and mineral (StockMOM) at different collection points within and around Fragments 1 and 2 of the Atlantic Forest biome.

	Fragment 1						Fragment 2					
	C-POM	C-MOM	POM	MOM	StockPOM	StockMOM	C-POM	C-MOM	POM	MOM	StockPOM	StockMOM
	g kg⁻¹		%		Mg ha⁻¹		g kg⁻¹		%		Mg ha⁻¹	
						0-0.05 m						
E	13.2a	20.8c	38.9a	61.1c	4.7a	7.4c	15.3b	28.0b	35.7a	64.5b	5.5b	10.0b
HR	8.5b	26.9b	24.2bc	75.8ab	3.0b	9.5b	11.6c	28.4b	29.0b	71.0a	4.1c	10.1b
CF	12.1a	51.1a	19.1c	80.9a	4.3a	18.4a	19.5a	41.4a	32.1ab	67.9ab	7.0a	14.8a
NTS	8.2b	21.4bc	28.0b	72.0b	2.9b	7.6bc	10.9c	21.2c	33.9a	66.0b	3.9c	7.5c
CV (%)	10.1	9.0	14.7	5.6	10.1	9.0	6.8	6.3	8.7	8.7	6.8	6.3
						0.05-0.10 m						
E	5.6b	19.6b	22.4b	77.6a	2.4b	8.3b	10.1ab	12.7c	44.4a	55.6b	4.1ab	5.2c
HR	5.1b	22.3ab	18.5b	81.4a	2.1b	9.4ab	8.1bc	17.5b	31.7b	68.2a	3.3bc	7.1b
CF	7.0a	24.0a	22.4b	77.5a	2.9a	10.1a	10.7a	27.2a	28.1b	70.9a	4.4a	11.2a
NTS	5.3b	13.9c	27.7a	72.3b	2.2b	5.9c	7.5c	17.1b	30.7b	69.3a	3.1c	7.0b
CV (%)	10.3	7.1	10.6	3.1	10.3	7.1	12.5	9.5	9.2	4.7	12.5	9.5
						0.10-0.20 m						
E	3.0b	19.8a	13.3a	86.7a	2.6b	17.0a	6.3ab	11.8c	34.9a	65.1b	5.1ab	9.7c
HR	3.6a	20.3a	15.0a	85.1a	3.1ab	17.4a	5.5ab	18.7b	22.8b	77.2a	4.5ab	15.3b
CF	3.9a	21.1a	15.7a	84.3a	3.7a	18.1a	6.4a	23.6a	21.6b	78.4a	5.2a	19.3a
NTS	3.1ab	15.1b	17.4a	82.6a	2.7ab	12.9b	4.6b	15.2bc	22.9b	77.0a	3.7b	12.4bc
CV (%)	12.1	9.6	17.4	3.1	12.0	9.6	15.1	12.2	17.8	6.1	15.1	12.2

Means followed by the same letter in the columns for each fragment and layer do not differ statistically by the Tukey test (5%). E: Fragment edge; HR: Half radius; CF: Center of the fragment; NTS: No-tillage system; CV (%): coefficient of variation.

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In the 0.10-0.20 m layer of fragment 1, the lowest C-POM contents were found in Point E, 3.0 g kg^{-1}, and in the surrounding NTS area, with 3.1 g kg^{-1}. In Fragment 2, the lowest level of C-POM was found in the NTS area, 4.6 g kg^{-1} (Table 4). These results suggest that the low plant heterogeneity of the NTS, since it does not have a diversified rotation (Boddey *et al.*, 2010), may compromise the dynamics of particulate matter entry into the soil over the years of cultivation (Ferreira *et al.*, 2018).

The highest C-MOM contents were found in the CF point in the 0-0.05 m layer in both fragments, reaching 51.1 and 41.4 g kg^{-1} in Fragments 1 and 2, respectively. In Fragment 2, the CF point presented higher contents in all evaluated layers (Table 4). In the layer 0.10-0.20 m in Fragment 1, E, HR and CF points presented the highest C-MOM contents, differing from the NTS area. These results are due to the higher levels of TOC in the CF point (Figure 2). In addition, not revolving the soil allows humification processes to occur completely, promoting the stabilization of SOM (Lal, 2018), and consequent carbon accumulation in the most recalcitrant fractions.

