

Edaphic attributes indicative of edge effect in Semideciduous tropical forest

Cristiane Figueira da Silva^a, Rodrigo Camara de Souza^a, Marcos Gervasio Pereira^{b,*},
Luiz Alberto da Silva Rodrigues Pinto^b, Robert Ferreira^b, Maria Elizabeth Fernandes Correia^c,
Carlos Eduardo Gabriel Menezes^d, Marcelo Antoniol Fontes^c, Tiago Paula da Silva^b

^a Instituto de Florestas, Programa de Pós-Graduação em Ciências Ambientais e Florestais, Universidade Federal Rural do Rio de Janeiro, BR 465, Km 7, 2389-000, Seropédica, Rio de Janeiro, Brazil

^b Instituto de Agronomia, Departamento de Solos, Universidade Federal Rural do Rio de Janeiro, BR 465, Km 7, 2389-000, Seropédica, Rio de Janeiro, Brazil

^c Embrapa Agrobiologia, BR 465, Km 7, 2389-000, Seropédica, Rio de Janeiro, Brazil

^d IFRJ - Instituto Federal de Educação, Ciência e Tecnologia do Rio de Janeiro Campus Pinheiral, Rio de Janeiro, Brazil

ARTICLE INFO

Keywords:

Glomalin
Arbuscular mycorrhizal fungi
Soil microbial biomass
Soil enzymatic activity
Edaphic fauna

ABSTRACT

Deforestation of native ecosystems causes microclimatic changes at the edge of the remaining forest fragments. This “edge effect” can modify soil attributes, although there is little information on this. Thus, this study aimed to evaluate the edge effect on soil microclimate conditions, chemical, microbiological and arthropod community attributes and their relationship with litter attributes in a fragment of Semideciduous Seasonal Forest, in Pirai, RJ, Brazil. In the middle of the dry period (June/2019), four ranges of distances parallel to each other were established from the edge of the forest fragment: Edge: 0 m; Range 1: 50 m; Range 2: 100 m; and Interior: 160 m. In each range, five sampling points were established, spaced 10 m apart, where soil samples were collected in the 0–5 cm layer and litter samples. This material was employed to determine microclimatic, chemical and biological (arthropod community and microbiological attributes) attributes of the soil; and litter stock, concentration and content of nutrients. Forest fragmentation altered litter attributes and consequently soil moisture and nutrients, the communities' attributes of soil arthropods and microorganisms. These modifications in such aspects of nutrient cycling could compromise the forest functioning and the conservation of local biodiversity. Thus, we suggested the planting of non-pioneer native tree species in distances closest to the forest edge and installing of ecological corridors to connect the forest fragment to other remnants, in order to diminish the edge effect.

1. Introduction

The Atlantic Forest is a hot spot for biodiversity conservation, due to high endemism and biodiversity, in addition to the large number of species that are threatened with extinction (Myers et al., 2000). Its remaining area is equivalent to less than 12% of its original total area in the country (Ribeiro et al., 2009). In the state of Rio de Janeiro, it is estimated that only 20% of its territory is represented by fragments of Atlantic Forest (Fundação SOS Mata Atlântica and Inpe, 2002). In general, these forest remnants are very small, isolated, disconnected from each other, and whose edge is in contact with the anthropic matrix consisting of agricultural and pasture areas (Tabarelli et al., 2005).

At the edge of forest fragments, the incidence of solar radiation is considerably higher (Wicklein et al., 2012). Thus, higher values of both

air temperature and soil temperature, and lower values of relative humidity features the edge, compared to the interior of forest fragments (Lima-Ribeiro, 2008). This “edge effect” favors the significant mortality of young and adult arboreal individuals (Malchow et al., 2006) and the predominance of pioneer forest species (Lima-Ribeiro, 2008), which results in a decrease in uniformity (Lippok et al., 2014) and diversity (Terra et al., 2018) of the plant community. Consequently, there are changes in the edge-interior gradient of forest fragments, with regard to biodiversity and interactions between species (Laurance et al., 2011), plant composition and richness (Rabelo et al., 2015), litter production and accumulation (Portela and Santos, 2007; Laurance and Vasconcelos, 2009; Machado et al., 2018). This pattern is also observed for soil chemical attributes (Schröder and Fleig, 2017; Terra et al., 2018; Barreto-Garcia et al., 2019) and soil biological attributes (Pereira et al.,

* Corresponding author.

E-mail addresses: cfigueirasilva@yahoo.com.br (C. Figueira da Silva), rcamara73@gmail.com (R. Camara de Souza), mgersvasiopereira01@gmail.com (M.G. Pereira), lrodrigues@yahoo.com.br (L.A. da Silva Rodrigues Pinto), feer.robert@gmail.com (R. Ferreira), correia@embrapa.br (M.E. Fernandes Correia), carlos.menezes@ifrrj.edu.br (C.E. Gabriel Menezes), marcelo.fontes@embrapa.br (M.A. Fontes), tiago8paula6@hotmail.com (T. Paula da Silva).

<https://doi.org/10.1016/j.actao.2021.103776>

Received 28 August 2020; Received in revised form 17 August 2021; Accepted 21 August 2021

Available online 27 August 2021

1146-609X/© 2021 Elsevier Masson SAS. All rights reserved.

2013; Santos et al., 2018). These changes between the edge and interior of tropical forests, which may be more impactful than those observed along an elevational gradient (Lippok et al., 2014), can be used to define edge effect indicators, capable of reflecting the conservation status of forest fragments (Machado et al., 2018; Santos et al., 2018).

There are still few studies aimed at evaluating the edge effect on soil attributes (chemical, physical and biological) and their relationship with litter in Atlantic Forest fragments. Therefore, it is important to conduct more studies with this approach, as they can contribute to the knowledge on these dynamics and decision-making in relation to the preservation, conservation and recovery of the biodiversity of this biome.

According to the literature, the edge effect alters the structure and composition of the plant community and improves the soil fertility in distances closest to the forest edge. Thus, we tested the hypothesis that the higher soil fertility in distances closest to the forest edge is a consequence of modifications in the litter attributes (stock and nutrients), which in turn alters soil biological attributes. Thus, the objective of the present study was to evaluate soil chemical, microbiological and arthropod community attributes and their relationship with the stock and chemical quality of litter, as indicators of the edge effect in a fragment of Semideciduous Seasonal Forest.

2. Material and methods

2.1. Study site and plot sampling

The fragment of Semideciduous Seasonal Forest in which the study was conducted is located at the geographical coordinates 22° 40' 05.2" S and 43° 50' 52.0" W, in the municipality of Pirai, State of Rio de Janeiro, Brazil. According to Köppen's classification, the climate of the region is Cwa, i.e. subtropical humid with dry winter and hot summer (Alvares et al., 2013).

From the edge towards the interior of the forest fragment, we delineated four parallel ranges: (1) Edge: 0 m; (2) Range 1: 50 m; (3) Range 2: 100 m; and (4) Interior: 160 m, in the middle of the dry season (June) of 2019. In each of the ranges, five sampling points were established, spaced approximately 10 m apart, to: (a) record soil temperature at 0–5 cm depth; (b) collect composite soil samples at 0–5 cm depth; (c) collect individual soil samples at 0–5 cm depth; and (d) collect the litter layer disposed on the soil surface.

2.2. Soil sampling and measurements

The soil temperature was determined in the field using a digital soil thermometer. The composite soil samples, each formed by three individual samples, were collected with an auger. The individual soil samples were collected using a specific metal probe similar to a barrel auger, whose soil containment structure had height of 17.5 cm and diameter of 8 cm. We collected the litter layer circumscribed in a collector with area of 0.0625 m². All the collected material was transferred to properly identified plastic bags and transported to the laboratory for analysis.

The composite soil samples were used to determine the soil water content, soil fertility, arbuscular mycorrhizal fungi community, soil microbial biomass, and total enzymatic activity. We first determined the soil water content in a subsample. Then, the rest of the composite soil samples were air-dried, pounded to break up clods and homogenized. A subsample of 50 g of the composite soil samples was used for the extraction of the arbuscular mycorrhizal fungi (AMF) spores. The rest of the soil composite samples were passed through a 2.0-mm-mesh sieve, thus obtaining air-dried fine earth (ADFE). Subsequently, subsamples of this material were used to determine total organic carbon (TOC), pH and the sorption complex (P, K⁺, Ca²⁺, Mg²⁺, Na⁺, Al³⁺, H⁺+Al³⁺). The individual soil samples were collected to evaluate the soil arthropod community. The litter layer, after drying in a forced air circulation oven (65 °C, 72 h), was weighed to determine its stock (dry mass) and concentrations of nutrients.

2.3. Soil and litter layer attributes analysis

The soil water content was determined by the gravimetric method (Donagemma et al., 2011). The sorption complex (P, K⁺, Ca²⁺, Mg²⁺, Na⁺, Al³⁺, H⁺+Al³⁺), which was used to calculate the values of the sum of exchangeable bases or cations (S Value), base saturation (V Value) and cation exchange capacity (T Value), and pH in water at 1:2.5 ratio (soil: water) were determined according to Donagemma et al. (2011). The TOC was determined according to Yeomans and Bremner (1988).

The spores of the AMF were extracted using the techniques of decanting and wet sieving (Gerdemann and Nicolson 1963), followed by centrifugation in water and sucrose (45%) (Jenkins, 1964). The spores were counted on textured-bottom plates, under stereo microscope, with subsequent identification of the species under optical microscope, according to the morphological characteristics of the spores (INVAM, 2019; CIGG, 2021), in order to estimate the spores abundance (SA). The relative frequency of occurrence (Fi) of AMF species was estimated, expressed by the number of replicates in which a given species was isolated, in relation to the total number of replicates.

