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Organic carbon dynamics in soil from forest fragments in the Atlantic Forest and Cerrado biomes

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ABSTRACT

The study aimed to evaluate changes in organic carbon concentrations and oxidizable fractions of soil organic matter in and around forest fragments in the Atlantic Forest (AF) and Cerrado (CE) biomes. Soil samples were collected from four forest fragments, two in the AF and two in the CE, in which three internal points were sampled: edge (ED), half radius (HR), and center (CF), as well as a point in the surroundings; no-tillage (NT) and permanent pasture (PP) in AF and CE, respectively. The total organic carbon (TOC) content and the carbon of the oxidizable fractions (F1, F2, F3, F4) were quantified. The CF of the AF forest fragments showed the highest TOC and C contents in the labile fractions F1 and F2 (the fraction most sensitive to changes in the environment), with the lowest contents in the ED. In the CE, the fragments showed different TOC contents and dynamics, with the highest TOC and F1 contents in the HR and the lowest in the CF of fragment 1, while in fragment 2 the highest TOC contents were in the CF and the lowest in the ED and HR, but they did not differ in the contents of the F1 and F2 fractions. The lower levels of TOC and C labile in the ED of the fragments are due to the negative interference of the edge effect, which, through abiotic factors, has modified the species composition and structure of the plant community, altering the dynamics of C storage and emission.

Keywords: Edge effect, Soil organic matter, Soil quality.

Dinâmica do carbono orgânico em solo de fragmentos florestais nos biomas Mata Atlântica e Cerrado

RESUMO

O objetivo do estudo foi avaliar mudanças nas concentrações de carbono orgânico e das frações oxidáveis da matéria orgânica do solo no interior e no entorno de fragmentos florestais dos biomas Mata Atlântica (MA) e Cerrado (CE). Foram coletadas amostras de solo em quatro fragmentos florestais, dois na MA e dois no CE, nos quais foram amostrados três pontos internos: borda (BO), metade do raio (MR) e centro (CF), além de um ponto no entorno; plantio direto (PD) e pastagem permanente (PP) na MA e no CE, respectivamente. Quantificou-se os teores de carbono orgânico total (COT) e o carbono das frações oxidáveis (F1, F2, F3, F4). O CF dos fragmentos florestais do MA, apresentaram os maiores teores de COT e de C nas frações lábeis F1 e F2 (fração mais sensível a alterações no ambiente), sendo os menores teores nas BO. No CE, os fragmentos apresentaram teores e dinâmica de COT distintos, sendo os maiores teores COT e F1 no MR e menores no CF do fragmento 1, já no fragmento 2 os maiores teores de COT foram no CF e os menores na BO e MR, porém não se diferem nos teores das frações F1 e F2. Os menores teores de COT e C-lábil nas BO dos fragmentos são provenientes das interferências negativas do efeito de borda, que através de fatores abióticos modificaram a composição de espécies e a estrutura da comunidade vegetal o que altera a dinâmica de armazenamento e emissão do C.

Palavras-chave: Efeito de borda, Matéria orgânica do solo, Qualidade do solo.

1. Introduction

The Cerrado and the Atlantic Forest are ecological hotspots among the world 25 biodiversity hotspots, with a great diversity of endemic species, but vulnerable to anthropogenic modifications, which cause various environmental impacts (Myers et al., 2000). The two biomes have their particularities: The Atlantic Forest varies in terms of climate, topography and soil, depending on the extent and variations in altitudes (Almeida, 2016); the Cerrado, on the other hand, has great diversity in its phytophysiognomy, forming a mosaic in its landscape, with deep soils and a large part of its extensions having topography that is well targeted by mechanized agriculture, (Guareschi et al., 2016; Malheiros, 2016).

Anthropogenic activities, such as the advance of urbanization and areas exploited by the implementation of agricultural and/or livestock activities associated with the reduction of forest habitats, are the main factors in the degradation of these ecosystems (Rusca et al., 2017; Ozório et al., 2019; Ozório et al., 2020). This way, these anthropogenic actions convert large forest areas into small patches (forest fragments). These patches become isolated and immersed in a matrix of non-forest environments, most lacking connectivity (Paciencia and Prado, 2004; Carvalho et al., 2009). The lack of these ecological corridors is detrimental to the gene flow of organisms, and fragmentation exposes these areas to external effects, the so called "edge effect" (Murcia, 1995).

The greater external disturbance in the fragments can cause effects such as increased penetration of sunlight, greater incidence of winds, higher temperatures in the environment, and the consequent increase in evapotranspiration, leading to a decrease in the relative air humidity and soil moisture (Laurence et al. 1998; 2000; Nascimento and Laurance, 2004). These factors favor the proliferation of pioneer species with different life cycles, modifying C deposition in the soil (Laurence et al., 2000; Paciencia and Prado, 2004; Barros and Fearnside, 2016).

As is well known, forests play a fundamental role in the biogeochemical cycles of C on the planet, controlling the dynamics of C storage and the concentration of carbon dioxide (CO_2) in the atmosphere (Ma et al., 2017; Tonucci et al., 2023; Damian et al., 2023). Organic C is in dynamic equilibrium in these environments, with practically constant levels over time (Assunção et al., 2019). However, as previously mentioned, the edges of fragments can lose considerable amounts of C and/or modify the dynamics of C storage and emission to increase the negative impact on global warming (Barros and Fearnside 2016). In this way, when fragmented, old growth forests that previously functioned as C sinks become susceptible to C losses and contribute to an increase in atmospheric C (Ma et al., 2017; Oliveira et al., 2023).

Most studies on the C cycle in forest fragments focus on assessing plant biomass and litter, and the long-term effects on the dynamics of soil C storage and emission are still poorly understood (Nascimento; Laurance, 2004; Barros; Fearnside, 2016), this is worse in the Cerrado and Atlantic Forest biomes, which still have gaps in their understanding of the distribution of carbon stocks in tree vegetation (Scolforo et al., 2015) and the dynamics of C in the soil (Morais et al., 2013). These two biomes are still suffering from the conversion of native vegetation areas for human use and occupation of the land, putting the existing biodiversity at risk, as well as the capture and storage of C in the soil (Scolforo et al., 2015; Alencar et al., 2020; Santos et al., 2024).

Thus, the general hypothesis is that the edge effect associated with the extractive exploitation of timber and other resources in the fragments of the Cerrado and Atlantic Forest biomes has been promoting an imbalance in the dynamics of C in the peripheral zones, reducing C levels, especially in the labile C fractions of the soil and accelerating the process of oxidation of soil organic matter (SOM) and the emission of CO_2 into the atmosphere. Given the above, this study aimed to evaluate changes in the concentrations of organic carbon and oxidizable fractions of soil organic matter in and around forest fragments in the Atlantic Forest and Cerrado biomes.

2. Material and Methods

For the Atlantic Forest biome, soil samples were collected from two forest fragments located in Terra Roxa, Western region of Paraná, Brazil (Figure 1, Table 1), with a phytophysiognomy classified as Semideciduous Seasonal Forest (Campos; Silveira Filho, 2010), both rectangular. The region climate is subtropical (Cfa-type), according to the Köppen classification (Caviglione et al., 2000).

For the Cerrado biome, soil samples were collected from two forest fragments located in Aquidauana and Anastácio in the Cerrado-Pantanal ecotone region, state of Mato Grosso do Sul, Brazil (Santos et al., 2014) (Figure 1, Table 1). The region climate is classified as Aw-type (Tropical Humid) (Peel et al., 2007), with vegetation that is characteristic of the Cerrado *stricto sensu*, with possible variations to Cerradão (Silva Junior, 2005; Reis et al., 2023). In the Atlantic Forest biome, the study areas are under Latossolo Vermelho Eutroférrico típico, with a 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). The chemical characterization of the points studied is shown in Table 2.

