EDGE INFLUENCE OVER FUNCTIONAL TREE TRAITS IN AN ATLANTIC FOREST REMNANT

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ABSTRACT – Habitat fragmentation is one of the leading causes of edge genesis and its effects. Functional tree traits such as wood density, height, and diameter are essential variables from which it is possible to infer several ecological processes. This study assessed the variability of the functional traits of trees over two habitats (edge and interior) of a forest remnant. The hypothesis tested were i) the functional traits would have lower values at the edges than the interior, and ii) environmental variables would influence such differences. This study was carried out in the largest Atlantic Forest remnant within Serra da Tiririca State Park, Brazil, by establishing ten plots (50 × 20 m) among different habitats. Within each plot, wood samples were taken from all trees with a diameter of ≥ 10 cm. It was recorded the altitude, distance from the plots to the edge, and fire records as possible explanatory variables (environmental variables). Wood density was obtained using the immersion method. To verify differences in functional traits by habitat, the Wilcoxon test was applied. Additionally, the influence of explanatory variables on functional traits through generalized linear models was evaluated. One hundred eighty-five trees were recorded at the edges and 218 trees at the interior of the remnant. Wood density and tree height were significantly lower in the edges than in the interior. Furthermore, the best models indicated significant relationships between wood density and habitats, as well as diameter and distance to the edge. This study was effective in raising suitable variables to predict edge effects.

Keywords: Wood density; Tropical rainforest; Habitat fragmentation.

INFLUÊNCIA DAS BORDAS SOBRE CARACTERÍSTICAS FUNCIONAIS DAS ÁRVORES EM UM REMANESCENTE DE MATA ATLÂNTICA

RESUMO – A fragmentação de habitats é uma das principais causas da criação de bordas e seus efeitos. Características funcionais das árvores, como a densidade da madeira, altura e diâmetro, são variáveis essenciais que permitem inferir vários processos ecológicos. Este estudo avaliou a variabilidade das características funcionais das árvores em dois tipos de habitats (borda e interior) de um remanescente florestal. Foram testadas as hipóteses de que i) as características funcionais teriam menores valores nas bordas do que no interior, e que ii) as variáveis ambientais influenciam essas diferenças. Este estudo foi realizado no maior remanescente de Mata Atlântica dentro do Parque Estadual da Serra da Tiririca, Brasil, estabelecendo dez parcelas (50 × 20 m) entre diferentes habitats. Dentro de cada parcela foram retiradas amostras de madeira de todas as árvores com diâmetro ≥ 10 cm. Além disso, foram registradas a altitude, distância das parcelas até a borda e registros de queimadas como possíveis variáveis explicativas (variáveis ambientais). A densidade da madeira foi obtida através do método de imersão. Para verificar diferenças nas características funcionais por tipo de habitat, foi aplicado o teste de Wilcoxon. Adicionalmente, foi avaliada a influência das variáveis explicativas sobre as características funcionais por meio de modelos lineares generalizados. Cento e oitenta e cinco árvores foram registradas nas bordas e 218 árvores no interior do remanescente. A densidade da madeira e a altura das árvores foram significativamente menores nas bordas do que no interior. Além disso, os melhores modelos

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http://dx.doi.org/10.1590/1806-908820220000003

indicaram relações significativas entre densidade da madeira e o tipo de habitat; assim como, entre o diâmetro e distância até a borda. Este estudo foi eficaz em abordar variáveis adequadas para prever os efeitos de borda no remanescente.

Palavras-Chave: Densidade da madeira; Floresta tropical; Fragmentação de habitat.

1. INTRODUCTION

Forest edges play an essential role in the ecosystem balance, receiving more recently, particular attention in ecological studies (Murcia, 1995; Laurance et al., 2007; Magnago et al., 2017). Edges or transition zones originate mainly because of habitat fragmentation (Laurance et al., 2002), which causes isolation from the forest matrix (remnants), reduces local biodiversity, and changes the microclimate conditions that affect the edge populations on the remnants (edge effect) (Laurance et al., 2018). Among the main changes associated with the edge effect, high solar radiation, high temperature, low humidity, and strong winds stand out (Laurance and Curran, 2008; Laurance et al., 2011; Magnago et al., 2015). However, edges are dynamic in space and time and can also be induced by numerous biotic and abiotic factors (Laurance et al., 2018).