Glomalin-related soil protein (easily extractable-GRSP and total-GRSP) was evaluated on the ADFE samples (Wright and Updhyaya, 1998). Each of the fractions was extracted using 1.0 g of soil. Easily extractable-GRSP (EE-GRSP) was obtained from extraction in autoclave using 8 mL of 20 mM sodium citrate solution at pH 7.4, at temperature of 121 °C for 30 min. The amount of total-GRSP (T-GRSP) was determined using 8 mL of 50 mM sodium citrate, with pH 8.0 at 121 °C, for 60 min. To extract this fraction, more than one autoclaving cycle was performed, when necessary, until the samples reached a yellow-light color. In both fractions, after autoclaving, the material obtained was centrifuged at 4000 rpm for 20 min. In the supernatant, glomalin was quantified by the method of Bradford (1976) modified by Wright et al. (1996), available at the website www.usda.gov, using bovine serum-albumin as standard. Glomalin concentrations for both fractions were corrected to mg g⁻¹ of soil considering the total volume of supernatant and the dry mass of the soil.

The total microbial activity of the soil was quantified through the respiration method (CO₂ released) (Jenkinson et al., 1981), while carbon of soil microbial biomass (C-SMB) was evaluated by the fumigation-incubation method (De-Polli and Guerra, 1999). Microbial indices, microbial quotient (qMIC) and metabolic quotient of the soil, were also determined (Anderson and Domsch, 1993).

Enzyme activity was evaluated by quantifying the hydrolysis of fluorescein diacetate (FDA) (Schnurer and Rosswal, 1982). One gram of ADFE was transferred to 50-mL flasks, which received 20 mL of 60 mM sodium phosphate buffer (SPB) at pH 6.0, and shaken for 15 min. Then, 100 µL of fluorescein diacetate (substrate) were added. After shaking for 2 h, 1 mL was collected and transferred to a 2.5-mL Eppendorf tube, using 1 mL of acetone to stop the reaction. Colorimetric determination was performed in a spectrophotometer at 490 nm.

The individual soil samples obtained with the metal probe were inserted into a set of slightly modified Berlese-Tullgren funnels (Garay, 1989), for the extraction and quantification of the soil arthropods. These organisms were then identified in major taxonomic groups (class, order, family), according to other studies (Menezes et al., 2009; Camara et al., 2012, 2017, 2018; 2018; Pereira et al., 2013; Ferreira et al., 2017, 2018; Corrêa Neto et al., 2018). Thus, the following parameters were obtained: total number of individuals extracted; relative participation (%) of each taxonomic group in the community; richness (total number of taxonomic groups); uniformity (U, Pielou index); and diversity (H', Shannon index). The indexes mentioned above were calculated according to Odum (1988).

The litter stock (dry mass, g) was converted to Mg ha⁻¹. Subsequently, this material was ground, and subsamples were subjected to sulfuric digestion (Tedesco et al., 1995), for the quantification of the concentrations (g kg⁻¹) of N, P, and K. Then, we estimated the content of N, P, and K (kg ha⁻¹) by the product obtained between the litter stock

and the nutrient concentration.

2.4. Data analysis

The homogeneity of the variance of the results for the attributes considered was evaluated by the Levene test ($p < 0.05$). When this premise was met, the means were compared by the Tukey parametric test ($p < 0.05$) and, when this did not occur, the means were compared by the Kruskal-Wallis nonparametric test ($p < 0.05$). Pearson's correlations were also performed to verify the effect of ranges from the edge towards the interior of the forest fragment and of each of the attributes considered on the others. These univariate statistical analyses were performed using version 8.0 of the program STATISTICA.

Additionally, the mean values of all the soil (water content, fertility, arbuscular mycorrhizal fungi community, microbial biomass, total enzymatic activity, arthropod community), and litter layer (stock, nutrient concentrations, nutrient contents) attributes were used to perform multivariate analyses to assist in the interpretation of the influence of the edge effect on the set of soil attributes. We first performed the multivariate analyses considering the attributes of soil arthropod community, microclimatic soil conditions, soil chemical attributes and litter attributes. Later, we carried out the multivariate analyses considering the microbiological attributes (AMF and microbial biomass, and secondly, total enzymatic activity), microclimatic soil conditions, soil chemical attributes and litter attributes.

In the principal components analysis (PCA), which was carried out to identify associations among the ranges delineated at the four ranges from the edge towards the interior of the forest fragment and both the soil and litter attributes, we considered only the attributes that had high values of correlation (>0.70) with the principal components 1 or 2. Subsequently, we used the same selected attributes from PCA to perform the hierarchical clustering analysis (HCA) by Single Linkage or nearest neighbor and Gower similarity coefficient, in order to identify dissimilarities among the four ranges from the edge towards the interior of the forest fragment. These multivariate analyses were performed with version 2.17c of the program Paleontological Statistics (PAST).

3. Results

3.1. Soil microclimatic (temperature, water content) and litter layer attributes

We did not observe any significant differences among the four ranges from the edge towards the interior of the forest fragment, in terms of microclimatic soil conditions and the litter layer attributes (Table 1).

3.2. Chemical attributes of the soil

The highest values of pH, Ca^{2+} , Mg^{2+} , S Value and V Value were observed at the Edge and/or in Range 1 (ranges of 0 and 50 m from the forest edge, respectively), compared to the areas of Range 2 and Interior of the forest fragment (ranges of 100 and 160 m from the forest edge, respectively) (Table 2). However, in the case of Al^{3+} , the opposite pattern was observed, since the highest values of this attribute were

Table 2

Values of pH, P, K^+ , Ca^{2+} , Mg^{2+} , Na^+ , Al^{3+} and $\text{H}^+ + \text{Al}^{3+}$ contents, sum of exchangeable bases (S Value), cation exchange capacity (T Value), base saturation (V Value), and total organic carbon (TOC) of the surface layer (0–5 cm) at different ranges from the edge towards the interior, in a fragment of Semi-deciduous Seasonal Forest in Pirai, Rio de Janeiro, Brazil*.

Range (distance from the edge, m)	pH (H ₂ O)	TOC	P	K ⁺	Ca ²⁺	Mg ²⁺
		g kg ⁻¹	mg kg ⁻¹	cmol _c kg ⁻¹		
Edge (0 m)	4.90 a	36.23 a	3.36 a	0.04 a	2.10 a	1.57 a
Range 1 (50 m)	4.54 ab	39.31 a	3.53 a	0.05 a	1.68 ab	1.31 ab
Range 2 (100 m)	4.25 b	31.24 a	3.20 a	0.04 a	0.83 ab	0.80 ab
Interior (160 m)	4.19 b	26.11 a	2.72 a	0.03 a	0.69 b	0.62 b
Range (distance from the edge, m)	Na ⁺	Al ³⁺	H ⁺ + Al ³⁺	S Value	T Value	V Value
	cmol _c kg ⁻¹					%
Edge (0 m)	0.02 a	0.34 b	6.20 a	3.74 a	9.94 a	37.02 a
Range 1 (50 m)	0.02 a	0.60 ab	7.29 a	3.06 a	10.35 a	29.23 a
Range 2 (100 m)	0.02 a	1.06 a	6.99 a	1.68 b	8.68 a	19.73 b
Interior (160 m)	0.13 a	0.88 ab	6.37 a	1.47 b	7.84 a	18.38 b

*Mean values obtained from five replicates, followed by the same letter in the column, do not differ by Tukey or Kruskal-Wallis test at 5%.

observed in Range 2 (100 m from the forest edge), in comparison to the Edge (0 m) (Table 2). There were no significant differences between the ranges from the forest edge for the other chemical attributes of the soil (TOC, P, K, Na^+ , $\text{H}^+ + \text{Al}^{3+}$, and T Value) (Table 2).

We verified significant ($p < 0.05$) and negative correlations between the distance from the edge and pH ($r = -0.87$), soil available P ($r = -0.48$), K^+ ($r = -0.49$), Ca^{2+} ($r = -0.66$), Mg^{2+} ($r = -0.74$), TOC ($r = -0.50$), S Value ($r = -0.70$), and V Value ($r = -0.78$). Additionally, some chemical soil attributes presented significant and positive correlations with litter stock. This pattern was observed for pH ($r = 0.56$), available P ($r = 0.49$), Ca^{2+} ($r = 0.60$), Mg^{2+} ($r = 0.47$), S Value ($r = 0.56$), V Value ($r = 0.52$), and TOC ($r = 0.50$). The Al^{3+} presented significant and positive correlation with the distance from the forest edge ($r = 0.62$), whereas this same attribute presented significant and negative correlation with the litter stock ($r = -0.50$).

3.3. Soil arthropod community

In total for the forest fragment, 666 arthropods were collected from the soil (133.2 individuals, for the mean among the replicates), distributed in 18 taxonomic groups (total richness). Among them, prevailed Acari, Formicidae, Entomobryomorpha, and Coleoptera (50.9%, 30.0%, 6.6%, and 3.6% of relative participation in the community, respectively), whose set represented approximately 91.1% of all individuals collected in the community (Table 3). For the study area in

Table 1

Temperature (Temp), gravimetric moisture (Ug) of the surface layer (0–5 cm), stock, concentration (Conc) and total content (Cont) of nutrients (N, P, K) of the litter accumulated on the soil surface, at different ranges from the edge towards the interior, in a fragment of Semideciduous Seasonal Forest in Pirai, Rio de Janeiro, Brazil.

