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Carbon from above-ground biomass and litter accumulated in an Atlantic Forest fragment

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Abstract

This work aimed to quantify carbon (C) stocks from above-ground biomass (AGB) and accumulated litter in a fragment of the Atlantic Forest biome (edge and interior) in Northeastern Brazil. The study was carried out in areas with native vegetation, in a fragment of Atlantic tropical forest, municipality of Sirinhaém, Pernambuco, Brazil. AGB was quantified using the allometric equation proposed for tropical rainforests. The samples of plant material were dried at 60°C, weighed and ground, and then taken to the laboratory for analysis of organic C contents by dry combustion. AGB stocks were not different between the fragment edge and interior environments. The AGB stratification into diameter classes showed that large trees are important for the storage of biomass in trees. Litter biomass stocks also did not differ between edge and interior. The branch compartment showed higher levels of C. The C-AGB stocks were not different between edge and interior, similar to the C-litter. C stocks did not differ between interior and edge among tree species, except for *Protium heptaphyllum*, which had the highest C stocks at edges. With this study, we hope to contribute to improving C estimates in fragmented forests to support forest conservation policies, support REDD+ projects, and access to carbon credits.

Keywords: Carbon content; C pools; edges; fragmentation.

Introduction

Forests contain about 90% of the organic C stored in terrestrial vegetation and represent ~40% of the exchange of C between the atmosphere and the terrestrial biome (Ma et al., 2017; Matos et al., 2020).
Additionally, tropical forests play a significant role in the global C cycle through their ability to function as a sink or source of C into the atmosphere (Dibaba et al., 2019; Magnago et al., 2015). Forests accumulate biomass and C due to their growth, and this accumulation of C is partially offset by carbon emissions caused by natural and anthropogenic disturbances (Houghton, 2008).
In recent decades, tropical forests have acted as solid sinks of C dioxide; however, these C storage values have decreased in terrestrial ecosystems (Brienen et al., 2015). Forests can sequester large amounts of C per year, and it is estimated that tropical forests stock more than half of this flow. The net uptake of atmospheric CO2 can reach ~1 Pg C year^{-1} in mature neotropical forests (Houghton et al., 2015).
In this context, the Atlantic Forest stands out as the second-largest tropical rainforest in the Americas, with ~90% of its area in Brazilian territory. It represents one of the world's largest centers of biodiversity and endemism; it is estimated that 86% of its original size has already been deforested over the various economic cycles in Brazil (Balazina, 2019; Lima et al., 2020). However, the quantification and determination of biomass and C stocks in these forests are still incipient, and estimates of AGB stocks in the Atlantic Forest are rarely available (Lindner and Sattler, 2012). According to Gibbs et al. (2007), C stored in AGB of trees is typically the largest reservoir and is directly impacted by deforestation and degradation. Thus, estimating C in above-ground forest biomass (C-AGB) is critical in quantifying C stocks and fluxes in tropical forests. Therefore, a reliable approach to quantifying C stocks in the Atlantic Forest has been the AGB assessment (Matos et al., 2020). Another important point concerns the impacts of forest fragmentation on forest C stocks and the global C cycle. For Magnago et al. (2017), C stocks in trees can be negatively impacted by fragmentation and the direct influence of microclimatic conditions and soil changes. Habitat destruction usually leads to fragmentation, splitting into smaller, more isolated fragments (D'Albertas et al., 2018). Hansen et al. (2020) emphasize that the fragmentation of tropical forests results in severe losses of habitat and biodiversity and increased C emissions to the atmosphere. Fragmentation can affect abiotic components in these environments and cause significant changes in the forest structure, seriously impacting forest C stocks (Magnago et al., 2017).

Despite the importance of tropical forests as C sinks, millions of hectares of these forests have been lost in recent years due to conversion to agricultural land or pastures (Shimamoto et al., 2014).

Given the above, the objective of this work was to quantify C stocks from AGB and litter in a fragment of Atlantic Forest (edge and interior) in Northeastern Brazil. As the central working hypothesis, we expect a difference between C contents per species in different areas and between C stocks in these environments (edge and interior).