Many conditions that affect forest edges occasionally influence the composition of tree species (Laurance et al., 2002; Laurance et al., 2007; Laurance et al., 2011), such the topography (Gehlhausen et al., 2000), the population density of shrub-tree vegetation (Wright et al., 2010) and vulnerability to fires (Cochrane and Laurance, 2002). Such parameters directly depend on the variability of functional traits, such as wood density, tree diameter, and height (Laurance et al., 2006a), whose magnitude is strongly related to trees growth and biomass (Chave et al., 2014).

Variation in functional traits is usually related to climate change and resilience towards changes (Poorter et al., 2010; Gratani, 2014; Falster et al., 2018). In this sense, edge trees are often reported presenting low wood density, smaller diameters, and shorter heights compared to individuals from the interior of the forest remnant (Oliveira-Filho et al., 1997; Magnago et al., 2014; Rodrigues et al., 2016; Berenguer et al., 2018). However, some studies suggested that they do not significantly differ in functional traits concerning habitat types (Pires et al., 2014; Magnago et al., 2014; Couto-Santos et al., 2021). In context, functional traits can make it possible to infer successional ecological processes (Chazdon et al., 2010). Tree communities studied in Brazilian biomes reinforce the importance of wood density in the forest structure (e.g.: Baker et al., 2004; Berenguer et al., 2018; Zimermann et al., 2019). However, due to the severe lack of data, the usefulness of wood density is scarcely explored as a predictive tool for succession stages (Padilha and Marco-Junior, 2018). On the other hand, the variation in trees diameter and height have been widely explored in forestry studies (Feldpausch et al., 2011), mainly studies on restoration process (Salomão et al., 2014), phytosociology (Turchetto et al., 2017), and habitat fragmentation (Haddad et al., 2015).

The Atlantic Forest is one of the most currently threatened neotropical biomes of rainforests, being regarded as one of the five most important biodiversity hotspots in the biosphere (Myers et al., 2000), with only 12.4% of its original coverage remaining (SOS Mata Atlântica and INPE, 2019). Most forest reduction is attributed to habitat fragmentation caused by anthropogenic disturbances (Rezende et al., 2018). Although there is continuous devastation of this biome, studies in small remnants indicate high rates of species heterogeneity (e.g.: Rocha and Amorim, 2012; Eisenlohr and Oliveira-Filho, 2015; Pontes et al., 2019). In this sense, edge studies usually aim at assessing functional diversity (Tabarelli et al., 2010; Magnago et al., 2014; Couto-Santos et al., 2021). When exploring the functional traits of trees, they are continuously oriented to studies in small remnants (Nascimento and Laurance, 2006; Santos et al., 2008; Santo-Silva et al., 2016), with particular species (Costa et al., 2020), and in specific environmental gradients (Rodrigues et al., 2016).

However, evaluating the edges in the light of the functional traits could have a high explanatory content of their effects (Magnago et al., 2014) since changes in the performance of the functional traits affect the growth, reproduction, and survival of individuals

(Violle et al., 2007). In this sense, this study aimed to assess the variability in tree functional traits over two habitat (edge and interior) in a forest remnant in Brazil. The hypothesis tested were i) traits as wood density, height, and tree diameter have lower values at the edges than in the interior, and ii) environmental variables influence such differences.

2. MATERIAL AND METHODS

2.1. Study area

This study was carried out within Serra da Tiririca area, the largest forest remnant in the Serra da Tiririca State Park (PESET), located between the municipalities of Niterói and Maricá, in the State of Rio de Janeiro (22º48’- 23º00’ S; 42º57’ - 43º02’ W) (Figure 1). PESET comprises 3492 ha, and the studied sector shows 1975 ha, distributed among the continental section (1789 ha) and marine limits (187 ha). PESET is inserted in the Atlantic Forest biome, with its flora representing the formation of dense submontane rainforest, with portions of rocky outcrops (Barros, 2008). The climate of the region is humid and warm, with heavy rains in the summer and dry season in the winter (Köppen's Aw) (Alvares et al., 2013), with an annual average temperature of 23.7 °C, an average of the total annual precipitation ~ 1172 mm, annual relative humidity of ~ 80% and, the edaphic constitution is formed mainly by Agrisoils, Gleissosoils, Neossoils, Cambisoils, and Litossoils (INEA, 2015).