The lowest levels of C-MOM were observed in the 0.10-0.20 m layer, in the NTS area around Fragment 1, and in point E and NTS area of Fragment 2 (Table 4). The fact that only soybean/corn succession has been cultivated for several years in the areas of NTS, also influences on the lower carbon content of this fraction, because the greater diversity of plant residues left in systems with greater crop diversity considerably increases the entry of SOM in the most labile fraction of carbon and, consequently, over time, of the more recalcitrant fractions of C (Faccin *et al.*, 2017), when compared to systems with less diversity (Boddey *et al.*, 2010; Campos *et al.*, 2011).

The percentage of POM and MOM, which shows the representativeness of these fractions in relation to TOC, varied from 13.3 to 38.9% for POM, and from 61.1 to 86.7% for MOM in all points and layers evaluated in Fragment 1. In Fragment 2, this variation was from 21.6% to 44.4, and from 55.6% to 78.4%, respectively, for POM and MOM (Table 4). The high representativeness of MOM is associated with soil granulometry of the studied areas, since the most stable soil organic matter binds to the colloidal fraction (Cambardella and Elliott, 1992), which represents most of the soil granulometry of the study areas. In addition, the tropical climate plays a fundamental role in this behavior of distribution of the granulometric fractions of the POM, because it acts directly in the humification process of the SOM, converting the POM into MOM in a faster process than in temperate climate regions (Gmach *et al.,* 2018), providing greater representativeness of MOM in relation to POM. This fact was also highlighted by Rosset *et al*. (2019b) in the same area of this study, also in native areas and managed under NTS.

It is important to highlight that the percentage representativeness of the fractions had a similar pattern in both fragments studied (Table 4), where the percentage of POM decreased, and of MOM increased as a function of the increase in depth. This occurs mainly due to the greater contribution of particulate matter to the soil surface, which associated with non-revolving, transforms this labile material into recalcitrant along the profile (Lal, 2018; Reinsch *et al.*, 2018).

The highest StockPOM and StockMOM were observed in the CF points of both fragments (Table 4), corroborating the higher levels of TOC in this same point (Figure 2). Specifically, in Fragment 1, in the 0-0.05 m layer, the StockPOM was similar between the E and CF points, with values of 4.7 and 4.3 Mg ha^{-1}, respectively. In Fragment 2, in Point CF, the StockPOM presented the highest value, 6.7 Mg ha^{-1}, in the 0-0.05 m layer, differing from the other points.

In Fragment 1, the CF point presented StockMOM of 18.4 Mg ha^{-1}, differing from the other points in the 0-0.05 m layer. In Fragment 2, the StockMOM was 14.7 Mg ha^{-1}, 11.2 Mg ha^{-1} and 19.3 Mg ha^{-1} in layers 0-0.05, 0.05-0.10 and 0.10-0.20 m, respectively, in the CF Point, higher than all other points studied (Table 4). Lower values of StockPOM and StockMOM in the areas of NTS around the two studied fragments are notorious, especially in the 0-0.05 m layer.

The highest StockPOM and StockMOM, mainly in the CF Point (Table 4) are due to the highest levels of TOC (Figure 2), C-POM and C-MOM (Table 4). Because it is more isolated in relation to the other points, the CF Point presents greater diversity of forest strata and constant litter deposition (Malchow *et al*., 2017), which allows biogeochemical processes to be completed (Smith, 2012; Gmach *et al*. 2018), thus enabling to find high stocks of both fractions (Melo *et al*., 2016). In a study in a system with permanent pasture, regeneration and native forest in the Atlantic Forest biome, Nogueira *et al*. (2016) also found higher stocks of POM and MOM in the native forest area compared to different production systems, as similarly evidenced by Rosset *et al*. (2019b) in the same edaphoclimatic conditions and management systems.