Results and discussion

AGB stocks

Average AGB stocks were not significantly different (t-test, p>0.05) between edge and interior environments (Table 1). Since it has been a fragmented area in the past (over 50 years), these biomass stocks have probably remained stable, especially at the edge, where the more significant opening of the crowns and the entry of light allows for the growth of new individuals in the forest community.

Laurance et al. (2018) point out that the initial loss of AGB due to the mortality of remaining trees can gradually recover through the regeneration of new trees in the forest community. Other studies in rainforests have also evaluated the impacts caused by edge formation on AGB stocks. For example, Rocha et al. (2019) quantified AGB storage at the edge and interior in Atlantic Forest fragment and obtained results ranging from 90-120 Mg ha^{-1}, with the most significant stocks located in the interior.

Razafindratsima et al. (2019) showed that the total AGB was not different between edge and interior tree communities, averaging de 188 Mg ha^{-1} (edge) and 242 Mg ha^{-1} (interior). Lima et al. (2020) estimated that the loss of biomass in the Atlantic Forest biome could be equivalent to deforestation of more than 50,000 km^2, translating into the loss of billions of dollars in C credits.

As for the AGB stratification, stocks at the edge and inside were significantly different between DBH classes (Kruskal-Wallis, p < 0.05) between diameter classes of the arboreal component DBH ≥ 5 cm (Figure 2).

At edges, more than 30% of the total AGB (~36 Mg ha^{-1}) was found in individuals with >35 cm DBH (Figure 2). About 50% of AGB stocks were present in the two classes of trees with the highest DBH in the forest interior. Marchiori et al. (2016) identified that individuals from tree strata with DBH ≥ 40 cm, even if weakly represented in the area (1.6%), had a significant influence on the total biomass, representing ~26% of this value. Often, these trees have a low density in terms of individuals in the forest community but with a high contribution in terms of basal area, which contributes a lot to the high AGB stocks. In both areas (edge and interior), AGB stocks were lower in smaller trees (5-15 cm DBH class). However, trees in the second diameter class (15-25 cm) stood out in biomass accumulation in the interior, which was not observed at the edge (Figure 2). Possibly, there was greater recruitment of new individuals at the edge, precisely because of the existing seed bank in the place associated with the more significant input of luminosity in these areas, contributing to the increase of biomass in medium and large-sized individuals, in terms of DBH. Bradford and Murphy (2018) demonstrated that large diameter trees contributed mainly to the biomass (~33%). In Costa Rica, Clark et al. (2019) observed that large trees represented an average of 2.5% of the total number of individuals inventoried, constituting approximately a quarter of the average basal area and total AGB. In Mexico, Navarrete-Segueda et al. (2018) concluded that most of the AGB were stored in large trees (50-186 cm DBH); in some plots, this tree size contributed almost 75% of the AGB stock.

In general, the AGB did not differ between edge and interior; a possible explanation for this could be the forest structure itself, which managed to recover from the effects generated by forest fragmentation. Another highlight would be a more significant number of more prominent individuals in the two classes with the largest DBH in the fragment, which increased the AGB stocks at edges and increased the number of individuals who occasionally settled in the area.

Litter biomass stock

Litter biomass accumulated on the forest floor (Mg ha^{-1}) did not differ by Student's t-test (t = -1.94, df = 17.76, p>0.05) between interior and edge stocks (Table 1). In the interior, it was verified an average of 3.6 Mg ha^{-1}, while at the edge stocks were 2.7 Mg ha^{-1}. A probable explanation lies in the forest structure itself and the changes in the environment that ensured the recruitment, and consequently, the deposition of plant material for the litter.

Souza et al. (2021) also evaluated the litter biomass accumulated along an interior-edge gradient of an Atlantic Forest fragment and estimated stocks ranging from 8.95-12.08 Mg ha^{-1}. However, as in the present study, these authors did not identify a significant difference between interior-edge gradients. On the other hand, in the Atlantic Forest, Vidal et al. (2007) reported that litter production was generally lower at edges. Litter production probably remained in balance in these places, not suffering severe changes over the years after the formation of the edge.