The use and occupation of the PESET occurred from the first prehistoric nomadic groups (Kneip, 1995) through the occupation by the Tupi indigenous people until the arrival of the Portuguese colonizers (Barros, 2008). In the colonial era, the intense Portuguese trade on the Brazilian wood *Paubrasilia echinata* (Lam.) Gagnon, H.C. Lima & G.P. Lewis and other large trees transformed the natural landscape into devastated areas (Barros, 2008). Between the 16th and 17th centuries, *sesmarias*, extractive activities, and the establishment of sugar cane mills were primarily responsible for the devastation of vast extensions of native forests in the Atlantic Forest (Barros, 2008). With the decline of monocultures between the 19th and 20th centuries, natural areas managed to recover their native vegetation, but not for a long time (Barros, 2008). From the mid-20th century until today, large subdivisions and real estate growth dictate the dynamics and transformation of landscapes (Vallejo, 2005). On November the 29th, 1991, State Law No. 1,901 (Rio de Janeiro, 1991) determined the creation and control of the PESET.

2.2. Sample collection and data analyses

Ten plots of 50 x 20 m (1 ha) were unsystematically established between November 2019 and December 2020. Five plots no more distant than 20 m from an anthropogenic edge and five inside the remnant (plots average nearest to edge = 175 m) were set, all with a minimum distance of 200 m from each other (Figure 1).

In each plot, woody trees were sampled following the protocol proposed by Chave (2006); where, cross-sections of the xylem were taken with a Pressler probe (Haglöf Sweden®, 500 mm, Sweden) in the transversal direction of the trunk and at breast height. Also, each height (estimated from the length of high pruning poles) and diameter at breast height (DBH) of all trees ≥ 10 cm were recorded. In addition, environmental data (altitude, the closest distance between the edge of each plot, and the edge of the forest in a straight line) and the occurrence of fires were measured. The woody samples were dried in an oven at 105 ± 2 °C and weighed on an analytical precision scale (Marte Cientifica©, AD330, Brazil). The immersion method (ABNT, 2003) was used to estimate the density of wood samples, using Equation 1:

Source: the authors.
Fonte: os autores.

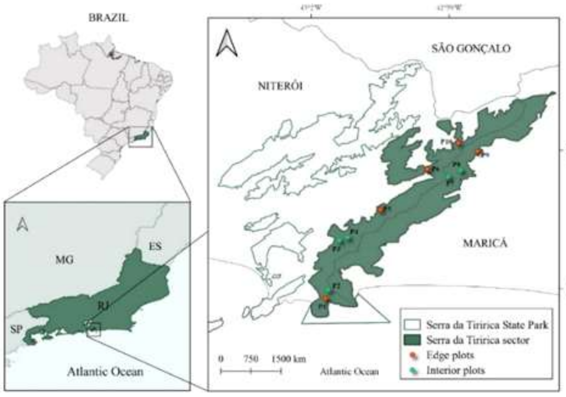

Figure 1 – Map and location of the study area, showing the plots (P) studied in Serra da Tiririca, Serra da Tiririca State Park, between 2019 and 2020.

Figura 1 *– Mapa e localização da área de estudo, mostrando as parcelas (P) estudadas na Serra da Tiririca, Parque Estadual da Serra da Tiririca, entre 2019 e 2020.*

$$p = \frac{m}{mdiff} \qquad \text{Eq.1}$$

where ρ = wood density (g.cm^{-3}); m = dry weight of the wood (g); *mdiff* = weight difference of the submerged wood (g), which corresponds to its volume (cm^3). The woody samples were deposited in the *Herbário Museu Nacional* (R).