Range (distance from the edge, m)	Temp	Ug	Stock	ConcN	ConcP	ConcK	ContN	ContP	ContK
	°C	g g ⁻¹	Mg ha ⁻¹	g kg ⁻¹			kg ha ⁻¹		
Edge (0 m)	21.7 (0.4)*	10.08 (3.31)	9.54 (2.94)	1.27 (0.50)	0.35 (0.06)	0.19 (0.06)	11.47 (4.59)	3.22 (0.62)	1.66 (0.26)
Range 1 (50 m)	21.7 (0.1)	9.98 (1.18)	9.65 (4.92)	0.71 (0.26)	0.35 (0.02)	0.17 (0.04)	7.04 (4.26)	3.39 (1.74)	1.57 (0.71)
Range 2 (100 m)	21.6 (0.2)	9.46 (2.23)	7.03 (3.02)	1.00 (0.22)	0.36 (0.04)	0.14 (0.02)	7.19 (4.04)	2.57 (1.34)	1.00 (0.45)
Interior (160 m)	21.9 (0.1)	8.52 (2.68)	6.23 (2.14)	1.02 (0.22)	0.38 (0.02)	0.15 (0.02)	6.51 (3.09)	2.39 (0.86)	0.96 (0.39)

*Standard deviation in parentheses.

Table 3

Relative participation (%) of the taxonomic groups, total richness (TR), uniformity (Unif) and diversity (Diver) of the soil arthropod community at different ranges from the edge towards the interior, in a fragment of Semideciduous Seasonal Forest, Pirai, Rio de Janeiro, Brazil*.

Range (distance from the edge, m)	Aca	Ara	Chi	Col	Dpd	Dpl	Ent	For	Hym	Isp	Ipt
Edge (0 m)	49.5	2.3	0.9	5.0	0.5	1.8	5.4	29.3	0.0	0.5	0.5
Range 1 (50 m)	33.6	0.0	0.0	2.5	0.0	0.8	7.4	50.8	0.8	0.0	1.6
Range 2 (100 m)	35.8	0.0	1.2	1.2	1.2	3.7	9.9	40.7	0.0	0.0	1.2
Interior (160 m)	66.0	0.4	1.2	3.7	0.4	2.1	6.2	16.6	0.0	0.4	0.0
Total	50.9	0.9	0.9	3.6	0.5	2.0	6.6	30.0	0.2	0.3	0.6
Range (distance from the edge, m)	LCol	LDipt	LLep	Pse	Sym	Spl	Thy	Tot	TR	Unif	Diver
Edge (0 m)	0.9	2.7	0.0	0.0	0.5	0.5	0.0	44.4	14	0.56	2.13
Range 1 (50 m)	0.0	0.0	0.8	0.8	0.0	0.0	0.8	24.4	10	0.55	1.82
Range 2 (100 m)	0.0	3.7	0.0	0.0	1.2	0.0	0.0	16.2	10	0.64	2.13
Interior (160 m)	0.4	1.2	0.0	0.0	1.2	0.0	0.0	48.2	12	0.48	1.74
Total	0.5	1.8	0.2	0.2	0.8	0.2	0.2	133.2	18	0.49	2.05

Aca: Acari; Ara: Araneae; Chi: Chilopoda; Col: Coleoptera; Dpd: Diplopoda; Dpl: Diplura; Ent: Entomobryomorpha; For: Formicidae; Hym: Hymenoptera; Isp: Isopoda; Ipt: Isoptera; LCol: larvae of Coleoptera; LDipt: larvae of Diptera; LLep: larvae of Lepidoptera; Pse: Pseudoscorpionida; Sym: Symphyla; Spl: Symphypleona.

*Mean values obtained from five replicates.

general, the values of uniformity and diversity were equal to 0.49 and 2.05, respectively.

More than half (approximately 56%) of the taxonomic groups of soil arthropods showed higher relative participation at the Edge (0 m) and/or in Range 1 (50 m from the forest edge) (Table 3). These groups included Araneae, Coleoptera, Formicidae, Hymenoptera, Isoptera, Pseudoscorpionida, Symphypleona, Thysanoptera, larvae of Coleoptera, and larvae of Lepidoptera. On the other hand, approximately 39% of the taxonomic groups, including Acari, principally, Chilopoda, Diplopoda, Diplura, Entomobryomorpha, Symphyla, and larvae of Diptera, showed higher relative participation in Range 2 and/or Interior (100 and 160 m from the forest edge, respectively). There was no pattern of modification in the relative participation of Isopoda, along the gradient of ranges of distance from the forest edge.

Significant ($p < 0.05$) and positive correlations were verified between the relative participation of Isopoda in the soil arthropod community and the N content in the litter ($r = 0.49$) and between the relative participation of Coleoptera larvae and K content in the litter ($r = 0.55$). This same pattern of significant and positive correlation were verified between the relative participation of Araneae and soil pH ($r = 0.51$), Ca^{+2} content ($r = 0.74$), Mg^{+2} content ($r = 0.52$), S Value ($r = 0.68$), and V Value ($r = 0.68$) in the soil. The relative participation of Isoptera also presented significant and positive correlation with total organic carbon content ($r = 0.47$). However, significant and negative correlations were observed between the relative participation of Symphyla and gravimetric moisture ($r = -0.54$), and between the relative participation of Isoptera and N content in the litter ($r = -0.45$).

Total richness presented higher value at the Edge (0 m) when compared to the other ranges of distance towards the interior of the forest fragment (Table 3). In contrast, we did not observe a clear pattern of edge effect on the uniformity index (higher in Range 2 and lower in the Interior), diversity index (higher values both in Edge and Range 2, and lower in the Interior), and total number of individuals (higher in the

Interior and lower in Range 2) in the soil arthropod community.

3.4. Microbial biomass, GRSP and total enzymatic activity

Carbon of soil microbial biomass (C-SMB), total - glomalin related soil protein (T-GRSP), and soil basal respiration (SBR), in general, were higher at the Edge (0 m) when compared to the interior (160 m from the forest edge) (Table 4). In contrast, the total enzymatic activity evaluated by the quantification of the fluorescein diacetate hydrolysis (FDA) presented higher values in Range 2 and in the Interior of the forest fragment (100 and 160 m, respectively), when compared to the Edge and Range 1 (0 and 50 m, respectively) (Table 4). The values of easily extractable - glomalin related soil protein (EE-GRSP), metabolic quotient (qCO_2), and microbial quotient (qMIC) did not differ significantly among the ranges from the forest edge (Table 4).

The distance from the edge was significantly ($p < 0.05$) and negatively correlated with C-SMB ($r = -0.68$), T-GRSP ($r = -0.70$), EE-GRSP ($r = -0.53$) and SBR ($r = -0.49$). Additionally, C-SMB was significantly and positively correlated with litter stock ($r = 0.46$), pH ($r = 0.68$), Ca^{2+} ($r = 0.60$), Mg^{2+} ($r = 0.50$), and TOC ($r = 0.48$) in the soil. On the other hand, SBR showed a significant and negative correlation with the N content in the litter ($r = -0.52$) and a significant and positive correlation with Ca^{2+} ($r = 0.58$), Mg^{2+} ($r = 0.57$), and TOC ($r = 0.57$).

There were significant and positive correlations between GRSP fractions and some attributes, such as litter stock (EE-GRSP and T-GRSP; $r = 0.63$ and 0.67 , respectively), pH (EE-GRSP and T-GRSP; $r = 0.49$ and 0.71 , respectively), Ca^{2+} (EE-GRSP and T-GRSP; $r = 0.62$ and 0.84 , respectively), Mg^{2+} (EE-GRSP and T-GRSP; $r = 0.49$ and 0.69 , respectively), P (EE-GRSP and T-GRSP; $r = 0.70$ and 0.59 , respectively), and TOC (EE-GRSP and T-GRSP; 0.63 and 0.73) in the soil. We also observed significant and negative correlation between T-GRSP and P content in the litter ($r = -0.50$).

There were significant ($p < 0.05$) and positive correlation between

Table 4

Carbon of soil microbial biomass (C-SMB), soil basal respiration (SBR), metabolic quotient (qCO_2), microbial quotient (qMIC), easily extractable - glomalin related soil protein (EE-GRSP), total - glomalin related soil protein (T-GRSP), hydrolysis of fluorescein diacetate (FDA), and total richness (TR) and spore abundance (SA) of the AMF at different ranges from the edge towards the interior, in a fragment of Semideciduous Seasonal Forest, Pirai, Rio de Janeiro, Brazil*.

Range	C-SMB	SBR	qCO_2	qMIC	EE-GRSP	T-GRSP	TR	SA	FDA
(distance from the edge, m)	mg Cmic kg ⁻¹	Mg C-CO ₂ kg ⁻¹ h ⁻¹	mg C-CO ₂ g ⁻¹ C-SBM h ⁻¹	%	mg g ⁻¹			n. spores 50 g ⁻¹	µgFluoresc g ⁻¹ SS hour ⁻¹
Edge (0 m)	230.50 a	1.04 ab	4.62 a	0.61 a	2.48 a	4.26 a	9	190 c	84.00 b
Range 1 (50 m)	195.60 ab	1.23 a	6.85 a	0.53 a	2.69 a	3.52 ab	11	281 bc	83.21 b
Range 2 (100 m)	148.75 ab	0.80 b	5.89 a	0.52 a	2.24 a	2.21 ab	10	399 ab	97.66 a
Interior (160 m)	132.25 b	0.84 b	6.55 a	0.56 a	1.93 a	1.66 b	9	476 a	96.09 a

* Mean values obtained from five replicates followed by the same letter in the column do not differ by Tukey test.

the distance from the edge and FDA ($r = 0.76$) and significant and negative correlation between FDA and pH ($r = -0.79$), P ($r = -0.54$), K^+ ($r = -0.60$), Ca^{2+} ($r = -0.59$), Mg^{2+} ($r = -0.69$), and TOC ($r = -0.53$) in the soil.