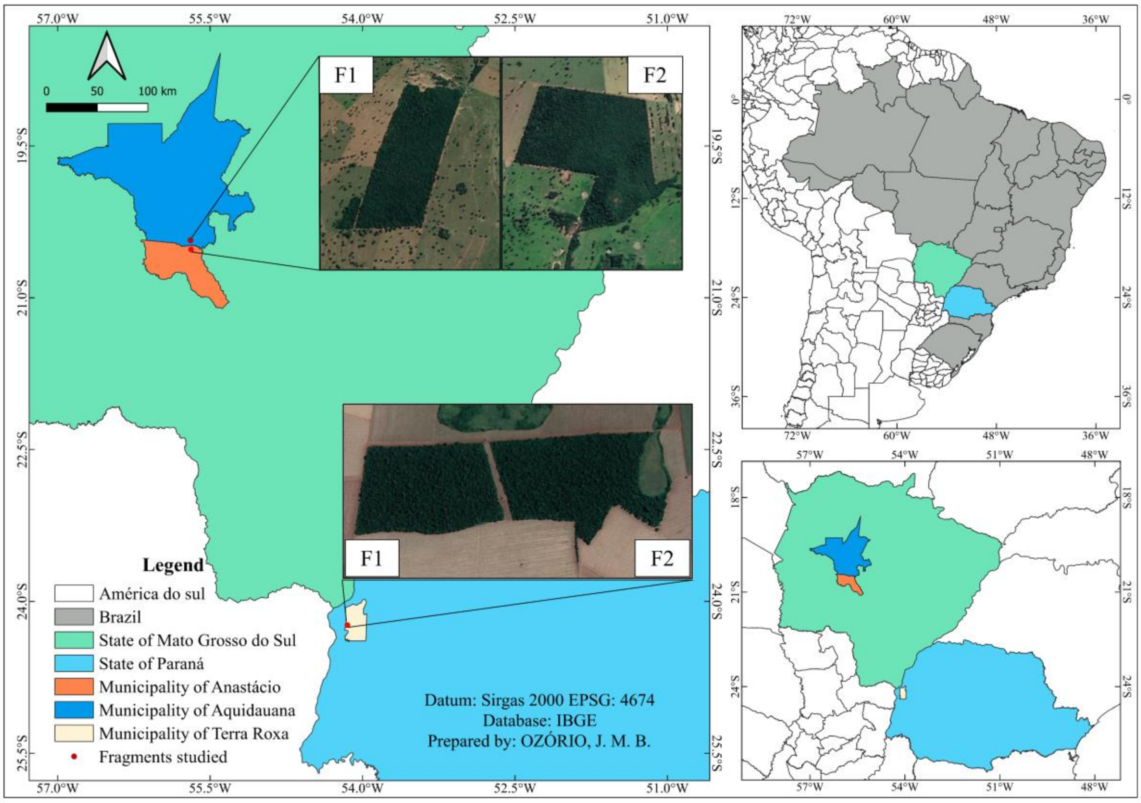

Figure 1. Location map of the municipalities of Terra Roxa, PR, Aquidauana and Anastácio, MS, Brazil. F1: Fragment 1; F2: Fragment 2.

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

Fragmentos	Descrição
Fragment 1 - AF	60.4 ha; 337 m of altitude, 24º14’05.56” South (S) e 54º09’30.63” West (W).
Fragmento 2 - AF	69.1 ha; 338 m of altitude, 24º14’04.37” South (S) e 54º08’51.89” West (W).
Fragment 1 – CE	55.7 ha; 209 m of altitude, 20º25’58.46” South (S) e 55º41’35.29” West (W).
Fragment 2 - CE	77.3 ha; 227 m of altitude, 20º31’12.48” South (S) e 55º41’09.25” West (W).

AF: Atlantic Forest; CE: Cerrado.

Table 2. Chemical characterization of the points studied in fragments 1 and 2 and the surrounding NT areas in the Atlantic Forest biome for the 0-0.2 m layer.

Determinations	Points ED, HR e	Points ED, HR e	NT around	NT around
pH ($CaCl_2$ 0,01M)	4.79	4.68	5.13	5.11
P (mg/dm^3)	8.08	4.14	10.84	30.15
K (cmolc/ dm^3)	0.52	0.59	0.39	0.47
Ca (cmol$_c$/ dm^3)	1.40	1.20	2.90	3.00
Mg (cmol$_c$/ dm^3)	1.10	0.80	1.40	2.00
Al (cmol$_c$/ dm^3)	0.11	0.10	0.03	0.03
H+Al (cmol$_c$/ dm^3)	5.00	2.20	3.20	3.50
SB (cmol$_c$/ dm^3)	3.02	2.59	4.69	5.47
C.T.C ((pH) 7,0)	8.02	4.79	7.89	8.97
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). BS: Sum of bases, C.E.C: Cation exchange capacity, V%: Base saturation.

Around the two fragments are areas of agricultural cultivation totaling 76.1 ha (Figure 1). The areas around the two forest fragments were cleared in 1970 to grow mint for 10 years. From 1980 onwards, soybean/corn succession was cultivated under a conventional tillage system (CTS) until 2002, when the areas were converted to the no-tillage system (NTS) using the same crop succession system as the CTS, which has remained the case. In these two forest fragments, until 2000, forest management took place with the removal of larger trees from the more peripheral portions of the fragments, i.e., until 2000, there were anthropic actions within these fragments modifying the vegetation.

For the Cerrado biome, the soil where the fragments are located is classified as Argissolo Vermelho-Amarelo (Santos et al., 2018), with a medium texture (762.9, 56.7, 180.4 g kg^{-1} of sand, silt, and clay, respectively in fragment 1, and 711.2, 112.6, and 176.2 g kg^{-1} of sand, silt and clay, respectively in fragment 2) (Santos et al., 2018), with both fragments being rectangular. The chemical characterization of the points studied is shown in Table 3.

The area surrounding fragment 1 is 420.7 ha of permanent pasture (PP) (*Urochloa decumbens*), established in 1980 and reformed with soil tillage, liming, and phosphate fertilization in 2008. Fragment 2 is surrounded by 1,250 ha of PP (*Urochloa decumbens*), established in 1992 and reformed with soil tillage, liming, and phosphate fertilization in 2007. Both PP areas show signs of degradation: low soil cover potential by the forage species, invasive plants, and stocking levels of 1 animal unit (AU) ha^{-1}.

The soil was collected at four points in the four fragments, three inside the fragments and one in the surrounding area. The internal points correspond to the edge of the fragment (ED), the central point between the edge and the center of the fragment, called the half radius (HR), and the center of the fragment (CF). The surrounding point corresponds to the areas under the no-tillage system or permanent pasture (NT/PP) around the Atlantic Forest and Cerrado fragments, respectively. The layout of the points is described in Table 4.

Four replicates were conducted over a 20 m² radius for each collection point. Undisturbed soil samples were collected into the fragments and around them in the areas under NTS and PP. The disturbed composite samples were collected using three single samples in the 0-0.05, 0.05-0.1, and 0.1-0.2 m layers.

Table 3. Chemical characterization of the points studied in fragments 1 and 2 and the surrounding areas in the Cerrado biome for the 0-0.2 m layer.

Determinations	Points ED, HR e CF do fragment 1	Points ED, HR e CF do fragment 2	PP around fragment 1	PP around fragment 2
pH ($CaCl_2$ 0,01M)	4.06	4.53	4.11	4.62
P (mg/dm^3)	2.86	2.76	1.68	1.68
K ($cmol_c/dm^3$)	0.11	0.15	0.03	0.06
Ca ($cmol_c/dm^3$)	0.30	1.30	0.40	0.80
Mg ($cmol_c/dm^3$)	0.20	0.70	0.20	0.60
Al ($cmol_c/dm^3$)	0.85	0.25	0.56	0.15
H+Al ($cmol_c/dm^3$)	3.10	2.80	3.50	1.30
SB ($cmol_c/dm^3$)	0.61	2.15	0.63	1.46
C.T.C (pH 7,0)	3.71	4.95	4.13	2.76
V%	16.4	43.4	15.3	52.9

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). BS: Sum of bases, C.E.C: Cation exchange capacity, V%: Base saturation.