Fire occurrence data were extracted from the database of the Queimadas Program - INPE (https://queimadas.dgi.inpe.br/queimadas/portal), filtering records of outbreaks between January 2010 and May 2021, in a limit distance of 5 km around the study site. The fire information applied in this study refers to the attribute fire risk - a meteorological estimate correlated to days without rain in a given location, type of vegetation, maximum temperature, minimum relative humidity, topography, latitude, and presence of local fire (INPE, 2021). The fire risk was evaluated based on the average of fires in a circular area of 100 m *in radius* from each plot. When no fire records were found within the perimeter, the average between the two closest to the plot was considered.

2.3. Statistical analysis

To test the normality of the response variables (wood density, height, and tree diameter), the Shapiro-Wilk test was used. When the assumption was not met, logarithmic and root-quadratic transformations were performed. If the variables did not meet the tests' assumptions even after transformations, they were treated using non-parametric tests, according to their initial distribution. For all statistical analyzes, a significance level of $p < 0.05$ was adopted. All statistical analyzes were generated in the R 4.1.1 statistical environment (R Core Team, 2021).

To assess whether the median wood density, diameter, and height of trees individuals showed significant differences between the edges and the interior of Serra da Tiririca, the non-parametric Wilcoxon test was applied. Additionally, the initial relationship between the three response variables was verified using Pearson's correlation coefficient. Also, the trees were separated by diameter and height classes and compared between edge and interior using the Wilcoxon test. Finally, to assess the influence of the explanatory variables (distance from plots to edge, altitude, fire risk, habitat type, and interactions) on the median per plot of the response variables, generalized linear models (GLM) were used. The distance-to-edge variable was log-transformed to reduce heteroscedasticity and increase the probability

Source: the authors.
Fonte: os autores.

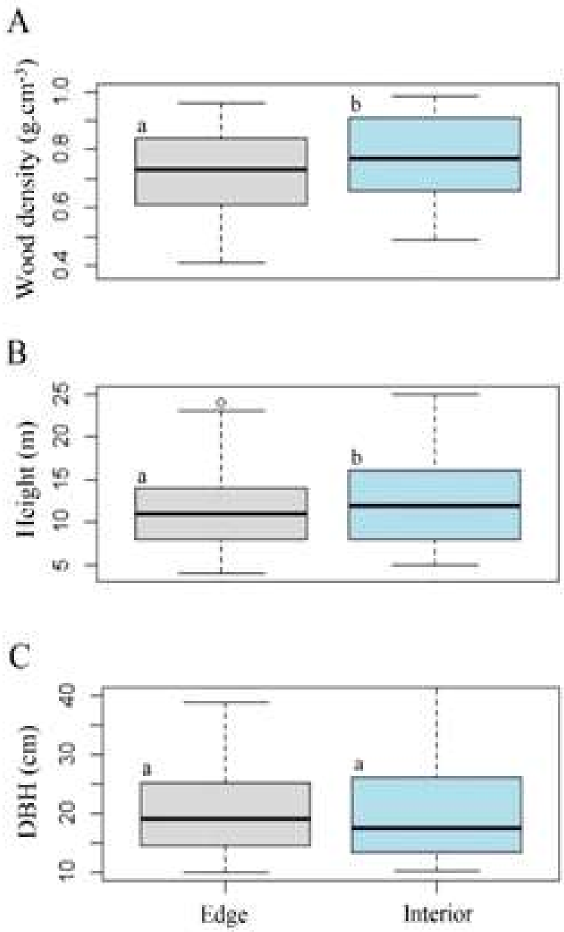

Figure 2 – Boxplots showing the variability of the wood density at the edge and the interior of remnant (A), height (B), and diameter at breast height (DBH) (C) of the tree individuals in the Serra da Tiririca, between 2019 and 2020. The line between the boxes represents the median, the limits of the boxes cover the 1st and 3rd quartiles, and dashes, the whole data. Different lowercase letters above the boxes indicate significant differences ($p < 0.05$).