The Points E, HR and areas NTS around both fragments presented lower CSI values in relation to the reference point (CF). The lowest values were observed in the NTS areas in the layer 0-0.05 m, 0.5 and 0.5 around Fragments 1 and 2, respectively (Table 5). These results indicate that none of the points evaluated, in both fragments, presented carbon storage higher than the inner point, as also reported for the TOC contents (Figure 2), because all values of this variable were lower than 1.0 (Table 5).

Table 5. Carbon stock index (CSI), SOM lability (L), lability index (LI) and carbon management index (CMI) of the different collection points, within and around Fragments 1 and 2.

	Fragment 1				Fragment 2			
	CSI	L	LI	CMI	CSI	L	LI	CMI
				0-0.05 m				
E	0.5b	0.6a	2.7a	147.9a	0.7b	0.5a	1.2a	83.4b
HR	0.5b	0.3b	1.3b	75.5b	0.6b	0.4b	0.9b	56.9c
CF	1.0a	0.2b	1.0b	100.0b	1.0a	0.5ab	1.0ab	100.0a
NTS	0.5c	0.4b	1.6b	76.7b	0.5c	0.5ab	1.1ab	57.3c
CV (%)	3.8	21.8	21.6	19.1	4.4	10.8	11.4	20.0
				0.05-0.10 m				
E	0.8b	0.3b	1.0ab	82.1ab	0.6b	0.8a	2.1a	123.6a
HR	0.9b	0.2b	0.8b	69.3b	0.7b	0.5b	1.2b	82.3b
CF	1.0a	0.3b	1.0b	100.0a	1.0a	0.4b	1.0b	100.0ab
NTS	0.6c	0.4a	1.3a	82.5ab	0.6b	0.4b	1.1b	75.4b
CV (%)	5.8	13.6	15.8	11.6	7.6	13.7	21.2	18.4
				0.10-0.20 m				
E	0.9a	0.1a	0.8a	76.1a	0.6c	0.5a	2.0a	122.9a
HR	0.9a	0.2a	0.9a	90.5a	0.8b	0.3b	1.1b	89.1ab
CF	1.0a	0.2a	1.0a	100.0a	1.0a	0.3b	1.0b	100.0ab
NTS	0.7b	0.2a	1.2a	83.2a	0.7bc	0.3b	1.1b	71.9b
CV (%)	9.5	21.7	27.4	16.5	11.5	25.5	31.8	22.5

Means followed by the same letter in the columns for each fragment and layer do not differ statistically by the Tukey test (5%). E: Fragment edge; HR: Half radius; CF: center of the fragment; NTS: No-tillage system; CV (%): coefficient of variation.

These changes in carbon stock in E and HR points and in the NTS area compared to the reference suggest that the conversion of natural areas into production systems can reduce soil carbon storage (Rosset *et al*., 2014; Reis *et al*., 2016). In addition, forest fragmentation reduced

the carbon stock in the points near the edge, possibly due to the changes it causes, with decreased TOC (Figure 2), by increasing luminosity and temperature (Camargo and Kapos, 1995), higher incidence of winds (Laurance *et al*., 1998), which can accelerate the oxidation process of SOM, releasing greater amounts of carbon dioxide into the atmosphere (Lal, 2018; Sperow, 2018; Magalhães *et al*., 2016). These results from the points near the edge contrast to those presented by Barros and Fearnside (2016), who found an increase in carbon stock on the edges of forest fragments in the Amazon.

The L values were below the unit in all points and layers evaluated, which indicates a predominance of C-MOM in relation to the C-POM (Table 5). The E point presented the highest L value (0.6), in the layer 0-0.05 m, in fragment 1, and in the layer 0.10-0.20 m there was no difference between the points, varying from 0.1 to 0.2 (Table 5). In Fragment 2, Point E presented the highest L values in all evaluated layers, 0.5; 0.8 and 0.5, for layers 0-0.05, 0.05-0.10 and 0.10-0.20 m. These results generally indicate low L of the C in these areas, because L represents the relationship between C-POM and C-MOM, which makes this variable an important indicator of soil quality, given the importance of balance between these fractions, for maintenance of C in the soil over time (Benbi *et al*., 2015; Jha, 2017).