Table 4. Description of the collection points and their distance from the edge of the fragments.

		Fragments (distance (m) from the edge)			
		Atlantic Forest		Cerrado	
		Fragments		Fragments	
Collection point	Descrição do ponto	1	2	1	2
P. 1	Center of the fragment (CF)	310	310	240	320
P. 2	Half radius (HR)	155	155	120	160
P. 3	Edge of the fragment (ED)	0	0	0	0
P. 4	Fragment surroundings (NT/PP)	310	310	240	320

The samples were air dried, crushed, and passed through a 2 mm sieve to obtain fine air-dried soil (FADS). Total organic carbon (TOC) was determined by oxidizing the organic matter with potassium dichromate in a heated sulphuric medium and titrated with ammoniacal ferrous sulphate (Yeomans; Bremner, 1988).

The fractionation of SOM by the different degrees of oxidation (lability) was carried out according to Chan et al. (2001), where four fractions were produced, with decreasing degrees of oxidation: Very easily oxidizable fraction (F1): C oxidized by $K_2Cr_2O_7$ in an acidic medium with 3 mol L^{-1} of H_2SO_4; - Easily oxidizable fraction (F2): difference between the C oxidized by $K_2Cr_2O_7$ in an acidic medium with 6 and 3 mol L^{-1} of H_2SO_4; moderately oxidizable fraction (F3): difference between the C oxidized by $K_2Cr_2O_7$ in an acidic medium with 9 and 6 mol L^{-1} of H_2SO_4; resistant fraction (F4): difference between the C oxidized by $K_2Cr_2O_7$ in an acidic medium with 12 and 9 mol L^{-1} of H_2SO_4.

The C content in the F1 fraction was considered the labile carbon (L_C) of the soil (Rangel et al., 2008), while the non-labile carbon (N_{LC}) was obtained by difference (N_{LC} = TOC - L_C), subsequently calculating the L_C/TOC ratio. The ratios between the F1/F4 and F1+F2/F3+F4 fractions were also calculated to obtain indexes to facilitate understanding of the dynamics between these fractions. The results were analyzed for normality and homogeneity of variance using the Shapiro-Wilk and Bartlett tests, respectively. Subsequently, in a completely randomized design, the results were submitted to analysis of variance using the F-test, evaluating each biome and fragment individually. The means were compared using the Tukey test at 5% probability. The R Core Team program (2019) and ExpDes.pt package (Ferreira et al., 2018) were used in the analyses.

3. Results and Discussion

In the areas of the forest fragments from the Atlantic Forest biome, the highest TOC contents were found at the CF point for both fragments, with contents of 63.2 and 60.91 g kg^{-1} in the 0-0.05 m layer of fragments 1 and 2, respectively (Figure 2).

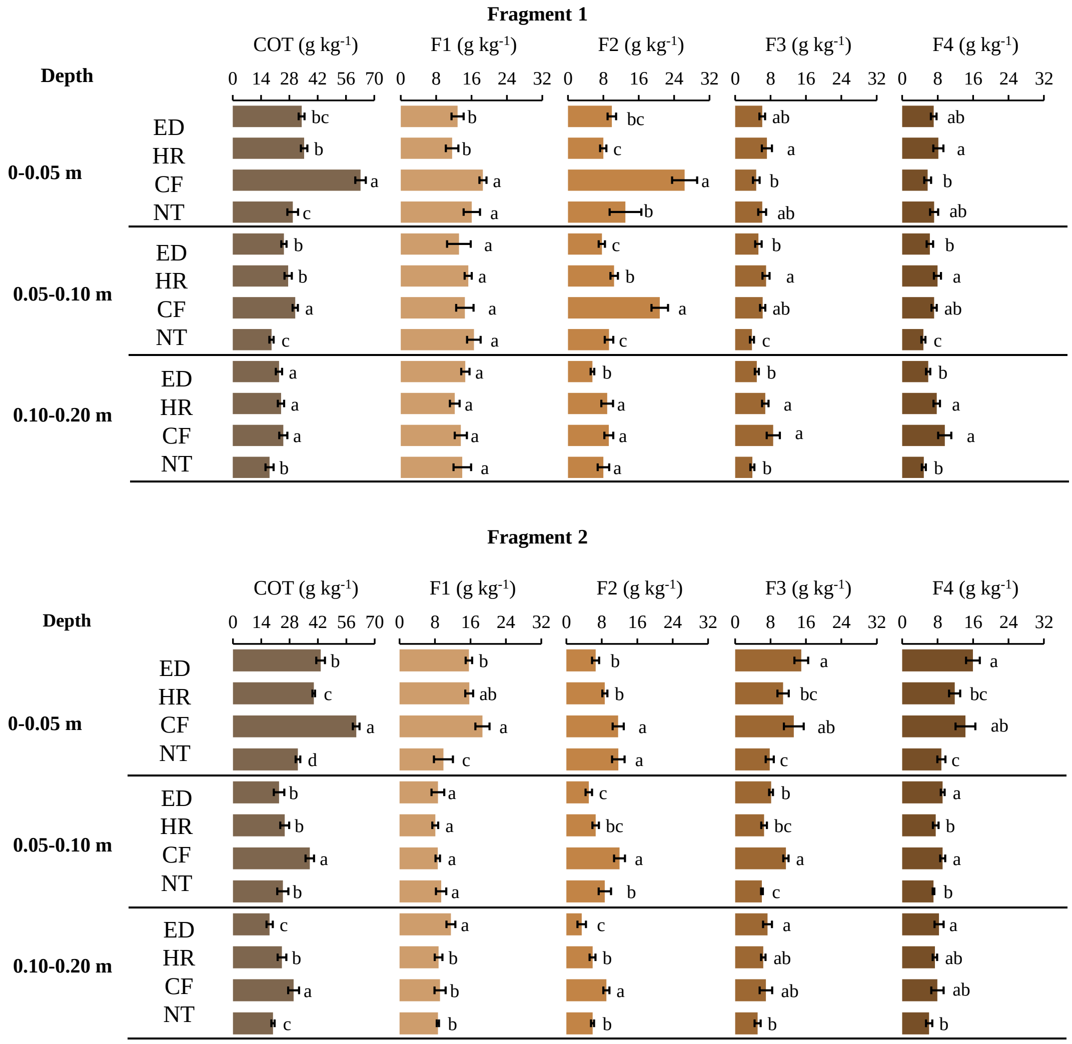

Figure 2. Oxidizable organic carbon fractions (F1, F2, F3, F4) from the different collection points in fragments 1 and 2 of the Atlantic Forest biome.

The ED area had lower TOC contents than the CF, from 34.07 g kg^{-1} in the 0-0.05 m layer of fragment 1 to 18.12 g kg^{-1} in the 0-0.05 m layer of fragment 2. The TOC contents at the ED point in both fragments were similar to those of the surrounding NT area in practically all layers. In the Cerrado biome, fragments 1 and 2 had different TOC contents (Figure 3). In fragment 1, HR had the highest TOC content in the 0-0.05 m layer, at 23.77 g kg^{-1}, although similar to the ED and CF points in the 0.05-0.10 m layers. In this fragment, the surrounding PP had the lowest TOC content in the 0-0.05 m layer. In fragment 2, the CF had the highest TOC content in the 0.05 m layer (17.76 g kg^{-1}) and did not differ from the ED in the 0.05-0.10 layer. In the 0.10-0.20 m layer, there were no differences between the internal points of the two fragments and the PP areas.

The C contents of the oxidizable fractions of the MOS of the Atlantic Forest showed some differences between the fragments (Figure 2). In the 0-0.05 m layer, the CF point showed the highest C contents in the F1 fractions (labile fraction), 18.58 and 18.71 g kg^{-1} in fragments 1 and 2, respectively, with the contents decreasing in depth. The CF also showed the highest contents of the F2 fraction at all depths in the two fragments, reaching 26.38 g kg^{-1} in the F2 fraction of fragment 1. The contents of the F3 and F4 fractions in fragment 1 are lower than the most labile fractions in the first two layers, with the lowest in the NT in the 0.05-0.10 m layer, with contents of 3.79 and 4.79 g kg^{-1}, respectively. Fragment 2 showed high F3 and F4 fractions levels at ED point in the 0-0.05 m layer, 14.96 g kg^{-1} and 15.96, respectively, and in the 0.10-0.20 m layer.