3.5. Community of arbuscular mycorrhizal fungi

The AMF spore abundance (SA) showed the similar pattern that was observed for the FDA, whose values were higher in the Interior (160 m from the forest edge) compared to the values observed in the Edge and Range 1 (0 and 50 m, respectively) (Table 4). While total richness (TR) tended to present higher values in the intermediate ranges from the edge, towards the forest interior (0 and 50 m, respectively) (Table 4). There was a significant ($p < 0.05$) and positive correlation between the distance from the edge and the SA ($r = 0.84$). We also verified significant and negative correlation between SA and pH ($r = -0.77$), K^+ ($r = -0.54$), Ca^{2+} ($r = -0.53$), and Mg^{2+} ($r = -0.53$) in the soil.

A total of 12 species of AMF belonging to six genera and five families were identified in the forest fragment (Table 5). The largest number of species belongs to the genus *Glomus* (5), followed by *Acaulospora* (3), *Ambispora* (1), *Cetraspora* (1), *Sieverdingia* (1), and *Rhizoglossum* (1).

Half of the collected FMA species occurred at all distances from the edge towards the forest interior, with some variation among them regarding the RFO of the species (Table 5). The exception was observed for *Sieverdingia tortuosa* and *Glomus macrocarpum*, which showed no variation for the RFO, when comparing the distances from the forest edge. There were three patterns, regarding the RFO of the species. The RFO increased, along the distance gradient from the edge to the interior of the forest fragment, for *Acaulospora mellea*, which did not occur at the edge, and *Acaulospora foveata*. The FRO of *Glomus* sp. 2, which did not occur at the edge, *Cetraspora pellucida*, *Glomus claviformis*, and *Glomus glomerulatum* tended to be higher in at least one of the intermediate distances from the edge (Range 1 and/or Range 2), in the referred gradient. The species *Acaulospora laevis* was collected only at Range 2, with a low FRO value. For the species *Acaulospora leptoticha* and *Rhizoglossum microaggregatum*, there was not no clear pattern in relation to the RFO.

We registered significant ($p > 0.05$) and positive correlations between the RFO of AMF species with some soil chemical attributes. This pattern occurred between the RFO of *Glomus* sp1 and the contents of Ca^{2+} ($r = 0.61$), Mg^{2+} ($r = 0.58$), S Value ($r = 0.61$), T Value ($r = 0.45$), V Value ($r = 0.55$), and TOC ($r = 0.58$). The RFO of *C. pellucida* also presented significant and positive correlations with P ($r = 0.62$),

whereas both RFO of *A. laevis* and *A. mellea* significantly and positively correlated with Al^{3+} ($r = 0.47$ and 0.53 , respectively). On the other hand, significant and negative correlations were found between the RFO of *A. mellea* and soil P ($r = -0.52$); and between the RFO of *S. tortuosa* and TOC ($r = -0.48$) and T Value ($r = -0.45$).

The hierarchical cluster analysis indicated changes in the RFO of AMF species, in the comparison among the ranges from the edge towards the interior of the forest fragment. The composition of the AMF community in the interior (160 m from the edge of the forest) showed dissimilarity around 60%, in relation to the community registered in the other ranges (Fig. 2). In turn, the composition of the AMF community in the Edge (0 m) showed dissimilarity of approximately 50%, in relation to the community observed in the intermediate ranges (Ranges 1 and 2, respectively at 50 and 100 m from the edge of the forest).

3.6. Influence of the edge effect on the set of soil attributes

The hierarchical cluster analysis (HCA), which considered the attributes of soil arthropod community, gravimetric soil moisture, soil chemical attributes and litter attributes, indicated the individualization between the ranges from the forest edge towards the interior, in three clusters (Fig. 1A). The first cluster was represented by the Edge (0 m), the second by Range 1 (50 m from the forest edge) and the third cluster was formed by the combination between Range 2 and the Interior (ranges of 100 and 160 m from the forest edge, respectively). For the Edge, there was a dissimilarity of approximately 52% in relation to the distance closest to it (Range 1). On the other hand, the dissimilarity of the Edge in relation to Range 2 and the Interior was comparatively higher (about 68%).

Principal component analysis indicated the refinement of the individualization among the ranges from the edge towards the forest interior (Fig. 1B). The relationship between principal components 1 and 2 explained a total of approximately 95% of the data variability. Considering the principal component 1 (main axis), which explained most of the data variability, in comparison with principal component 2 (approximately 58% and 36%, respectively), the areas closest to the forest edge (Edge and Range 1, respectively 0 and 50 m from the forest edge) were positioned on the right (eigenvectors with positive values). On the other hand, the most distant areas from the forest edge (Range 2 and Interior, respectively 100 and 160 m) were positioned on the left (eigenvectors with negative values). Based on the positioning of the areas in Fig. 1B, it was found that the environments were arranged in an increasing gradient of distance from the forest edge, in the sequence Edge, Range 1, Range 2 and Interior (0, 50, 100 and 160 m, respectively), from the left.

The ranges closest to the forest edge (Edge and Range 1, respectively 0 m and 50 m) were associated with higher values of total richness, total number of soil arthropods, relative participation of Coleoptera (larvae and adult individuals), Formicidae, Isopoda, Isoptera, and Symphyleona in the total community (Fig. 1B). This same pattern of higher values in the ranges closest to the forest edge occurred for litter stock, gravimetric soil moisture, N and K concentrations in the litter stock, N, P and K contents in the litter stock, and fertility of the soil surface layer, which included pH, soil available P, K^+ , Ca^{2+} , Mg^{2+} , sum of bases, base saturation, cation exchange capacity, and TOC). On the other hand, the most distant areas from the edge (Range 2 and Interior, respectively 100 and 160 m from the forest edge) were associated with higher values of relative participation of Entomobryomorpha and Symphyla, P concentration in the litter, Al^{3+} and $H^+ + Al^{3+}$.

The results of HCA and PCA integrating the microclimatic data, chemical and microbiological attributes of the soil, as well as the attributes of the litter, can be visualized in Fig. 3. The dendrogram of the HCA shows the formation of two clusters with a dissimilarity around 50% between them (Fig. 3A). The first cluster was formed by the innermost ranges (Range 2 and Interior, respectively 100 and 160 m from the forest edge) and the second cluster, by the outermost ranges

Table 5

Frequency of occurrence (%) of AMF species at different ranges from the edge towards the interior, in a fragment of Semideciduous Seasonal Forest, Pirai, Rio de Janeiro, Brazil.

AMF species	Edge (0 m)	Range 1 (50 m)	Range 2 (100 m)	Interior (160 m)
ACAULOSPORACEAE				
<i>Acaulospora laevis</i>	–	–	20	–
<i>Acaulospora foveata</i>	40	40	60	60
<i>Acaulospora mellea</i>	–	20	40	60
AMBISPORACEAE				
<i>Ambispora leptoticha</i>	40	20	40	20
GIGASPORACEAE				
<i>Cetraspora pellucida</i>	60	80	80	–
DIVERSISPORACEAE				
<i>Sieverdingia tortuosa</i>	60	60	60	60
GLOMERACEAE				
<i>Glomus claviformis</i>	40	20	60	40
<i>Glomus glomerulatum</i>	40	60	80	60
<i>Glomus macrocarpum</i>	100	100	100	100
<i>Rhizoglossum microaggregatum</i>	60	20	–	60
<i>Glomus</i> sp1	40	40	–	–
<i>Glomus</i> sp 2	–	40	20	20

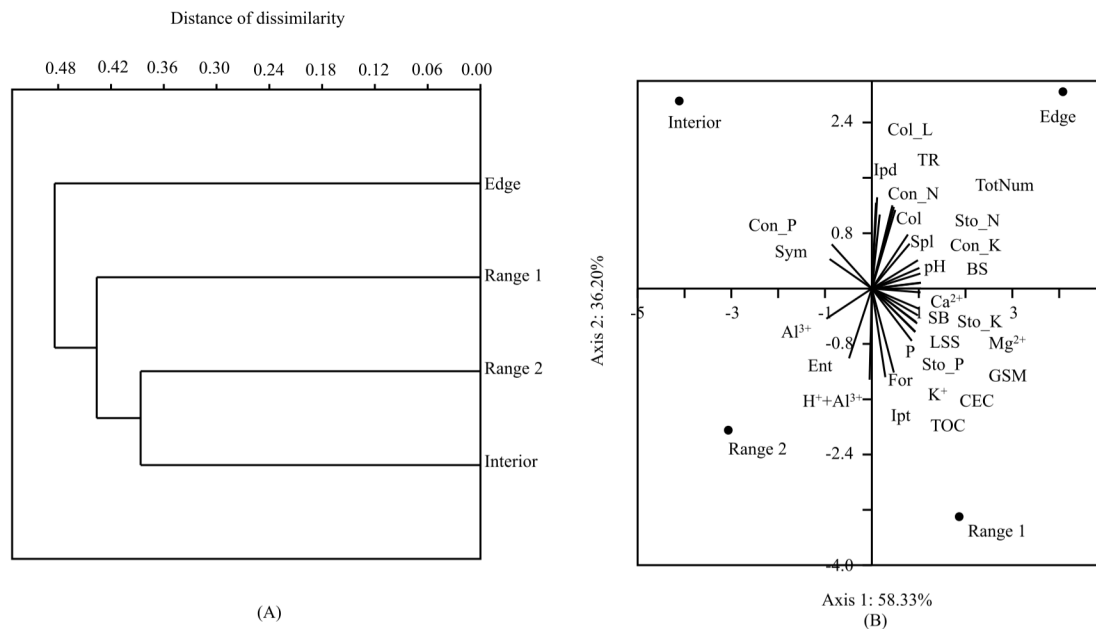


Fig. 1. Principal component analysis (A) and hierarchical cluster analysis (B) considering the gravimetric soil moisture (GSM), soil chemical attributes, litter attributes and soil arthropod community attributes in different ranges of distance from the edge (Edge: 0 m; Range 1: 50 m; Range 2: 100 m; Interior: 160 m), in a fragment of Semideciduous Seasonal Forest, Pirai, Rio de Janeiro, Brazil. Total soil organic carbon content (TOC); Sum of bases (SB); Base saturation (BS); Cation exchange capacity (CEC); Litter standing stock (LSS); litter concentration and stock of nutrients (Con_N, P, K; Sto_N, P, K, respectively); Total number of individuals (TotNum) and total richness of taxonomic groups (TR) in the soil arthropod community; relative participation (%) of Coleoptera (Col), Entomobryomorpha (Ent), Formicidae (For), Isopoda (Ipd), Isoptera (Ipt), Larvae of Coleoptera (LCol), Symphyla (Sym), Symphypleona (Spl).