Figura 2 *– Diagrama de caixas mostrando a variabilidade da densidade da madeira nas bordas e no interior da floresta (A), altura (B) e diâmetro à altura do peito (DAP) (C) dos indivíduos na Serra da Tiririca, entre 2019 e 2020. A linha entre as caixas representa a mediana, os limites das caixas cobrem o 1° e 3° quartis, e os traços, todos os dados. Diferentes letras minúsculas acima das caixas indicam diferenças significativas (p < 0,05).*

of standard distribution. For selecting the best GLMs, the best explanatory variables for each model were found through the *dropterm* function of the MASS package (Ripley et al., 2013). To assess the goodness of fit of the models, the explanatory variables were submitted to an analysis of variance with an F test and the measures of discrepancies were verified through deviance. Finally, models with the lowest values were selected, according to the Akaike Information Criterion (AIC) (Burnham et al., 2011), and the (adjusted) amount of deviance counted for each model was calculated from the Dsquared (D^2) function of the modEvA package (Barbosa et al., 2013). This function, known as pseudo-R^2 (or R^2 analog for GLM), calculates the variation ratio of each model (Guisan and Zimmermann, 2000). For all GLMs, Gaussian distribution with *identity link* was used.

3. RESULTS

In a total of 403 trees recorded, 185 were on the edges and 218 in the interior. Wood density and tree height showed significant differences between habitats (edge vs. interior). The median wood density was significantly lower ($z = 16261$; $p < 0.001$) at the edges (0.73 ± 0.14 g.cm^{-3}) when compared to the interior (0.77 ± 0.14 g.cm^{-3}). Likewise, the median height of the individuals was lower at the edge (11 m) than in the interior (12 m) ($z = 17120$; $p < 0.05$). In contrast, the diameter was not significantly different, with a median of 19.10 cm at the edges and 17.51 cm at the interior ($z = 21124$; $p = 0.41$) (Figure 2). Pearson's test showed that none of the variables showed significant correlations between them ($p > 0.05$).

The diameter classes followed a positive asymmetric distribution, showing significance between the edge and interior of the forest only for the tree classes between 10-20 cm ($z = 8671$; $p < 0.0001$). In contrast, height classes showed a symmetrical distribution trend but no significance in their classes (Figure 3).

The best GLMs for wood density, height, and tree diameter showed low coefficients of the uncertainties of the estimates about the explanatory variables (distance from the plots to the edges, altitude, fire risk, and habitat type) (Table 1). There was a significant difference between wood density and habitat type (Table 1) and a strong relationship in this model ($D^2 = 0.71$). Likewise, significant differences were found between median DBH and distance of plots to edge (Table 1) and a strong relationship in this model ($D^2 = 0.63$).

4. DISCUSSION

Variability on tree functional traits often allows us to understand how individuals interact in different ecological gradients (Violle et al., 2007). This paper aimed to assess the variability in functional traits of trees over two habitats (edge and interior) in an Atlantic Forest remnant. In this sense, significant

Source: the authors.
Fonte: os autores.