The LI showed the same pattern of L values, indicating higher values in Point E of both fragments evaluated in the 0-0.05 m layer, surpassing the LI of the reference (CF). The CMI, which expresses the evaluation of SOM in quantitative and qualitative terms, presented higher values than the reference point (CF) only in Point E (147.9) in the layer 0-0.05 m in Fragment 1, and the points evaluated did not present differences in the layer 0.10-0.20 m (Table 5). In Fragment 2, Point E presented values similar to those of CF in the 0.05-0.10 m and 0.10-0.20 m layers (Table 5). This increase in CMI in Point E may be related to the greater litter intake that forest fragments present in the extremities (Malchow *et al*., 2017; Nascimento and Laurance, 2006; Barros and Fearnside, 2016), and also due to the higher values of L and consequently LI (Table 5).

In both fragments studied, CMI values lower than the reference area were observed in the surrounding NTS areas (Table 5). These results demonstrate that the modification caused by the conversion of natural areas may compromise soil quality (Rosset *et al*., 2019b), mainly in surface layers, affecting the quality of SOM due to the low diversity of species in the soybean/corn succession over the years of cultivation, which directly influences the physical quality (Sales *et al*., 2018), chemistry (Souza *et al*., 2018) and the biological activity (Borges *et al.*, 2016) of the soil over the years of cultivation.

Forms of soil management that provide greater floristic heterogeneity and, consequently, higher CMI values, will act directly on the mentioned attributes, improving water infiltration (Souza *et al*., 2017) soil aggregation (Obour *et al*., 2018), porosity (Lal, 2018), among other quality indicators. Gazolla *et al*. (2015) obtained in their study a CMI value of 48.1 for layer 0-0.05 m in NTS with 10 years of implantation, compared to an area of native vegetation. Souza *et al*. (2018) studying NTS chronosequence in clay soil, obtained CMI of 112, 128 and 139 for NTS with 7, 11 and 16 years of implantation.

In Fragments 1 and 2, the CF point showed the highest $C-CO_2$ emission on the 1st day after incubation, 14.1 and 12.1 mg of $C-CO_2$ in 50 g of soil, respectively. The NTS areas presented the lowest emissions in the first evaluation, 5.5 and 5.9 mg of $C-CO_2$ in 50 g of soil, respectively (Figures 3 a, b). The points with the highest emissions on the 1st day were also the ones that presented the highest levels of TOC (Figure 2) and C-POM (Table 4) in the 0-0.05 m layer. This higher initial emission of $C-CO_2$ occurs when microbial activity is stimulated by the availability of labile organic residues, in this case C-POM, which accelerates the decomposition of SOM (Hurisso *et al*., 2016; 2018; Wade *et al.*, 2018), having a relationship between higher levels of TOC (Figure 2) and C-POM (Table 4) with the highest $C-CO_2$ emissions (Figures 2 a, b).