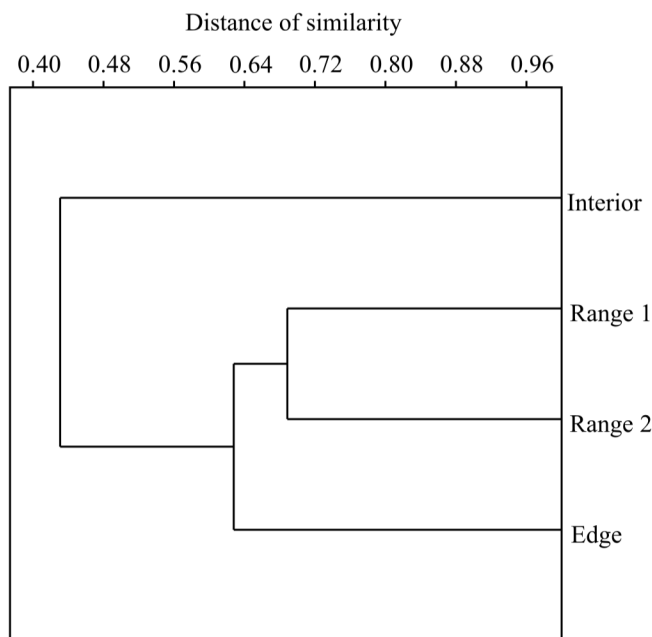


Fig. 2. Hierarchical cluster analysis for the frequency of occurrence of AMF species at different ranges from the edge towards the interior (Edge: 0 m; Range 1: 50 m; Range 2: 100 m; Interior: 160 m), in a fragment of Semideciduous Seasonal Forest, Pirai, Rio de Janeiro, Brazil.

(Edge and Range 1, respectively 0 and 50 m) (Fig. 3A).

The PCA (Fig. 3B) confirms the HCA (Fig. 3A), showing the variables that most contributed to the separation between these two groups. The distributions of the attributes had accumulated variance of 92.16% for components 1 and 2 (Fig. 3B). Most of the variables were positively correlated (>0.70) with axis 1, which best explains (69.63%) the dissimilarity between the ranges and were associated with Edge and

Range 1 (0 and 50 m, respectively), which are located in the upper and lower right quadrants. On the other hand, Range 2 and Interior (100 and 160 m from the forest edge, respectively) were positioned on the opposite side, i.e., in the upper and lower left quadrants, and were associated with the variables Al³⁺, Na⁺, SA and P content in the litter, which were negatively correlated (>-0.70) with axis 1.

4. Discussion

In general, the analysis of the set of results obtained for the chemical attributes of soil and litter stock, as well as the community of edaphic arthropods, indicated an intermediate dissimilarity (around 50%) between the Edge and the distance closest to it (Range 1, 50 m from the forest edge) and a high dissimilarity (around 70%) between the Edge and the group formed by the Interior (160 m from the forest edge) and the range closest to the Interior (Range 2, 100 m). In addition, the principal component analysis and correlation test indicated the following general patterns: (1) the forest edge (0 m) and/or the range of distance closest to the edge (50 m) were associated with higher values of pH, Ca²⁺, Mg²⁺, K⁺, available P, sum of bases, base saturation, cation exchange capacity, TOC content and gravimetric soil moisture in the surface layer (0–5 cm); total richness of the soil arthropod community; relative participation of Araneae, Coleoptera (larvae and adults), Formicidae, Hymenoptera, Isoptera, Lepidoptera larvae, Pseudoscorpionida, Symphypleona and Thysanoptera; litter layer stocks; N and K contents and N, P and K stocks in the litter layer; (2) the forest interior (160 m) and/or the range of distance closest to the interior (100 m) were associated with higher values of Al³⁺; P concentration in the litter layer; total number of soil arthropod community, relative participation of Acari, Chilopoda, Diplopoda, Diplura, Entomobryomorpha, Symphyla and Diptera larvae; (3) the forest interior (160 m) was associated with lower values of uniformity and diversity of the edaphic arthropod community.

In an area of Deciduous Seasonal Forest in the municipality of Santa Maria, State of Rio Grande do Sul, there was also an increase in pH, Ca, P and organic matter in the soil (0–20 cm depth), from the edge to the

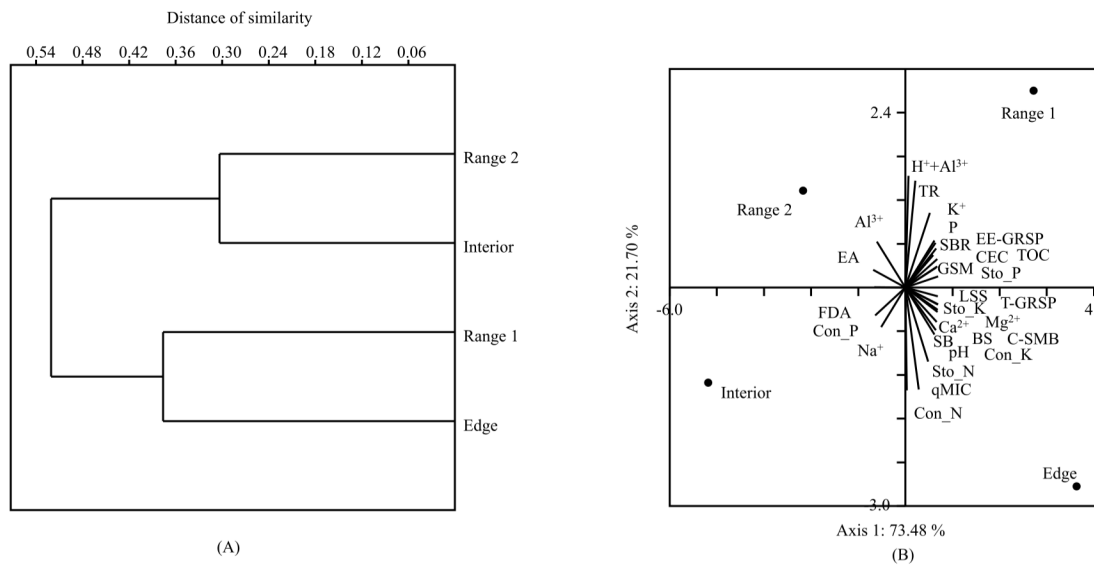


Fig. 3. Hierarchical cluster analysis (A) and principal component analysis (B) considering gravimetric soil moisture (GSM), chemical and microbiological attributes of the soil, TOC and litter attributes at different ranges from the edge towards the interior (Edge: 0 m; Range 1: 50 m; Range 2: 100 m; Interior: 160 m), in a fragment of Semideciduous Seasonal Forest, Pirai, Rio de Janeiro, Brazil. Total soil organic carbon content: TOC; Sum of bases: SB; Base saturation: BS; Cation exchange capacity: CEC; litter standing stock: LSS; litter concentration and stock of nutrients: Con_N, P, K; Sto_N, P, K, respectively. Assay for fluorescein diacetate: FDA; Carbon - soil microbial biomass: C-SMB; Spore abundance: SA; Total richness: TR; Microbial quotient: qMIC; Glomalin-related soil protein (easily extractable and total): EE-GRSP and T-GRSP, respectively.

distance of 50 m, whose values did not change as a function of the increase in the distance towards the interior of the forest fragments, due to changes in vegetation structure (Schröder and Fleig, 2017). The influence of vegetation was corroborated in studies conducted in a fragment of Semideciduous Seasonal Forest in Vitória da Conquista, in the interior of Bahia, since higher pH values in the surface soil layer (0–5 cm) at the edge (0–10 m) were significantly and positively correlated with the absolute density of the tree community, compared to the distance ranges of 40–50 m, 80–90 m and 400–410 m from the edge (Barreto-Garcia et al., 2019). In an area of Seasonal Forest in Pouso Alegre, in the interior of Minas Gerais, the soil at the edge showed higher availability of K⁺ for plants, which was associated with the release of this element by the occasional burning of plant material (Terra et al., 2018).

The litter stock on the surface of the forest varies according to the balance between its production and decomposition. Higher litter stock at the forest edge was a pattern also observed in an area of transition between Coastal Atlantic Forest and Seasonal Semideciduous Atlantic Forest (Portela and Santos, 2007) and in forest fragments in Central Amazonia (Laurance and Vasconcelos, 2009). This pattern was probably caused by the predominance of pioneer species (Lima-Ribeiro, 2008), that is, fast-growing species, which supply large amounts of leaf litter to the soil (Dickow et al., 2012). Higher litter stock value was also verified in a fragment of Semideciduous Seasonal Forest in less advanced successional stage, compared to one in a more advanced stage (Camara et al., 2018), in which the edge effect is potentially lower (Tabarelli et al., 2008).