Carbon content

The C content differed (p<0.05) between evaluated forest species. The levels of C in the leaves, barks, and branches varied between species from 411.07 to 489.95 g kg^{-1}. The species *E. ovata* stood out with the highest C levels in the leaf, bark, and branch compartment (Figure 3).

Carbon content in the leaves was similar among the species; the exception was *P. heptaphyllum* which had lower levels (447.48 g kg^{-1}). The *E. ovata* had the highest average content of 472.14 g kg^{-1} (Figure 3). In the bark compartment, among the species, *E. ovata* had the highest levels of C, with an average of 473.23 g kg^{-1}. On the other hand, the highest contents of C were observed for the branch compartment, with an average of 475.24 g kg^{-1}, once again highlighting the species *E. ovata* with the highest contents and the species *T. spruceanum* with the lowest contents (459.61 g kg^{-1}).

Behling et al. (2014) obtained a different result, where the leaves had higher values than the other compartments with an average of 49.45%, while the bark compartment had the lowest contents, 46.86%. Dallagnol et al. (2011) also reported a slight trend towards higher C contents in the leaves compartment. Dallagnol et al. (2011) found that C contents rarely exceeded 50%, with values between 39 and 50% typical. For Martin and Thomas (2011), assuming generic fractions for C contents in the tropical forest may overestimate forest C stocks by ∼3.3-5.3%. Accurate knowledge of the C content between species is essential to converting AGB estimates into C stocks allocated in the forest. Behling et al. (2014) emphasize that C quantifications should seek to determine the content for each species, as well as for each biomass component. Besides that, conversion

Table 1. AGB and litter stocks (in Mg ha^{-1}) in an Atlantic Forest in Northeastern Brazil.

	AGB	SE	Litter	SE
Edge	132.83	10.39	2.75	0.29
Interior	119.19	10.01	3.62	0.35

*Litter: The litter accumulated under the forest floor, AGB: above-ground biomass.

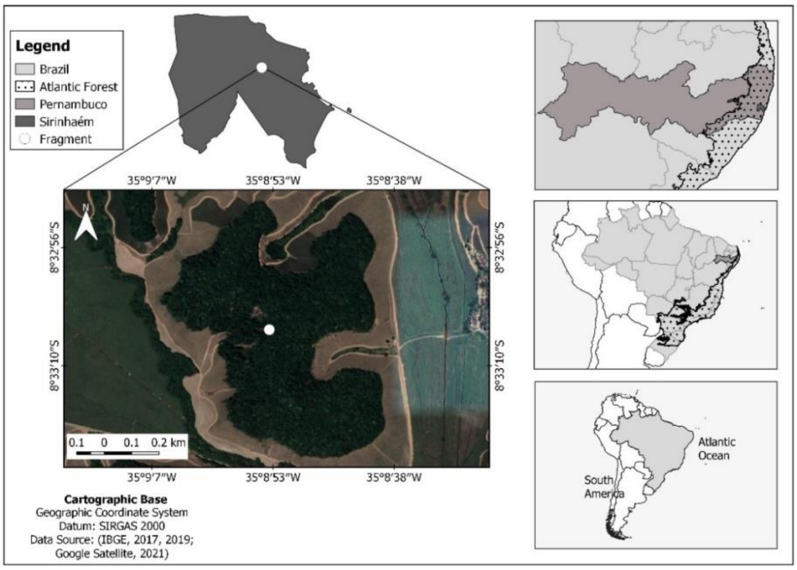

Fig 1. Location of the study area in a rainforest in northeastern Brazil.

Table 2. Stocks of C-AGB and C-litter in Atlantic Forest (edge and interior). SE: standard error of the mean.