The Cerrado also showed some differences between the fragments in the results of the oxidizable fractions (Figure 3). In fragment 1, as with the TOC levels, the HR point had the highest levels in F1, 8.13 g kg^{-1}, and the CF point showed the lowest levels in the 0-0.05 and 0.10-0.20 m layers, 4.25 and 3.00 g kg^{-1}, respectively.

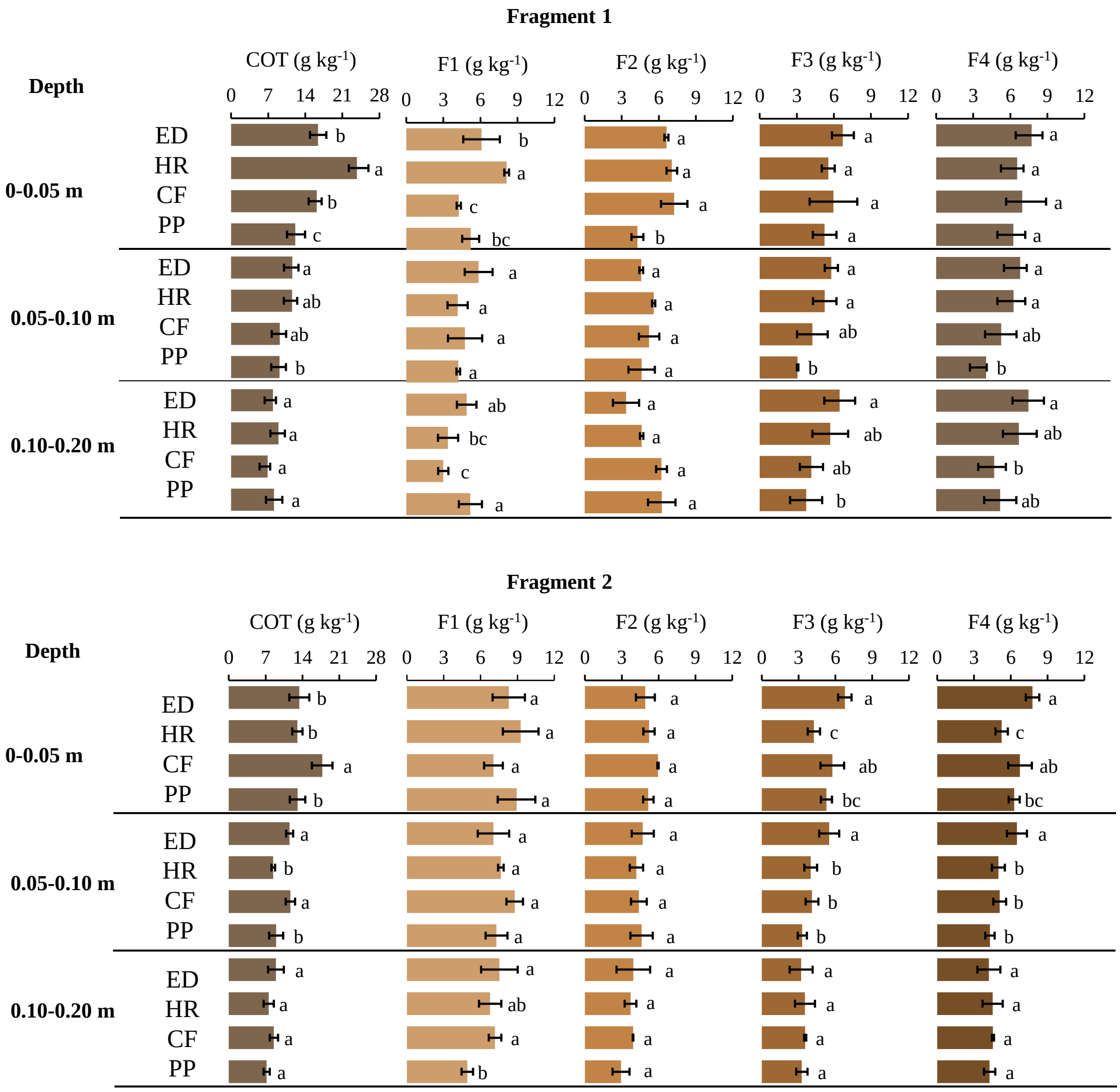

Figure 3. Oxidizable organic carbon fractions (F1, F2, F3, F4) from the different collection points in fragments 1 and 2 of the Cerrado biome.

Fragment 2 showed high contents of F1, with similar contents between the areas in the first two layers, but in the last layer, PP showed the lowest contents of F1, 4.92 g kg^{-1}. The F2 fraction only differed in the 0-0.05 m layer of fragment 1, with the lowest contents being 4.27 g kg^{-1} in PP. In the surface layer of fragment 1, the contents of the F3 and F4 fractions did not differ, but in the subsurface layers, the CF and PP points had the lowest contents of these fractions. In fragment 2, the ED point had the highest levels of non-labile fractions in the first two layers, with 6.77 and 7.77 g kg^{-1} of the F3 and F4 fractions, respectively, in the 0-0.05 layer, while HR and PP points had the lowest contents of these fractions.

The fragments from both biomes are remnants of deforestation processes from the 1970s, 1980s, and 1990s, with different sizes, shapes, and soil chemical and physical attributes, resulting in heterogeneous characteristics regarding TOC content within each biome. It is worth noting that these fragments have undergone and may still be undergoing changes in species composition and plant community structure, thus altering the dynamics of C in the soil (Laurence et al., 1998; Nascimento and Laurance, 2004; Barros and Fearnside 2016).

The higher TOC contents in the CF of the forest fragments of the Atlantic Forest biome and fragment 2 of the Cerrado biome show that the state of conservation at this point is due to greater isolation since the other points are subject to the edge effect and anthropogenic actions that abruptly alter the dynamics of C accumulation and maintenance at the edges of the fragments (Ma et al., 2017). These fragments have a regular shape and wide bases, which reduces the interference of edge effects on the CF, contributing to the dynamics of maintaining C in the CF (Ribeiro et al., 2010; Ferreira et al., 2023; Dias et al., 2023).

The edges have different microclimatic conditions to the inner areas of the fragment, with higher temperatures and lower humidity as a result of the greater incidence of sunlight and winds, making it possible to accelerate the decomposition processes of the SOM and, consequently, greater transfer of C from the plant compartment to the soil (Duiker and Lal, 2000; Oliveira et al., 2022). However, only a small fraction of the dead biomass is transferred to the soil, with much of the organic C being lost through oxidation due to increased biomass (Rolo et al., 2018).

Barros and Fearnside (2016) describe that factors such as strong winds, intense solar radiation, and greater evaporation, described above as catalysts for the processes of decomposition of soil organic matter (SOM), may also be increasing the mortality of adult trees in the edges of the fragments and thus providing more residues for decomposition, as well as opening more gaps in the canopy and further intensifying the factors. Laurence et al. (2000) also highlight the increased development of parasitic species, such as lianas, which accelerate tree mortality. The climax vegetation on the edges is gradually replaced by a vegetation of pioneer species, with a higher density of trees with thin trunks, lower density wood, and a low C/N ratio, increasing the decomposition rate of the litter (Ma et al., 2017; Farias et al., 2022).

Unlike the Atlantic Forest and fragment 2, fragment 1 of the Cerrado biome showed high TOC contents at the edges (HR and ED), higher than the CF. It is worth noting that the mortality of adult trees at the edge of the fragments and their replacement by pioneer vegetation occurred in all four fragments. Still, fragment 1 of the Cerrado was the smallest studied, with 55.7 ha, rectangular shape, and the smallest base width; it may be subject to a greater action of the edge effect, starting at the edges of the fragment and spreading to the center of the fragment, which may explain the low C contents in the CF, since the process of change in the community is still incipient in the CF, which leads to a reduction in TOC (Ribeiro et al., 2010; Falcão et al., 2020; Moraes et al., 2021). The process of biomass oxidation by microorganisms in the CF of fragment 1 is possibly faster than the transfer of organic compounds to the soil (Rolo et al., 2018; Pinto et al., 2023; Rosset et al., 2023).