Higher values of litter production in the edge area were also verified in a fragment of Seasonal Semideciduous Atlantic Forest in the municipality of Além Paraíba, State of Minas Gerais, and this effect was observed up to a distance of 60 m from the forest edge, while litter production was lower from 100 m, whose value was similar to that observed in the interior (distance of 350 m from the forest edge) (Machado et al., 2018). Additionally, litter decomposition occurs more slowly and contributes to its accumulation on the soil surface at the forest edge, due to the control of the population of saprophagous arthropods because of the important presence of predators in this community, when compared with the interior of forest fragments (Pereira et al., 2013).

The increase in litter stock has conditioned higher total organic carbon content in the soil and supply of nutrients through the litter (Freitas et al., 2016), which contribute to the increase in soil fertility and soil water content (Veen et al., 2019), a fact corroborated by the positive correlations between litter stock and gravimetric moisture, Ca²⁺ content, Mg²⁺ content, S Value and V Value in the soil, close to the forest edge. These conditions favored the highest values of total richness, diversity and relative participation (%) of different taxonomic groups in the community of edaphic arthropods present at the edge of the forest fragment, which are distributed in various trophic guilds, such as Araneae, Hymenoptera, Pseudoscorpionida, which involve exclusively predatory organisms; Coleoptera (adults and larvae), Formicidae, Lepidoptera and Thysanoptera larvae, predators/saprophagous; Isoptera and Symphypleona, saprophagous.

Some studies have shown that Formicidae had higher relative participation in the soil arthropod community, at the edge of fragments of Dense Montane Ombrophilous Forest, in comparison with the interior (Pereira et al., 2013). Formicidae predominated in areas where the edge effect is potentially greater, such as in small fragments (<3.5 ha), to the detriment of medium and large size fragments (23 and 62 ha, respectively) of Dense Montane Ombrophilous Forest (Camara et al., 2017); in pasture areas and/or secondary fragments in the initial successional stage, compared to those fragments in more advanced successional stages, in the Submontane Semideciduous Seasonal Forest (Menezes et al., 2009) and Lowland Dense Ombrophilous Forest (Ferreira et al., 2017, 2018). Indeed, the activity of Formicidae in the soil may be higher at the edge, a fact attested by the increase in the removal of seeds of *Erythroxylum pellerianum* A. St.-Hil, an abundant perennial shrub species whose secondary dispersers are ants, in comparison with the interior, in Cerrado areas (Christianini and OLIVEIRA, 2013).

The lower values of uniformity and diversity in the community of edaphic arthropods were due to the significant relative participation of Acari, which involves predatory/saprophagous organisms, within the forest fragment. Acari had relative participation approximately five times greater in the interior of a fragment of Dense Montane Ombrophilous Forest, when compared to the edge (Pereira et al., 2013). The favoring of some taxonomic groups of edaphic arthropods at the ranges closer to the interior of the forest fragment has also been reported in

other studies. Representatives of the Chilopoda taxonomic group were verified only in fragments of Dense Montane Ombrophilous Forest of medium and large size (23 and 62 ha, respectively), not being verified in a smaller fragment (<3.5 ha) (Camara et al., 2017). Symphyla individuals were only observed in a fragment of Semideciduous Seasonal Forest in a more advanced successional stage and was absent in the fragment with lower degree of evolution of the successional stage, which was associated with Araneae, Coleoptera and Hymenoptera (Camara et al., 2018). Diplura taxonomic group was restricted to an area of Submontane Dense Ombrophilous Forest and was not verified in abandoned plantations of *Corymbia citriodora* at different stages of natural regeneration of native arboreal and shrub species in the understory (Camara et al., 2012).

In general, considering the relative participation in the soil arthropod community, different taxonomic groups were significantly and positively correlated with soil fertility, content and/or stock of nutrients in the litter, temperature and gravimetric moisture. The higher soil fertility in forest ecosystems, which can be expressed by higher values of pH, base saturation (mainly Ca^{2+} and Mg^{2+}), cation exchange capacity and P availability, favors the edaphic arthropod community (Giácomo et al., 2017). This pattern is due to the presence of litter with a higher chemical quality for the action of soil arthropods, especially saprophagous organisms, and the decomposing microbiota, due to higher contents of nutrients, such as Ca (Camara et al., 2018), N, K, Mg, and lower C/N ratio (Ferreira et al., 2018). Additionally, higher values of gravimetric moisture also favor the edaphic arthropod community (Corrêa Neto et al., 2018).

For the microbiological attributes, two main patterns were verified for most of the variables. The first pattern indicated that the edge effect promoted an increase in the values of the variables C-SMB, T-GRSP, and SBR. The second pattern showed that the forest edge promoted a decrease in the values of FDA, SA, and RFO of both *A. mellea* and *A. foveata*. Higher levels of C-SMB, T-GRSP, and SBR may be associated with higher stocks of litter and total organic carbon at the edge and in the range closest to it (0 and 50 m, respectively, from the forest edge), compared to Range 2 and the interior (100 and 160 m from the forest edge, respectively). This result can be verified by the PCA, in which the relationships between these variables were close, and also through Pearson's correlations, which were significant and positive between C-SMB, SBR, and T-GRSP with litter stock and/or TOC in soil. These factors can interfere with the microclimatic conditions of the soil, with decrease in soil temperature (more stable variations and with lower amplitude) and increase in soil moisture retention, which favors respiratory metabolism, population, and microbial biomass of the soil (Silva et al., 2012).

The mean values observed for T-GRSP and EE-GRSP fractions in the present study were lower and higher, respectively, compared to the mean values observed in secondary fragments of the Atlantic Forest in initial, intermediate and advanced successional stages (Silva et al., 2016). The accumulation of glomalin in the soil depends on several factors, such as species richness in the AMF community, composition of the plant community and soil attributes (Singh et al., 2016). This pattern was confirmed in this study by means of the positive correlations observed between GRSP fractions and pH, Ca^{2+} , Mg^{2+} , P and TOC, in addition to the litter stock.

Previous studies have reported positive correlations of GRSP fractions with TOC, pH, P, Ca^{2+} and Mg^{2+} (Wu et al., 2014; Šarapatka et al., 2019; Wang et al., 2019). Ca^{2+} can participate in the establishment of arbuscular mycorrhizae by stimulating the growth of hyphae, which, with the consequent decomposition of this fungal structure, promotes the deposition of GRSP, which may clarify the correlation between this element and the protein produced by AMF (Wu et al., 2014). However, some studies report the occurrence of negative correlations of GRSP fractions with pH and Ca^{2+} (Lovelock et al., 2004).

The pattern of higher values of FDA in the interior of the forest fragment, in turn, may be related to the possible difference in the chemical composition of the litter in the comparison among the ranges

of distance from the forest edge. This result can also be verified by the PCA, which separated the most distant ranges from the ranges closest to the forest edge, with significant contributions of the chemical attributes of the litter to such separation, regarding the correlations (>0.70) with the principal components. Higher FDA activity in the interior of the forest fragment and in the range closest to it (Range 2, 100 m from the forest edge) may lead to higher rate of litter decomposition, which could justify the lower stocks in the interior compared to the forest edge. Indeed, there was a linear relation between litter decomposition rates and soil enzymatic activity (Kang and Freeman, 2009).

Of the 12 AMF species observed, the species *A. mellea* and *A. foveata* seem to demonstrate more clearly the edge effect. Both species showed a decrease in the relative frequency of occurrence in the ranges closest to the edge. The absence of spores of *A. mellea* was also observed at the edge of another area of Seasonal Semideciduous Forest in the municipality of Vitória da Conquista, located in northeastern Brazil (Santos et al., 2018). As far as the AMF community, the establishment of a pattern of distribution of the species along an increasing gradient of distance from the forest edge is hampered by the influence of several biotic and abiotic factors related to the environments, as well as the different survival strategies of these fungi (Souza et al., 2003). However, the variation in spore abundance and relative frequency of occurrence of the AMF species, in the comparison between the interior and edge of the forest fragment, may be associated with differences between these areas in relation to some soil chemical attributes. In this study, this pattern was indicated by negative or positive correlations between SA and pH and contents of nutrients in the soil (Ca^{2+} , K^{+} , and Mg^{2+}), and between the frequency of occurrence of certain AMF species and some of these soil chemical attributes. In addition, possible variations in the composition of plant species, caused by the edge effect (Rabelo et al., 2015), may also have influenced this result, because the plant community can alter the composition and distribution of AMF in the soil (Oehl et al., 2010).

Soil moisture can also influence the number of spores, with a tendency of higher sporulation in drier environments, to the detriment of those in which there is a higher soil water content (Durazzini et al., 2016). The pattern of reduction in spore abundance at the ranges closest to the edge, compared to the interior, was also observed in an area of Montane Semideciduous Seasonal Forest, in the dry season (Santos et al., 2018).

We recorded low and significant variations, respectively, in the total richness and frequency of occurrence of AMF species, in the comparison among the ranges from the forest edge, towards the forest interior. This pattern is in accordance with the result obtained in Mediterranean-type forest, in which the species richness in the mycorrhizal fungi community was not significantly different along the disturbance gradient, while the composition of the species was altered (Sapsford et al., 2020). Modifications in AMF communities may alter symbiotic interactions between microorganisms and host plants, affecting the health and recruitment of trees, especially for AMF-dependent tree species (Tonn and Ibáñez, 2016). In addition, decreases in the population of certain species of mycorrhizal fungi may predispose trees to decrease, as a result of other abiotic or biotic factors, at the edges of forest fragments (Sapsford et al., 2017).

The multivariate analyses indicated that forest fragmentation modifies the dynamics of chemical attributes and the community of soil invertebrates and microorganisms at the edge and at the distance closest to it (50 m), which are directly or indirectly related to changes in litter attributes, in comparison with the interior and with the distance closest to it, in the studied area.

5. Conclusions

The edge effect caused by forest fragmentation led to modifications in most of the soil attributes, including the microclimatic, chemical and biological (arthropod community and microbiological attributes)

attributes of the soil up to the distance of 50 m, and these changes can be attributed to variations in litter attributes.