In Fragments 1 and 2, between the 4th and 6th day, and between the 13th and 21st day of incubation, $C-CO_2$ emission peaks were evident (Figures 3 a, b). These emission peaks occur due to the death of part of the microorganisms that serve as food for the remnants, generating emission peaks after the decreases (Gonçalves et al., 2002), an effect known as prining (Ghosh et al., 2018; Kuzyakov et al., 2000). In both fragments, from the 25th day on, the emission began to stabilize (Figures 3 a, b), i.e., no $C-CO_2$ emission peaks were observed. This stabilization in $C-CO_2$ emission occurs by reducing the availability of labile organic materials readily available to microbial attack. This pattern was also observed by Loss et al. (2013) in Goiás and Rosset et al. (2019b) in Paraná, studying the emission of mineralizable carbon in Latosol in different management systems.
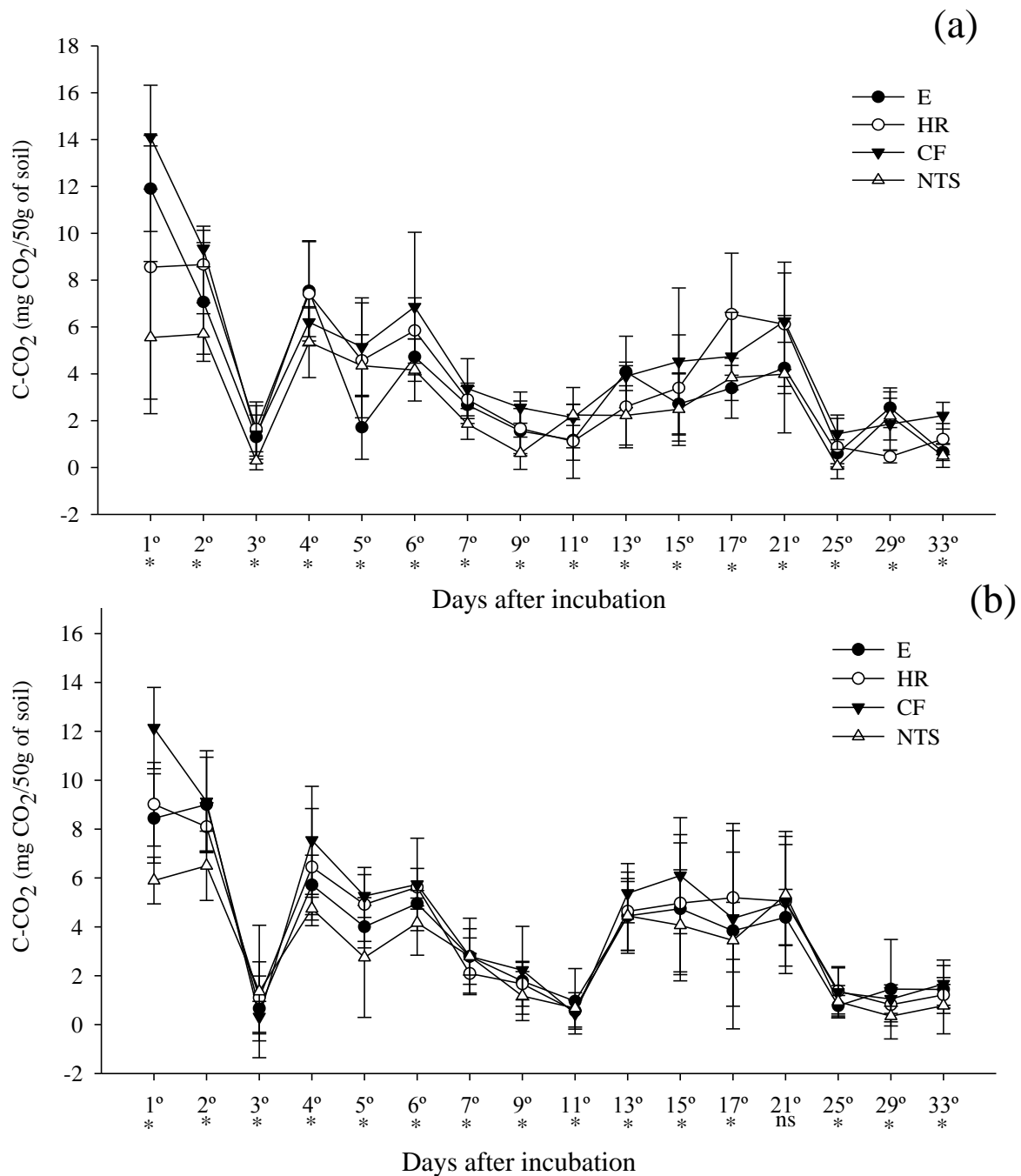

Figure 3. Mineralizable carbon of the soil incubated in the laboratory until the 33rd day of the different collection points within and around Fragments 1 (a) and 2 (b). * = Significant by Tukey test at 5%; ns = Not significant by Tukey test at 5%.