The similarity between the TOC contents of ED points of the Atlantic Forest fragments and the NT can be related to the interference of the edge factor, which reduced the TOC contents in the ED points of fragments. On the other hand, the similar TOC contents between the PP areas and the internal points of both fragments in the 0.10-0.20 m layer can be explained by the contribution of the root biomass of the pasture, which, when decomposing, increases the C content in subsurface layers (Salton et al., 2014).

The Atlantic Forest showed high levels of C in the bioavailable form (labile C), both in the F1 and F2 fractions, compared to the other fractions, which in turn may be associated with the greater contribution of residues and physical protection of the SOM (occluded in aggregates) (Rosset et al., 2016; Ozório et al., 2019; Ozório et al., 2020; Marafon et al., 2020). The iron oxides present in the soil studied (Latossolo Vermelho Eutroférrico típico) contribute to the complexation of organic matter, hindering the degradation process of soil microorganisms (Rosset et al., 2016), but it is also worth noting the contribution of oxides to soil aggregation and consequently the physical protection of organic matter to slow down the rate of decomposition (Gelaw et al., 2015; Zhao et al., 2017).

The aggregation process begins with the formation of micro-aggregates through the interaction between organic molecules, polyvalent cations, and mineral particles from the clay fraction, mainly kaolinite and Fe oxides, followed by meso-aggregates and macro-aggregates are formed by the mechanical bonding of micro-aggregates during the growth process of roots and fungal hyphae, giving greater stability and physical protection to the organic matter occluded within the aggregates (Tisdall; Oades, 1982; Six et al., 2004; Gelaw et al., 2015; Martins et al., 2015). In addition to the high contents of labile C fractions, another factor that draws attention is the location of the highest levels of labile and moderately labile C in the CF of the two Atlantic Forest fragments, which corroborates the TOC results and reinforces the hypothesis of an edge effect in these fragments.

Ozório et al. (2019), evaluating the same fragments as the present study, observed greater deposits of litter in the ED of the fragments, but this litter came from vegetation composed of pioneer species, with a low C/N ratio, which reduces the recalcitrance of SOM, and favors the process of mineralization of C and slows down the humification of SOM (Rolo et al., 2018, Assunção et al., 2019), Thus, even without soil tillage and destructuring, the C in the labile fractions tends to decrease over time due to low replenishment, especially in the more subsurface layers (Ma et al., 2017).

The results of the N_{LC} contents showed similar patterns to the TOC contents, while the proportion of labile carbon did not show similar patterns to the TOC contents (Figures 2 and 3). In the Atlantic Forest, the CF point showed the highest levels of N_{LC} in both fragments. Concerning L_C/C, the NT area of fragment 1 and the ED point of fragment 2 had the highest values. In fragment 1 of the Cerrado, HR had the highest N_{LC} content and L_C/C values, along with ED within the fragment, while the PP area had the highest L_C/C values and the lowest N_{LC} content. Fragment 2 did not show a homogeneous distribution of N_{LC} and L_C/C in depth.

The F1/F4 and F1+F2/F3+F4 ratios are important tools for assessing the balance in the distribution of C, where values close to 1 indicate a balance between the labile and recalcitrant fractions (Chan et al., 2001; Loss et al., 2014; Oliveira et al., 2021). In the Atlantic Forest, the CF point showed the highest F1/F4 and F1+F2/F3+F4 ratios in the 0-0.05 m layer of fragment 1. In fragment 2, the F1+F2/F3+F4 values did not differ between HR and CF points and the NT area (Table 5).

The NT areas in the 0.05-0.10 m layer showed the highest ratio values in both fragments. In the 0.10-0.20 m layer of fragment 1, the NT area showed the highest values of both ratios, while the values of these ratios did not differ between the points in fragment 2 (Table 5). The HR point showed the highest values for the F1/F4 and F1+F2/F3+F4 ratios in the 0-0.05 m layer of Cerrado fragments 1 and 2 (Table 6). In the 0.05-0.10 m layer, the F1+F2/F3+F4 ratio had the highest values in the PP area and at the CF point. In the 0.10-0.20 m layer, the highest values for both ratios were observed in the PP (Table 6).

Table 5. Non-labile carbon (N_{LC}), labile carbon/C total ratio (L_C/C), and the ratio between the oxidizable fractions (F1/F4 and F1+F2/F3+F4) of the different collection points of fragments 1 and 2 of the Atlantic Forest biome.

	Fragment 1				Fragment 2			
	N_{LC} g kg^{-1}	L_C/C %	F1/F4	F1+F2/F3+F4 ----------------------	N_{LC} g kg^{-1}	L_C/C %	F1/F4	F1+F2/F3+F4 -------------------------
				0-0.05 m				
ED	21.22b	37.7b	1.82bc	1.74bc	27.65b	36.2ab	0.98a	0.72b
HR	23.72b	32.9b	1.42c	1.29c	24.19c	39.4a	1.34a	1.08a
CF	44.61a	29.4b	3.28a	4.33a	42.20a	30.7b	1.33a	1.12a
NT	13.60c	54.16a	2.25b	2.21b	22.16c	30.9b	1.14a	1.31a
CV%	11.1	9.98	16.17	17.11	5.41	5.35	18.03	14.6
				0.05-0.10 m				
ED	12.13b	52.0b	2.10b	1.82b	14.12b	38.0a	0.94bc	0.79b
HR	12.15b	55.7b	1.92b	1.73b	17.53b	31.5ab	1.07ab	1.04b
CF	16.43a	46.8b	2.01b	2.64a	29.33a	22.7b	0.69c	0.86b
NT	2.67c	86.1a	3.47a	3.04a	15.26b	38.0a	1.32a	1.37a
CV%	16.66	17.42	13.38	13.3	12.96	7.36	12.51	12.63
				0.10-0.20 m				
ED	8.28ab	63.8ab	2.49a	1.87b	6.53c	63.9a	1.40a	0.97a
HR	11.97a	51.1b	1.57b	1.45bc	15.40b	36.4bc	1.19a	1.06a
CF	11.43a	54.3b	1.44b	1.27c	20.85a	30.5c	1.18a	1.26a
NT	4.24b	76.6a	2.89a	2.53a	11.13bc	43.7b	1.43a	1.31a
CV%	18.21	25.63	17.99	14.81	18.3	10.87	16.05	17.14

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

Table 6. Non-labile carbon (N_{LC}), labile carbon/C total ratio (L_C/C), and the ratio between the oxidizable fractions (F1/F4 and F1+F2/F3+F4) of the different collection points of fragments 1 and 2 of the Cerrado biome.