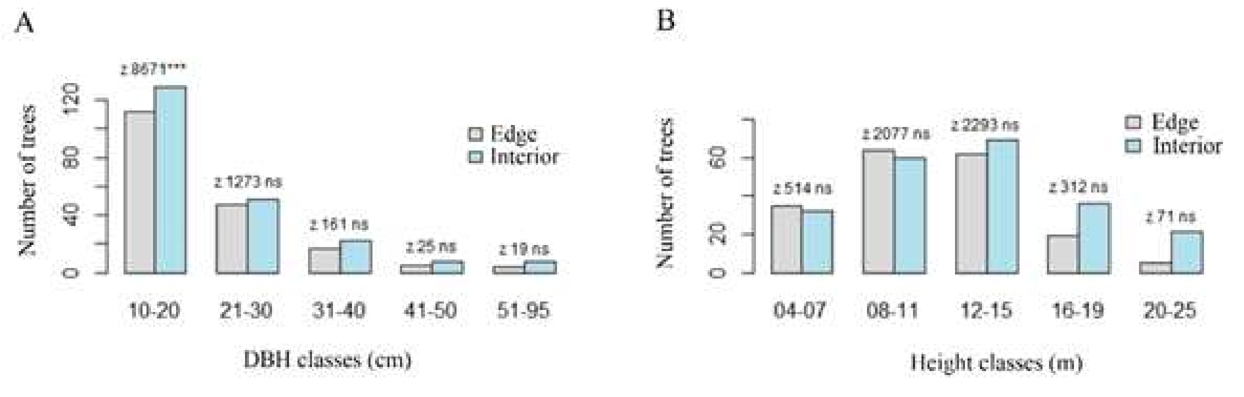

Figure 3 – Number of trees per class of diameter (A) and height (B), comparing the edges and the interior of Serra da Tiririca, between 2019 and 2020. DBH = diameter at the breast height. $p < 0.0001$ '***'; ns = non-significant.
Figura 3 – *Número de árvores por classes de diâmetro (A) e altura (B), comparando as bordas e o interior da Serra da Tiririca, entre 2019 e 2020. DAP = diâmetro a altura do peito. p < 0,0001 '***'; ns = não significativo.*

Table 1 – Generalized linear models generated by the relationships between wood density, height, and diameter *versus* explanatory variables and their interactions.
Tabela 1 *– Modelos lineares generalizados gerados pelas relações entre densidade da madeira, altura e diâmetro* ***versus*** *variáveis explicativas e suas interações.*

Model = Wood density ~ Distance to edge (log) + Habitat					**AIC -29.04**
Variable	Estimate	Std. Error	Deviance	Resid. dev.	p(>F)
(Intercept)	1.050	0.080		0.051	
Distance to edge	-0.317	0.076	0.001	0.050	0,434
Habitat - Interior[1]	0.384	0.093	0.035	0.014	0.004**
Model = Height ~ Altitude + Habitat					**AIC 49.51**
	Estimate	Std. Error	Deviance	Resid. dev.	p(>F)
(Intercept)	13.40	1.48		39.28	
Altitude	-0.01	0.01	7.09	32.18	0.22
Habitat - Interior[1]	1.38	1.29	4.49	27.69	0.32
Model = DBH ~ Altitude + Fire risk + Distance to edge (log)					**AIC 59.15**
	Estimate	Std. Error	Deviance	Resid. dev.	p(>F)
(Intercept)	-4.43	11.22		219.97	
Altitude	-0.07	0.02	44.68	175.28	0.11
Fire risk	35.18	13.49	10.84	164.44	0.40
Distance to edge	8.85	3.51	84.62	79.81	0.04*

Negative parameters indicate inverse effects and positive, direct effects. Akaike Information Criteria (AIC); p < 0.01 '**', 0.05 '*'; 1difference with the edge habitat. Source: the authors.
*Parâmetros negativos indicam efeitos inversos e positivos, efeitos diretos. Critério de Informação de Akaike (AIC); p < 0,01 '**', 0,05 '*'; 1diferença com o habitat de borda. Fonte: os autores.*

differences were observed in functional traits (wood density and tree height) related to habitat type. These traits showed lower values for the edges compared to the interior. Furthermore, it was found that the environmental variables influenced the variation of the functional traits (wood density and tree diameter), which are fundamental to explaining the trees individuals' ecological role.

Wood density is a property that is vulnerable to environmental changes due to its relationship with the mass and volume of trees (Chave et al., 2006). Wood density can vary according to habitat type, presenting lower values in anthropic forests and edges when compared to undisturbed forests and the interior (Muller-Landau, 2004; Laurance et al., 2006b; Berenguer et al., 2018). However, few authors reported that wood density has no variation to the edges and interior of the remnants (Magnago et al., 2014, Santo-Silva et al., 2016; Dreyer et al., 2020). Significant differences were found in wood density compared to habitat type in the present study, with lower values for edges than for the interior. In this context, divergences between studies could indicate the lack of patterns in this functional trait. Potential explanations are the local range limitation of the wood density (Atlantic Forest, 0.6 - 0.8 $g.cm^{-3}$) (Padilha and Marco-Junior, 2018) and their phylogenetic evolution (Chave et al., 2006). In perspective, the variation in wood density is mainly related to the type of soil and water regimes (Rüger et al., 2012), where trees with lower wood densities retain more water (Borchert, 1994). However, this is not relevant in Serra da Tiririca because it is a rainforest where the average monthly rainfall exceeds 95 mm (INEA, 2015). In contrast, variability could also be associated with regional historical-ecological events (Poorter et al., 2019), influenced by the succession of individuals in different habitat types. In this sense, the wood density of Serra da Tiririca - which presents an average close to the average of Atlantic Forest species (0.70 $g.cm^{-3}$) (Chave et al., 2009) - would be influenced by recognized events, as the intense extraction of charcoal between the 18th and 20th centuries (Oliveira et al., 2020), as well as by the local floristic heterogeneity (Barros, 2008).