The highest accumulations of C-CO$_2$ after the 33rd day of incubation were observed in the CF, 75.7 and 69.7 mg CO$_2$ in 50 g of soil in Fragments 1 and 2, respectively (Figure 4). The results also show that both fragments present a pattern of gradual total emission reduction when moving from the CF Point to the E, i.e., lower soil microbial activity is observed. The highest accumulations of total C-CO$_2$ occurred exactly in the points where the highest levels of TOC (Figure 2) and the highest levels of C-POM (Table 4) were obtained, ratifying the pattern also presented by Wade *et al*. (2018) and Rosset *et al*. (2019b).
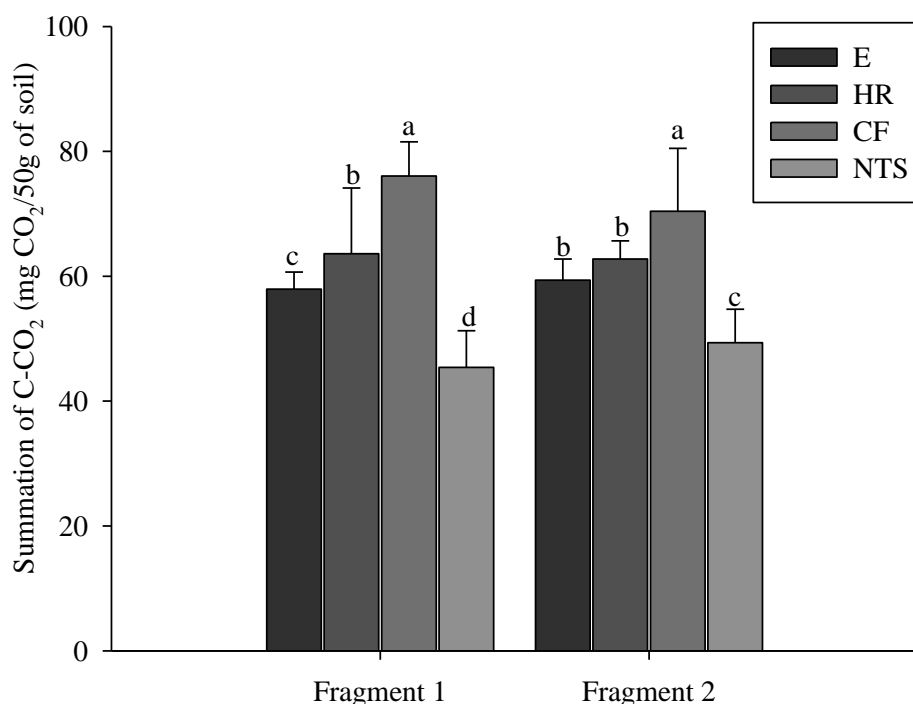

Figure 4. Summation of C-CO$_2$ (mg CO$_2$/50g of soil), during the incubation period of the soil in the laboratory, in the different collection points within and around Fragments 1 and 2. Means with the same letter do not differ statistically by the Tukey test (5%). E: Fragment edge; HR: Half radius; CF: Center of the fragment; NTS: No-tillage system. Dashes on the bars represent the standard deviation of the data.

The NTS areas around the fragments presented the lowest total values of C-CO$_2$ emission, 45.6 and 49.9 mg CO$_2$ in 50 g of soil, which represents 39.8% and 28.3% reduction for the highest emission points, for Fragments 1 and 2, respectively (Figure 4). In turn, the lowest levels of TOC (Figure 2) and C-POM (Table 4) were also observed in the areas of NTS, indicating the direct relationship of the organic matter of easier decomposition with the highest accumulations of total C-CO$_2$, and consequent microbiological activity (Barreto *et al*., 2009). Loss *et al*. (2013) and Rosset *et al*. (2019b) observed lower values of C-CO$_2$ accumulation in NTS, compared to the area of native vegetation. The results contrast with those presented by Benbi *et al*. (2015), in which the managed areas showed higher evolution of C-CO$_2$, in relation to areas under native vegetation, after 32 days of incubation.

4. CONCLUSIONS

The levels of total organic carbon and particulate fraction of soil organic matter from the internal points of the forest fragments were higher than those of the no-tillage system areas around them, indicating that the conversion of native areas into cultivation systems compromises quantitatively and qualitatively the organic fraction of the soil.

The carbon management index showed a distinct pattern among the studied fragments, and was not sensitive to identify internal changes in forest fragments.

The mineralizable carbon analysis indicated that the conversion of native areas into no-tillage systems, causes less microbial activity, also evidencing an increase in microbial activity when entering the most peripheral areas to the more central areas of the forest fragment in the Atlantic Forest biome.

5. ACKNOWLEDGMENTS

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