Litter attributes influenced the highest values of virtually all the chemical and biological (arthropod community and microbiological) attributes evaluated, at the distances closest to the forest edge (Edge and Range 1, respectively, 0 and 50 m from the forest edge).

We suggest the adoption of measures that contribute to the conservation of local biodiversity. These include the planting of non-pioneer native tree species (secondary and climax) at the Edge and Range 1 (0 m and 50 m from the edge toward the interior of the forest fragment, respectively), as well as the assessment of the possibility of installing ecological corridors to connect the studied forest fragment to other remnants observed in the area of study.

Authors contributions

Cristiane Figueira da Silva – Conceptualization; Date curation; Formal analysis; Investigation; Methodology; Project administration; Resources; Software; Validation; Visualization; Roles/Writing - original draft; Writing - review & editing. **Rodrigo Camara de Souza** - Conceptualization; Date curation; Formal analysis; Investigation; Methodology; Project administration; Resources; Software; Validation; Visualization; Writing - original draft; Writing - review & editing. **Marcos Gervasio Pereira** - Conceptualization; Funding acquisition; Project administration; Supervision; Validation; Visualization; Roles/Writing - original draft; Writing - review & editing. **Luiz Alberto da Silva Rodrigues Pinto** - Formal analysis. **Robert Ferreira** - Formal analysis. **Maria Elizabeth Fernandes Correia** - Validation; Visualization; Roles/Writing - original draft. **Carlos Eduardo Gabriel Menezes** - Formal analysis. **Marcelo Antonio Fontes** - Formal analysis. **Tiago Paula da Silva** - Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This study was financed by the Brazilian Federal Agency for Support and Evaluation of Graduate Education (CAPES, finance code 001).

References

- Alvares, C.A., Stape, J.L., Sentelhas, P.C., Gonçalves, J.L.M., Sparovek, G., 2013. Köppen's climate classification map for Brazil. *Meteorol. Z.* 22, 711–728. <https://doi.org/10.1127/0941-2948/2013/0507>.
- Anderson, T.H., Domsch, K.H., 1993. The metabolic quotient for CO₂ (qCO₂) as a specific activity parameter to assess the effects of environment conditions, such as pH, on the microbial biomass of forest soils. *Soil Biol. Biochem.* 25, 393–395. [https://doi.org/10.1016/0038-0717\(93\)90140-7](https://doi.org/10.1016/0038-0717(93)90140-7).
- Barreto-Garcia, P.A.B., Scoria, R.N., Paula, A., 2019. Edge effect on chemical attributes of soil in a seasonal forest. *Rev. Árvore* 43, e430109. <https://doi.org/10.1590/1806-90882019000100009>.
- Bradford, M.M., 1976. A rapid and sensitive method for the quantification of microgram quantities of protein utilizing the principle of protein-dye binding. *Anal. Biochem.* 72, 248–254. [https://doi.org/10.1016/0003-2697\(76\)90527-3](https://doi.org/10.1016/0003-2697(76)90527-3).
- Camara, R., Correia, M.E.F., Villela, D.M., 2012. Effects of eucalyptus plantations on soil arthropod communities in a Brazilian Atlantic Forest conservation. *Biosci. J.* 28, 445–455.
- Camara, R., Gomes, J.M., Pereira, M.G., Piña-Rodrigues, F.C.M., 2017. Atlantic Forest size effect on structure and composition of soil arthropods community, RJ, Brazil. *Floresta* 47, 145–156. <https://doi.org/10.5380/rf.v47i2.39878>.
- Camara, R., Santos, G.L., Pereira, M.G., Silva, C.F., Silva, V.F.V., Silva, R.M., 2018. Effects of natural Atlantic Forest regeneration on soil fauna, Brazil. *Floresta e Ambiente* 25, e20160017. <https://doi.org/10.1590/2179-8087.001716>.
- Christianini, A.V., Oliveira, P.S., 2013. Edge effects decrease ant-derived benefits to seedlings in a neotropical savanna. *Arthropod Plant Interact* 7, 191–199. <https://doi.org/10.1007/s11829-012-9229-9>.
- CICG, 2021. Coleção Internacional de Cultura de Glomeromycota., 26, August 2021. accessed. <https://sites.google.com/site/cicgma/home?authuser=0>.
- Corrêa Neto, T.A., Anjos, L.H.C., Camara, R., Pereira, M.G., Correia, M.E.F., Jaccoud, C.F. S., 2018. Relação fauna do solo-paisagem em plantio de eucalipto em topossequência. *Floresta* 48, 213–224. <https://doi.org/10.5380/rf.v48i2.55041>.
- De-Polli, H., Guerra, J.G.M., 1999. C, N e P na biomassa microbiana do solo. In: Santos, G.A., Camargo, F.A.O. (Eds.), *Fundamentos da matéria orgânica do solo: ecossistemas tropicais e subtropicais*. Genesis, Porto Alegre, pp. 389–411.
- Dickow, K.M.C., Marques, R., Pinto, C.B., Höfer, H., 2012. Produção de serapilheira em diferentes estágios sucessionais de uma Floresta Subtropical secundária, em Antonina. PR. *Cerne* 18, 75–86. <https://doi.org/10.1590/S0104-77602012000100010>.
- Donagemma, G.K., Campos, D.V.B., Calderano, S.B., Teixeira, W.G., Viana, J.H.M., 2011. *Manual de métodos de análise de solo*. Embrapa Solos, Rio de Janeiro.
- Durazzini, A.M.S., Teixeira, M.A., Adami, A.A.V., 2016. Quantificação de esporos de fungos micorrízicos arbusculares (FMAs) em solo sob diferentes cultivos de cafeeiros. *Rev. Agrogeambiental* 8, 83–91. <https://doi.org/10.18406/2316-1817v8n42016923>.
- Ferreira, C.R., Souza, R.C., Correia, M.E.F., Resende, A.S., Anjos, L.H.C., Pereira, M.G., 2017. Edaphic arthropods in different successional stages of Atlantic forest and abandoned pasture areas. *Commun. Sci.* 8, 296–306. <https://doi.org/10.14295/cs.v8i2.1750>.
- Ferreira, C.R., Correia, M.E.F., Camara, R., Resende, A.S., Anjos, L.H.C., Pereira, M.G., 2018. Soil fauna changes across Atlantic Forest succession. *Commun. Sci.* 9, 162–174. <https://doi.org/10.14295/cs.v9i2.2388>.
- Freitas, I.C., Santos, F.C.V., Custódio Filho, R.O., Correia, V., 2016. Carbono no solo, acúmulo e qualidade da serapilheira em sistemas de produção familiar. *Floresta* 46, 31–38. <https://doi.org/10.5380/rf.v46i1.42065>.
- Fundação SOS Mata Atlântica, Inpe Instituto Nacional Pesquisas Espaciais, 2002. *Atlas da evolução dos remanescentes florestais e ecossistemas associados no domínio da Mata Atlântica no período 1995-2000*. Fundação SOS Mata Atlântica/São José dos Campos. INPE, São Paulo.
- Garay, I., 1989. Relations entre l'hétérogénéité des litières et l'organisation des peuplements d'arthropodes édaphiques. *École Normale Supérieure. Publications du Laboratoire de Zoologie* 35, 191.
- Gerdemann, J.W., Nicolson, T.H., 1963. Spores of mycorrhizal endogone species extracted from soil by wet sieving and decanting. *Trans. Br. Mycol. Soc.* 46, 235–244. [https://doi.org/10.1016/S0007-1536\(63\)80079-0](https://doi.org/10.1016/S0007-1536(63)80079-0).
- Giacomini, R.G., Souza, R.C., Alves, M.C., Pereira, M.G., Arruda, O.G., González, A.P., 2017. Soil fauna: Bioindicator of soil recovery in Brazilian savannah. *Rev. Bras. Ciência Avícola* 12, 236–243. <https://doi.org/10.5039/agraria.v12i2a5443>.
- INVAM, 2019. International culture collection of (vesicular) arbuscular mycorrhizal fungi. <http://invam.caf.wvu.edu/s>, 9September2019. accessed.
- Jenkins, W.R., 1964. A rapid centrifugal-flotation technique for separating nematodes from soil. *Plant Dis.* 48, 692.
- Jenkinson, D.S., Ladd, J.N., 1981. Microbial biomass in soil: measurement and turnover. In: Paul, E.A., Ladd, J.M. (Eds.), *Soil Biochemistry*, vol. 5. Marcel Dekker, NewYork, pp. 415–471.
- Kang, H., Freeman, C., 2009. Soil enzyme analysis for leaf litter decomposition in global wetlands. *Commun. Soil Sci. Plan.* 40, 3323–3334. <https://doi.org/10.1080/00103620903325935>.
- Laurance, W.F., Vasconcelos, H.L., 2009. Consequências ecológicas da fragmentação florestal na Amazônia. *Oecol. bras.* 13, 434–451. <https://doi.org/10.4257/oeco.2009.1303.03>.
- Laurance, W.F., Camargo, J.L.C., Laurance, S.G., Pimm, S.L., Stouffer, P.C., 2011. The fate of Amazonian Forest fragments: a 32-year investigation. *Biol. Conserv.* 144, 56–67. <https://doi.org/10.1016/j.biocon.2010.09.021>.
- Lima-Ribeiro, M.S., 2008. Efeitos de borda sobre a vegetação e estruturação populacional em fragmentos de Cerradão no Sudoeste Goiano, Brasil. *Acta Bot. Bras.* 22, 535–545. <https://doi.org/10.1590/S0102-33062008000200020>.
- Lippok, D., Beck, S.G., Renison, D., Hensen, I., Apaza, A.E., Schleuning, M., 2014. Topography and edge effects are more important than elevation as drivers of vegetation patterns in a neotropical montane forest. *J. Veg. Sci.* 25, 724–733. <https://doi.org/10.1111/jvs.12132>.
- Lovelock, C.E., Wright, S.F., Clark, D.A., Ruess, R.W., 2004. Soil stocks of glomalin produced by arbuscular mycorrhizal fungi across a tropical rain forest landscape. *J. Ecol.* 92, 278–287. <https://doi.org/10.1111/j.0022-0477.2004.00855.x>.
- Machado, M.R., Souza, R.C., Calvi, G.P., Piña-Rodrigues, F.C.M., Leles, P.S.S., 2018. Litterfall: a Bio-indicator for edge effect in a semi-deciduous seasonal forest. *Floresta Ambient* 25, e20170528. <https://doi.org/10.1590/2179-8087.052817>.
- Malchow, E., Koehler, A.B., Netto, S.P., 2006. Efeito de borda em um trecho da Floresta Ombrófila Mista, em Fazenda Rio Grande. PR. *Rev. Acadêmica* 4, 85–94. <https://doi.org/10.7213/cienciaanimal.v4i2.9357>.
- Menezes, C.E.G., Correia, M.E.F., Pereira, M.G., Batista, I., Rodrigues, K.M., Couto, W.H., Anjos, L.H.C., Oliveira, I.P., 2009. Macrofauna edáfica em estágios sucessionais de Floresta Estacional Semidecidual e pastagem mista em Pinheiral (RJ). *Rev. Bras. Ciênc. Solo* 33, 1647–1656. <https://doi.org/10.1590/S0100-06832009000600013>.
- Myers, N., Mittermeier, R.A., Mittermeier, C.G., Fonseca, G.A.B., Kent, J., 2000. Biodiversity hotspots for conservation priorities. *Nature* 403, 853–858. <https://doi.org/10.1038/35002501>.
- Odum, E.P., 1988. *Ecologia*. Editora Guanabara Koogan, Rio de Janeiro.
- Oehl, F., Laczko, E., Bogenrieder, A., Stahr, K., Bösch, R., Van Der Heijden, M., Sieverding, E., 2010. Soil type and land use intensity determine the composition of arbuscular mycorrhizal fungal communities. *Soil Biol. Biochem.* 42, 724–738. <https://doi.org/10.1016/j.soilbio.2010.01.006>.
- Pereira, G.H.A., Pereira, M.G., Anjos, L.H.C., Menezes, C.E.G., 2013. Decomposição da serrapilheira, diversidade e funcionalidade de invertebrados do solo em um fragmento de Floresta Atlântica. *Biosci. J.* 29, 1317–1327.