Dendrometric traits are essential to assess the forest structure. The height and diameter of trees also vary according to the habitat types (Nascimento and Laurance, 2006). In this study, significant differences in the tree heights across habitat types were detected. Taller trees, as expected, occurred inside the remnant than at the edges. Potential causes for this pattern are the high mortality rate of trees at the edges, caused mainly by the direct interaction with the edge effects, such as winds and fires (Cochrane and Laurance, 2002; Poorter et al., 2010; Laurance and Curran, 2008).

In contrast, no significant differences were found in the median tree diameter compared between habitats, but significant differences in the diametric classes were recorded. Edges showed fewer trees between 10 to 20 cm when compared to the interior. In this context, it is worth pointing out that this pattern might be related to forest succession. Serra da Tiririca is a secondary forest, where the edge conditions favor the establishment and growth of pioneer and secondary species (Laurance et al., 2006b; Nascimento and Laurance, 2006; Chazdon et al., 2010).

The best models indicate the relationship of the plots to edges as the direct influence of wood density and tree diameter. These response variables are good predictors of the edge effect, which can exceed 300 m of distance from the edge to the interior (Laurance et al., 2002), varying the intensity of the parameter according to the size of the remnant (Nascimento and Laurance, 2006; Laurance et al., 2006a, b; Laurance et al., 2018). None of the functional traits were significantly related to the fire risk. However, adding the fire risk to the model allowed the significant relationship between diameter and distance from the edges. In this context, other unmeasured variable responses could be associated with fire risk with the edges because edges are highly vulnerable to fires and are strongly related to the frequent juxtaposed to pastures and frequent anthropogenic fires (Cochrane and Laurance, 2002).

5. CONCLUSIONS

There are significant differences in the functional traits between trees individuals in comparing the edge and interior of the remnant. Wood density and height showed lower values at the edges, while the diameter was not different. Wood density and diameter were the functional traits most related to habitat type and the distance to the edge, respectively, being good predictors of the edge effect. In contrast, there was no relationship between height and explanatory variables.

Here, the variability of functional traits tells us how essential studies on forest edges are for a complete understanding of their effects. Furthermore, it is vital to continue studies on the plots installed in Serra da Tiririca to follow the dynamic of individuals in space-time on habitat types. Finally, we recommend using our findings to assist the park's management in conserving the forest remnant.

AUTHOR CONTRIBUTIONS

This study was part of the master dissertation of the first author. Felipe Zuñe-da-Silva: Conceived and designed the study, data collection, data analysis, and text written; Pablo José Francisco Pena Rodrigues, Consuelo Rojas-Idrogo and Guillermo Eduardo Delgado-Paredes: technical review and text review; Alex Enrich-Prast and Cassia Mônica Sakuragui: research supervision, technical review, and text review. All authors approved the final version of the manuscript.

6. ACKNOWLEDGMENT

We wish thank to the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – Brasil (CAPES) for providing the first author with a scholarship (Grant No. 88887.500463/2020-00). We are grateful to André Costa, Erbersson Conceição, Rafael Fonseca and Angêlo Coutinho for the valuable field assistance, and PESET/INEA for research authorizations. The authors give a special thanks to Dra. Vera Huszar and Dra. Andrea Costa for the suggestions and first revision of the manuscript, and we also wish to extend our thanks to Dra. Bárbara de Sá Haiad for facilitating access to the Departamento de Botânica - Museu Nacional/UFRJ and Dr. Nilber da Silva for receiving the wood samples in the Herbário Museu Nacional (R).

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