	Fragment 1				Fragment 2			
	N_{LC} g kg^{-1}	L_C/C %	F1/F4	F1+F2/F3+F4	N_{LC} g kg^{-1}	L_C/C %	F1/F4	F1+F2/F3+F4
			--				--------------------------	
0-0.05 m								
ED	10.30b	37.2a	0.80b	0.89ab	0.37b	61.9a	1.06b	0.90b
HR	15.63a	34.2ab	1.24a	1.26a	0.29b	71.1a	1.76a	1.53a
CF	11.93b	26.3b	0.63b	0.93ab	0.59a	39.7b	1.05b	1.05b
PP	6.86c	43.2a	0.86ab	0.85b	0.31b	68.4a	1.43ab	1.23ab
CV%	14.1	7.72	21.56	19.73	16.78	16.78	16.1	14.83
0.05-0.10 m								
ED	5.59a	50.8a	0.87a	0.83b	4.50a	61.0c	1.08b	0.98b
HR	7.36a	36.2a	0.66a	0.85b	1.13c	90.8a	1.54a	1.32ab
CF	4.41a	51.9a	0.92a	1.09ab	2.93b	75.0b	1.74a	1.44a
PP	4.90a	46.2a	1.04a	1.24a	1.70c	81.1ab	1.69a	1.58a
CV%	26.91	22.23	19.96	18.04	21.86	20.43	12.91	12.87
0.10-0.20 m								
ED	2.99b	0.37b	0.67ab	0.75b	1.40b	84.2b	1.79a	1.56a
HR	5.55a	0.61a	0.53b	0.67b	1.19b	89.4b	1.53ab	1.35ab
CF	3.88ab	0.56ab	0.63ab	1.11ab	1.37b	83.9b	1.58a	1.37ab
PP	2.91b	0.35b	1.06a	1.27a	2.27a	68.4a	1.15b	1.05b
CV%	31.17	22.40	32.62	22.98	21.18	17.69	12.21	16.16

*Means followed by the same letter in the columns for each fragment and soil layer do not differ statistically by the Tukey test (5%). ED: Edge of the fragment; HR: Half of the radius; CF: Center of the fragment; PP: Permanent Pasture; CV (%): coefficient of variation.

As mentioned above, the Cerrado fragments differ in size and shape, contributing to a difference in the carbon dynamics of these soils. The lower contents of labile C in the CF of fragment 1, similar to the PP in the 0.0-0.05 m layer, are directly related to the advancement of the edge effect to the center of the fragment due to its shape and size and the similarity between the contents of the non-labile C fractions also helps to understand this process (Ribeiro et al., 2010). The changes in the structure of the vegetative community may still be recent and incipient in the CF, which has not allowed a large accumulation of SOM from pioneer species or the complete decomposition of the residues of climax species.

In this fragment, Ozório et al. (2019) observed greater deposits of litter in HR point and a similar amount of litter between CF and ED points, with CF having a slightly lower amount than ED. Thus, with little residue available for humification, the more labile fractions are quickly mineralized, leaving only the moderately and non-labile fractions, which results in an imbalance in the dynamics of C in the center of the fragment (Ma et al., 2017). In the subsurface layers of fragment 1, the non-labile fractions dominated at both collection points, with C levels in the labile fraction being lower than the PP and a greater contribution from root biomass. Therefore, it is likely that the superiority in TOC and labile C levels on the peripheries of the fragment is due to the displacement of a greater flow of C from the vegetation to the soil, especially in the HR, which has less interference from climatic factors that catalyze decomposition processes, but this material is not accumulated in depth due to the rapid mineralization of SOM (Barros and Fearnside, 2016; Ma et al., 2017).

The similarity between the labile and moderately labile C contents of the points in fragment 2 and the PP area may be associated with the greater contribution of SOM, which, even in sandy soils, has contributed to the constant replenishment of labile C fractions. Unlike fragment 1, this fragment does not show a very abrupt reduction in the labile C content at depth. The levels of non-labile C, F3, and F4 showed few differences between the collection points in the Cerrado biome fragments, especially in the more subsurface layers, which shows that this fraction is more resistant to C losses due to anthropogenic actions, stabilizing the soil C contents (Sierra et al., 2007), however, the process of humification of the SOM and stabilization of the more recalcitrant fractions is impaired due to the breakdown of the dynamics of residue accumulation and rapid mineralization (Assunção et al., 2019).

4. Conclusions

Forest fragmentation reduces the carbon content of the edges of the fragments to contents similar to those of the surrounding areas under a no-tillage system. Concerning the carbon content of the oxidizable fractions, the point in the center of the fragment has the highest carbon content in the labile and moderately labile fractions (F1 and F2) in the surface layers, decreasing in depth. On the other hand, the points on the edge and half of the radius have the lowest contents of labile and moderately labile carbon fractions, which contributes to the decrease in total organic carbon at these points and confirms the negative interference of the edge effect and timber extraction on carbon dynamics in the outermost areas of the fragments.

In the Cerrado biome, the fragments showed different levels of total organic carbon. In fragment 1, the point at the middle of the radius has the highest total organic carbon content in the surface layer, and the point at the center of the fragment has total organic carbon contents similar to the point at the edge, resulting from the advance of the edge effect to the center of the fragment. As with the total organic carbon content, the point in the middle of the radius had the highest surface labile C content, and the point in the middle of the fragment had the lowest, which is due to the still developing accumulation of residues with a low C/N ratio and their rapid mineralization.

In fragment 2, the point in the center of the fragment has the highest levels of total organic carbon in the surface layer, but in the subsurface layers, it does not differ from the point on the edge. This fragment showed high levels of labile C, with similar levels between points. The levels of non-labile carbon show little difference between the points collected in both fragments, which shows that these recalcitrant fractions are more resistant to carbon loss.

Authors' Contribution

Jefferson Matheus Barros Ozório wrote the project, carried out analysis and wrote the manuscript. Jean Sérgio Rosset did the project correction and the manuscript. Naelmo de Souza Oliveira carried out laboratory analyses and corrected the manuscript. Camila Beatriz da Silva Souza was the responsible to sample collection and laboratory analysis. Paulo Guilherme da Silva Farias was the responsible to sample collection and laboratory analysis. Luan Soares Bispo was the responsible to sample collection and laboratory analysis. Jolimar Antonio Schiavo did the project correcting and the manuscript.

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Bibliographic References

Alencar, A., Shimbo, J.Z., Lenti, F., Balzani Marques, C., Zimbres, B., Rosa, M., Arruda, V., Castro, I., Ribeiro, J.P.F. M., Varela, V., Alencar, I., Piontekowski, V., Ribeiro, V., Bustamante, M.M.C., Sano, E.E., Barroso, M. 2020. Mapping three decades of changes in the brazilian savanna native vegetation using landsat data processed in the google earth engine platform. Remote Sensing, 12(6), 924. DOI: https://doi.org/10.3390/rs12060924

Almeida, D.S. 2016. Recuperação ambiental da Mata Atlântica. Editus, Santa Cruz.

Assunção, S.A., Pereira, M.G., Rosset, J.S., Berbara, R.L.L., García, A.C. 2019. Carbon input and the structural quality of soil organic matter as a function of agricultural management in a tropical climate region of Brazil. Science of the Total Environment, 658, 901-911. DOI: https://doi.org/10.1016/j scitotenv.2018.12.271.

Barros, H.S., Fearnside, P.M. 2016. Soil carbon stock changes due to edge effects in central Amazon forest fragments. Forest Ecology and Management, 379, 30-36. DOI: https://doi.org/10.1016/j.foreco.2016.08.002.

Campos, J.B., Silveira Filho, L. 2010. Série Ecossistemas Paranaenses – Floresta Estacional Semidecidual. Governo do Estado do Paraná. 5, 8p.

Carvalho, F.M., Júnior, P.D.M., Ferreira, L.G. 2009. The Cerrado into-pieces: Habitat fragmentation as a function of landscape use in the savannas of central Brazil. Biological conservation, 142(7), 1392-1403. DOI: https://doi.org/10. 1016/j.biocon.2009.01.031.

Caviglione, J.H., Kiihl, L.R.B., Caramori, P.H., Oliveira, D. 2000. Cartas climáticas do Estado do Paraná. Iapar, Londrina.

Chan, K.Y., Bowman, A., Oates, A. 2001. Oxidizible organic carbon fractions and soil quality changes in an oxic paleustalf under different pasture leys. Soil Science, 166(1), 61-67. DOI: https://doi.org/10.1097/00010694-200101000-00009.

Damian, J.M., Silva Matos, E., Pedreira, B.C., Faccio Carvalho, P.C., Premazzi, L.M., Cerri, C.E.P. 2023. Intensification and diversification of pasturelands in Brazil: Patterns and driving factors in the soil carbon stocks. Catena, 220, 106750. DOI: https://doi.org/10.1016/j.catena.2022.106750.