- Portela, R.C.Q., Santos, F.A.M., 2007. Produção e espessura da serapilheira na borda e interior de fragmentos florestais de Mata Atlântica de diferentes tamanhos. *Rev. Bras. Bot.* 30, 271–280. <https://doi.org/10.1590/S0100-84042007000200011>.
- Rabelo, F.R.C., Rodal, M.J.N., Silva, A.C.B.L., Lima, A.L.A., 2015. Dinâmica da vegetação em um fragmento de mata atlântica no nordeste do Brasil. *Ciência Florest.* 25, 23–36. <https://doi.org/10.1590/1980-509820152505023>.
- Ribeiro, M.C., Metzger, J.P., Martensen, A.C., Ponzoni, F.J., Hirota, M.M., 2009. The Brazilian Atlantic Forest: how much is left, and how is the remaining forest distributed? Implications for conservation. *Biol. Conserv.* 142, 1141–1153. <https://doi.org/10.1016/j.biocon.2009.02.021>.
- Santos, R.S., Barreto-Garcia, P.A.B., Scoriza, R.N., 2018. Fungos micorrízicos arbusculares e serapilheira como indicadores do efeito de borda em fragmento de floresta estacional. *Ciência Florest.* 28, 324–335. <https://doi.org/10.5902/1980509831603>.
- Sapsford, S.J., Paap, T., Hardy, G.E.S.J., Burgess, T.I., 2017. The “chicken or the egg”: which comes first, forest tree decline or loss of mycorrhizae? *Plant Ecol.* 218, 1093–1106. <https://doi.org/10.1007/s11258-017-0754-6>.
- Sapsford, S.J., Paap, T., Hopkins, A.J.M., Hardy, G.E.S.T.J., Burgess, T.I., 2020. Habitat fragmentation in a Mediterranean-type forest alters resident and propagule mycorrhizal fungal communities. *Pedobiologia* 78, 150611. <https://doi.org/10.1016/j.pedobi.2019.150611>.
- Šarapatka, B., Alvarado-Solano, D.P., Čizmar, D., 2019. Can glomalin content be used as an indicator for erosion damage to soil and related changes in organic matter characteristics and nutrients? *Catena* 181, 104078. <https://doi.org/10.1016/j.catena.2019.104078>.
- Schnurer, J., Rosswall, T., 1982. Fluorescein diacetate hydrolysis as a measure of total microbial activity in soil and litter. *Appl. Environ. Microbiol.* 43, 1256–1261. <https://doi.org/10.1128/AEM.43.6.1256-1261.1982>.
- Schröder, T., Fleig, F.D., 2017. Spatial patterns and edge effects on soil organic matter and 453 nutrients in a forest fragment of southern Brazil. *Soil Res.* 55, 649–656. <https://doi.org/10.1071/SR16186>.
- Silva, M.S.C., Silva, E.M.R., Pereira, M.G., Silva, C.F., 2012. Estoque de Serapilheira e Atividade Microbiana em Solo sob Sistemas Agroflorestais. *Floresta e Ambiente* 19, 431–441. <https://doi.org/10.4322/floram.2012.058>.
- Silva, C.F., Pereira, M.G., Santos, V.L., Miguel, D.L., Silva, E.M.R., 2016. Fungos micorrízicos arbusculares: composição, comprimento de micélio extrarradicar e glomalina em áreas de Mata Atlântica, Rio de Janeiro. *Ciência Florest.* 26, 419–433. <https://doi.org/10.5902/1980509822743>.
- Singh, A.K., Rai, A., Singh, N., 2016. Effect of long term land use systems on fractions of glomalin and soil organic carbon in the Indo-Gangetic plain. *Geoderma* 277, 41–50. <https://doi.org/10.1016/j.geoderma.2016.05.004>.
- Souza, R.G., Maia, L.C., Sales, M.F., Trufem, S.F.B., 2003. Diversidade e potencial de infectividade de fungos micorrízicos arbusculares em áreas de caatinga, na região de Xingó, Estado de Alagoas, Brasil. *Acta Bot. Bras.* 26, 49–60. <https://doi.org/10.1590/S0100-84042003000100006>.
- Tabarelli, M., Pinto, L.P., Silva, J.M.C., Hirota, M.M., Bedê, L.C., 2005. Desafios e oportunidades para a conservação da biodiversidade na Mata Atlântica Brasileira. *Megadiversidade* 1, 132–138.
- Tabarelli, M., Lopes, A.V., Peres, C.A., 2008. Edge-effects drive tropical forest fragments towards an early-successional system. *Biotropica* 40, 657–661. <https://doi.org/10.1111/j.1744-7429.2008.00454.x>.
- Tedesco, M.J., Gianello, C., Bissani, C.A., Bohnen, H., Volkweiss, S.J., 1995. *Análise de solo, plantas e outros materiais*, two ed. Universidade Federal do Rio Grande do Sul, Porto Alegre.
- Terra, M.C.N.S., Teodoro, G.S., Pifano, D.S., Fernandes, F.B., Silva, T.M.C., Van Den Berg, E., 2018. Tree responses to soil and edge effects in a Semideciduous Forest remnant. *Floresta e Ambiente* 25 e20160542. <http://orcid.org/0000-0003-4646-2414>.
- Tonn, N., Ibáñez, I., 2016. Plant-mycorrhizal fungi associations along an urbanization gradient: implications for tree seedling survival. *Urban Ecosyst.* 20, 823–837. <http://orcid.org/10.1007/s11252-016-0630-5>.
- Veen, G.F., Fry, E.L., Ten Hooven, F.C., Kardol, P., Morriën, E., De Long, J.R., 2019. The role of plant litter in driving plant-soil feedbacks. *Front. Environ. Sci.* 7, 1–10. <http://orcid.org/10.3389/fenvs.2019.00168>.
- Wicklein, H.F., Christopher, D., Carter, M.E., Smith, B.H., 2012. Edge effects on sapling characteristics and microclimate in a small temperate Deciduous Forest Fragment. *Nat. Area J.* 32, 110–116. <https://doi.org/10.3375/043.032.0113>.
- Wright, S.F., Upadhyaya, A., 1998. A survey of soils for aggregate stability and glomalin, a glycoprotein produced by hyphae of arbuscular mycorrhizal fungi. *Plant Soil* 198, 97–107. <https://doi.org/10.1023/A:1004347701584>.
- Wright, S.F., Franke-Snyder, M., Morton, J.B., Upadhyaya, A., 1996. Time-course study and partial characterization of a protein on hyphae of arbuscular mycorrhizal fungi during active colonization of roots. *Plant Soil* 181, 193–203. <https://doi.org/10.1007/BF00012053>.
- Wu, Q.S., Ni, Q.D., Que, Y.C., Huang, W., 2014. Calcium and calmodulin involve in mycorrhizal and root development in *Trifoliate Orange* colonized by *Rhizophagus intraradices*. *Not Bot Horti Agrobo* 42, 380–385. <https://doi.org/10.15835/nbha4229635>.
- Yeomans, J.C., Bremner, J.M., 1988. A rapid precise method for routine determination of organic carbon in soil. *Commun. Soil Sci. Plan.* 19, 1467–1476. <https://doi.org/10.1080/00103628809368027>.