Dias, T.D.C., Silveira, L.F., Francisco, M.R. 2023. Spatiotemporal dynamics reveals forest rejuvenation, fragmentation, and edge effects in an Atlantic Forest hotspot, the Pernambuco Endemism Center, northeastern Brazil. Plos one, 18(9), e0291234. DOI: https://doi.org/10.1371/journal. pone.0291234.

Duiker, S.W., Lal, R. 2000. Carbon budget study using CO2 flux measurements from a no till system in central Ohio. Soil and Tillage Research, 54(1-2), 21-30. DOI: https://doi.org/ 10.1016/S0167-1987(99)00101-4.

Falcão, K.S., Monteiro, F.N., Ozório, J.M.B., Souza, C.B.S., Farias, P.G.S., Menezes, R.S., Panachuki, E., Rosset, J.S. 2020. Carbon stock and soil aggregation under different use systems in the Cerrado. Brazilian Journal of Environmental Sciences, 55(2), 242–255. DOI: https://doi.org/10.5327/ Z2176-947820200695.

Farias, P.G.S., Souza, C.B.S., Rosset, J.S., Ozório, J.M.B., Panachuki, E., Schiavo, J.A., Lima, P.R., Marra, L.M. 2022. Physical fractions of organic matter and mineralizable soil carbon as quality indicators in areas under different forms of use in the Cerrado-Pantanal Ecotone. Environmental Monitoring and Assessment, 194(7), 517. DOI: https://doi.org/10.1007/s10661-022-10163-z.

Ferreira, E.B., Cavalcanti, P.P., Nogueira, D.A. 2018. ExpDes.pt: Pacote Experimental Designs (Portuguese). R package version 1.2.0. https://CRAN.R-project.org/package=ExpDes.pt.

Gelaw, A.M., Singh, B.R., Lal, R. 2015. Organic carbon and nitrogen associated with soil aggregates and particle sizes under different land uses in Tigray, Northern Ethiopia. Land Degradation & Development, 26(7), 690-700. DOI: https://doi.org/10.1002/ldr.2261.

Guareschi, R.F., Pereira, M.G., Perin, A. 2016. Densimetric fractionation of organic matter in an agricultural chronosequence in no-till areas in the Cerrado region, Brazil. Semina: Ciências Agrárias, 37(2), 595-610. DOI: http://dx.doi.org/10.5433/1679-0359.2016v37n2p595.

Ferreira, I.J.M., Campanharo, W.A., Fonseca, M.G., Escada, M.I.S., Nascimento, M.T., Villela, D.M., Brancalion, L.F.S.M., Anderson, L.O., Nagy, L., Aragão, L.E. 2023. Potential aboveground biomass increase in Brazilian Atlantic Forest fragments with climate change. Global Change Biology, 29(11), 3098-3113. DOI: https://doi.org/10.1111/gcb.16670.

Laurance, W.F., Delamônica, P., Laurance, S.G., Vasconcelos, H.L., Lovejoy, T.E. 2000. Rainforest fragmentation kills big trees. Nature, 404(6780), 836-836. DOI: http://dx.doi.org/10.1038/35009032.

Laurance, W.F., Ferreira, L.V., Rankin-de Merona, J.M., Laurance, S.G. 1998. Rain forest fragmentation and the dynamics of Amazonian tree communities. Ecology, 79(6), 2032-2040. DOI: https://doi.org/10.2307/176707

Loss, A., Pereira, M.G., Costa, E.M., Beutler, S.J. 2014. Frações granulométricas e oxidáveis de matéria orgânica sob diferentes sistemas de uso do solo, no Paraná, Brasil. Bioscience Journal, 30, 43-54.

Ma, L.; Shen, C.; Lou, D.; Fu, S.; Guan, D. Ecosystem carbon storage in forest fragments of differing patch size. Scientific reports, 7(1), 1-8, 2017. DOI: https://doi.org/10.1038/s41598-017-13598-4.

Malheiros, R. 2016. A influência da sazonalidade na dinâmica da vida no bioma Cerrado. Revista Brasileira de Climatologia, 19, 113-128. DOI: http://dx.doi.org/10.5380/abclima.v19i0.48876

Marafon, G., Barbosa, R.S., Jesus Lacerda, J.J., Martins, V., Silva, J.D.D.F., Costa Jr, O.S. 2020. C and P pool restoration by a no-tillage system on Brazilian Cerrado Oxisol in Piauí State. Environmental monitoring and assessment, 192(254), 1-14. DOI: https://doi.org/10.1007/s10661-020-8221-6.

Martins, C., Costa, L., Schaefer, C.E.G.R., Soares, E.M.B., Santos, S.R.D. 2015. Frações da matéria orgânica em solos sob formações deciduais no norte de Minas Gerais. Revista Caatinga, 28, 10-20. DOI: http://dx.doi.org/10.1590/1983-21252015v28n402rc.

Morais, D.H.O., Silva, C.A., Rosset, J.S., Farias, P.G.S., Souza, C.B.S., Barros Ozório, J.M., Castilho, S.C.P., Marra, L.M. 2021. Stock and indices of carbon management under different soil use systems. Brazilian Journal of Environmental Sciences, 56(2), 286–295. DOI: https://doi.org/10.5327/Z21769478867.

Morais, V.A., Scolforo, J.R.S., Silva, C.A., Mello, J.M.D., Gomide, L.R., Oliveira, A.D.D. 2013. Carbon and biomass stocks in a fragment of cerradão in Minas Gerais state, Brazil. Cerne, 19, 237-245. DOI: https://doi.org/10.1590/S0104-77602013000200007.

Murcia, C. 1995. Edge effects in fragmented forests: implications for conservation. Trends in ecology & evolution, 10(2), 58-62. DOI: https://doi.org/10.1016/S0169-5347 (00)88977-6.

Myers, N., Mittermeier, R.A., Mittermeier, C.G., Fonseca, G. A., Kent, J. 2000. Biodiversity hotspots for conservation priorities. Nature, 403(6772), 853-858. DOI: https://doi.org/10.1038/35002501.

Nascimento, H.E., Laurance, W.F. 2004. Biomass dynamics in Amazonian forest fragments. Ecological applications, 14(sp4), 127-138. DOI: https://doi.org/10.1890/01-6003.

Novais, D.B., Ferreira, J.S., Garcia, P.A.B.B. 2016. Fertilidade do solo como indicador do efeito de borda em fragmento florestal, Vitória da Conquista, Bahia. Revista Verde de Agroecologia e Desenvolvimento Sustentável, 11(4), 185-189. DOI: https://doi.org/10.18378/rvads.v11i4.4081.

Oliveira, D.M.D.S., Tavares, R.L.M., Loss, A., Madari, B.E., Cerri, C.E.P., Alves, B.J.R., Pereira, M.G., Cherubin, M.R. 2023. Climate-smart agriculture and soil C sequestration in Brazilian Cerrado: a systematic review. Revista Brasileira de Ciência do Solo, 47, e0220055. DOI: https://doi.org/10.36783/18069657rbcs20220055.

Oliveira, N.S., Schiavo, J.A., Lima, M.F., Laranjeira, L.T., Nunes, G.P., Cruz, S.C. 2021. Isotopic variations of carbon and nitrogen and their implications on the conversion of Cerrado vegetation into pasture. Brazilian Journal of Environmental Sciences, 56(2), 266–273. DOI: https://doi.org/10.5327/Z21769478845.

Oliveira, N.S., Schiavo, J.A., Pereira, M.G., Coêlho, R.S., Ozório, J.M.B., Moraes, E.M.V. 2022. Pedogenesis of soils with accumulation of organic carbon in the subsurface horizons in a saline lake in the Pantanal wetland of Nhecolândia, Brazil. Journal of South American Earth Sciences, 117, 103816. DOI: https://doi.org/10.1016/j.jsames.2022.103816.

Ozório, J.M.B., Rosset, J.S., Schiavo, J.A., Panachuki, E., Souza, C.B.S., Menezes, R.S., Ximenes, T.S., Castilho, S.C. P., Marra, L.M. 2019. Estoque de carbono e agregação do solo sob fragmentos florestais nos biomas Mata Atlântica e Cerrado. Brazilian Journal of Environmental Sciences, (53), 97-116. DOI: https://doi.org/10.5327/Z2176-947820190518.

Ozório, J.M.B., Rosset, J.S., Schiavo, J.A., Souza, C.B.D.S., Farias, P.G.D.S., Oliveira, N.D.S., Menezes, R.S., Panachuki, E. 2020. Physical fractions of organic matter and mineralizable soil carbon in forest fragments of the Atlantic Forest. Revista Ambiente & Água, 15(6), e2601. DOI: https://doi.org/10.4136/ambi-agua.2601.

Paciencia, M.L., Prado, J. 2004. Efeitos de borda sobre a comunidade de pteridófitas na Mata Atlântica da região de Una, sul da Bahia, Brasil. Brazilian Journal of Botany, 27, 641-653. DOI: https://doi.org/10.1590/S0100-84042004000400005.

Peel, M.C., Finlayson, B.L., McMahon, T.A. 2007. Updated world map of the Köppen-Geiger climate classification. Hydrology and earth system sciences, 11(5), 1633-1644. DOI: https://doi.org/10.5194/hess-11-1633-2007.

Pinto, L.A.S.R., Morais, I.S., Ozório, J.M.B., Melo, T.R., Rosset, J.S., Pereira, M.G. 2023. Soil aggregation and associated organic matter under management systems in sandy-textured soils, subtropical region of Brazil. Environmental Monitoring and Assessment, 195(1), 253. DOI: https://doi.org/10.1007/s10661-022-10892-1.

R Core Team. 2019. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org/.

Rangel, O.J.P., Silva, C.A., Guimarães, P.T.G., Guilherme, L.R.G. 2008. Frações oxidáveis do carbono orgânico de Latossolo cultivado com cafeeiro em diferentes espaçamentos de plantio. Ciência e Agrotecnologia, 32, 429-437.

Reis, L.B.S., Miranda, S.D.C., Machida, W.S. 2023. Aspectos ecológicos, funcionais e anatômicos de três espécies lenhosas de cerradão. Revista Brasileira de Geografia Física, 16(02), 968-985.

Ribeiro, S.C., Jacovine, L.A.G., Soares, C.P.B., Martins, S.V., Nardelli, Á.M.B., Souza, A.L.D. 2010. Quantificação de biomassa e estimativa de estoque de carbono em uma capoeira da Zona da Mata Mineira. Revista Árvore, 34, 495-504. DOI: http://dx.doi.org/10.1590/S0100-67622010000300013.

Rolo, V., Olivier, P.I., Pfeifer, M., van Aarde, R.J. 2018. Functional diversity mediates contrasting direct and indirect effects of fragmentation on below-and above-ground carbon stocks of coastal dune forests. Forest Ecology and Management, 407, 174-183. DOI: https://doi.org/10.1016/j.foreco.2017.10.059.

Rosset, J.S., Lana, M.D.C., Pereira, M.G., Schiavo, J.A., Rampim, L., Sarto, M.V.M. 2016. Frações químicas e oxidáveis da matéria orgânica do solo sob diferentes sistemas de manejo, em Latossolo Vermelho. Pesquisa Agropecuária Brasileira, 51, 1529-1538. DOI: https://doi.org/10.1590/s0100-204x2016000900052.

Rosset, J.S., Tavares, O.C H., Pereira, M.G., Carmo Lana, M., Schiavo, J.A., Barros Ozório, J.M., Silva, M.V., Andrade, L. H.C., Lima, S.M. 2023. Chemical and Spectroscopic Characteristics of Humic Acids Under No-Tillage and Forest Systems. Communications in Soil Science and Plant Analysis, 12, 1-18. DOI: https://doi.org/10.1080/00103624.2023.2277415.

Rusca, G.G., Moraes, M.C.P., Valente, R.A., Piña-Rodrigues, F.C.M. 2017. Análise espacial dos fragmentos florestais no entorno de uma unidade de conservação de proteção integral. Brazilian Journal of Environmental Sciences, (44), 85-94. DOI: https://doi.org/10.5327/Z2176-947820170146.

Salton, J.C., Mercante, F.M., Tomazi, M., Zanatta, J.A., Concenço, G., Silva, W.M., Retore, M. 2014. Integrated crop-livestock system in tropical Brazil: Toward a sustainable production system. Agriculture, Ecosystems & Environment, 190, 70-79. DOI: https://doi.org/10.1016/j.agee.2013.09.023.

Santos, H.G., Jacomine, P.K.T., Anjos, L.H.C., Oliveira, V.A., Lumbreras, J.F., Coelho, M.R., Almeida, J.A., Araújo Filho, J.C., Oliveira, J.B., Cunha, T.J.F. 2018. Sistema Brasileiro de Classificação de Solos. 5ª ed. revisada e ampliada. Brasília, DF: Embrapa, 531p.

Santos, S.C., Brito, H.C., Rufino, I.A.A. 2024. Changes in Soil Organic Carbon Stocks Due to Land Use Changes in the Extended São Francisco River Basin. Sociedade & Natureza, 36, e69655. DOI: https://doi.org/10.14393/SN-v36-2024-69655.

Santos, J.A.D.S.; Teodoro, P.E.; Correa, A.M.; Soares, C.M. G.; Ribeiro, L.P.; Abreu, H.K.A.D. 2014. Desempenho agronômico e divergência genética entre genótipos de feijão-caupi cultivados no ecótono Cerrado/Pantanal. Bragantia, 73 (4), 377-382. DOI: https://doi.org/10.1590/1678-4499.0250.

Scolforo, H.F., Scolforo, J.R.S., Mello, C.R., Mello, J.M., Ferraz Filho, A.C. 2015. Spatial distribution of aboveground carbon stock of the arboreal vegetation in Brazilian biomes of Savanna, Atlantic Forest and Semi-Arid Woodland. PLoS One, 10(6), e0128781. DOI: https://doi.org/10.1371/journal.pone.0128781.

Sierra, C.A., del Valle, J.I., Orrego, S.A., Moreno, F.H., Harmon, M.E., Zapata, M., Colorado, G.J., Herrera, M.A., Lara, W., Restrepo, D.E., Berrouet, L.M., Loaiza, L.M., Benjumea, J.F. 2007. Total carbon stocks in a tropical forest landscape of the Porce region, Colombia. Forest Ecology and Management, 243(2-3), 299-309. DOI: https://doi.org/10.1016/j.foreco.2007.03.026.

Silva Júnior, M.C. 2005. 100 Árvores do Cerrado: guia de campo. Brasilia-DF: Rede de sementes do cerrado, 278 p.

Six, J., Bossuyt, H., Degryze, S., Denef, K. 2004. A history of research on the link between (micro) aggregates, soil biota, and soil organic matter dynamics. Soil and tillage research, 79(1), 7-31. DOI: https://doi.org/10.1016/j.still.2004.03.008.

Tisdall, J.M., Oades, J.M. 1982. Organic matter and water-stable aggregates in soils. Journal of soil science, 33(2), 141-163. DOI: https://doi.org/10.1111/j.1365-2389.1982.tb01755.x

Tonucci, R.G., Vogado, R.F., Silva, R.D., Pompeu, R.C.F.F., Oda-Souza, M., Souza, H.A.D. 2023. Agroforestry system improves soil carbon and nitrogen stocks in depth after land-use changes in the Brazilian semi-arid region. Revista Brasileira de Ciência do Solo, 47, e0220124. DOI: https://doi.org/10.36783/18069657rbcs20220124.

Yeomans, J.C., Bremner, J.M. 1988. A rapid and precise method for routine determination of organic carbon in soil. Communications in soil science and plant analysis, 19(13), 1467-1476. DOI: https://doi.org/10.1080/00103628809368027

Zhao, D., Xu, M., Liu, G., Ma, L., Zhang, S., Xiao, T., Peng, G. 2017. Effect of vegetation type on microstructure of soil aggregates on the Loess Plateau, China. Agriculture, ecosystems & environment, 242, 1-8. DOI: https://doi.org/10.1016/j.agee.2017.03.014.