	C-AGB (Mg C ha^{-1})	SE	C-Litter (Mg C ha^{-1})	SE
Edge	63.76	±4.99	1.20	±0.12
Interior	57.21	±4.80	1.59	±0.15

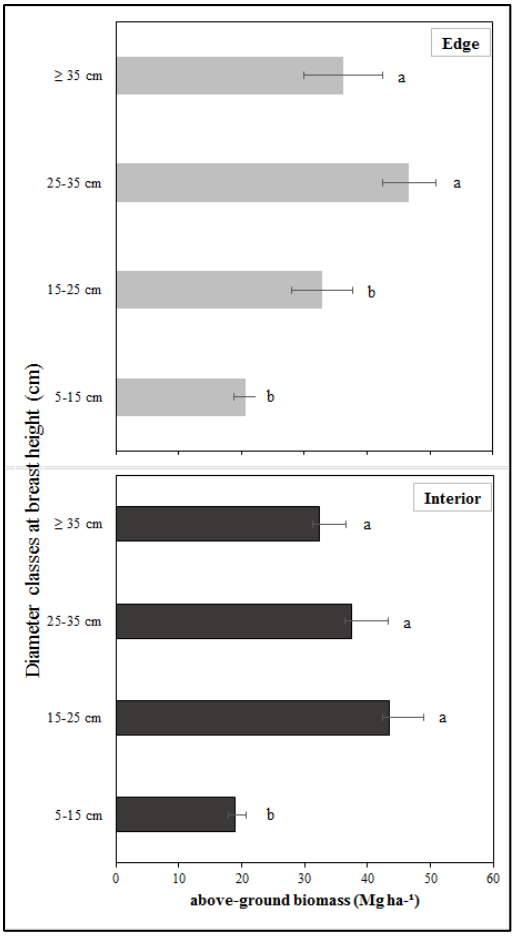

Fig 2. Contribution of different diameter classes to the AGB stock.

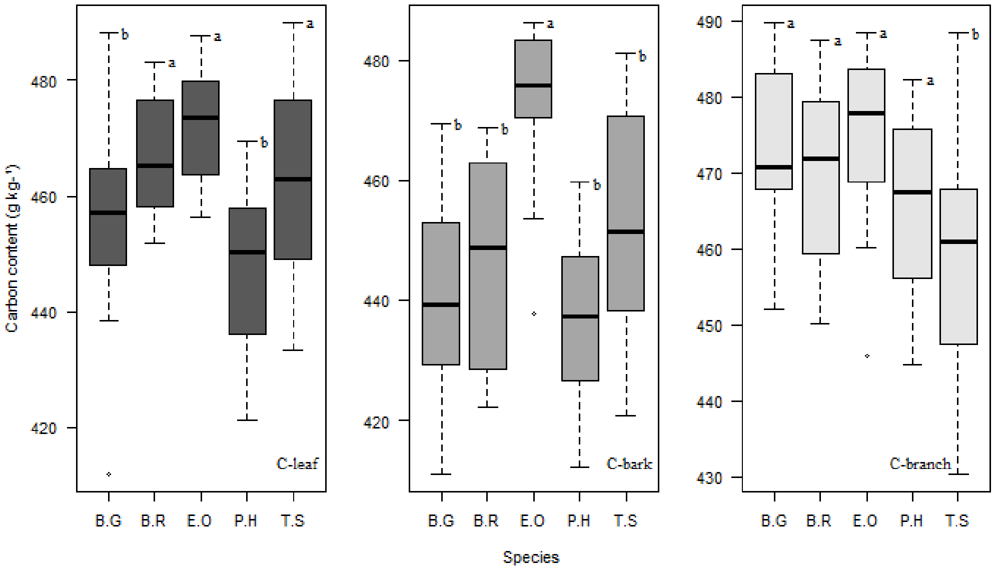

Fig 3. Carbon content in tree species (DBH≥5 cm). Means followed by the same letter do not differ from each other by the Scott-Knott test at 5% probability. *B.G: *B. guianense*, B.R: *B. rubescens*, E.O: *E. ovata*, P.H: *P. heptaphyllum* e T.S: *T. spruceanum*.

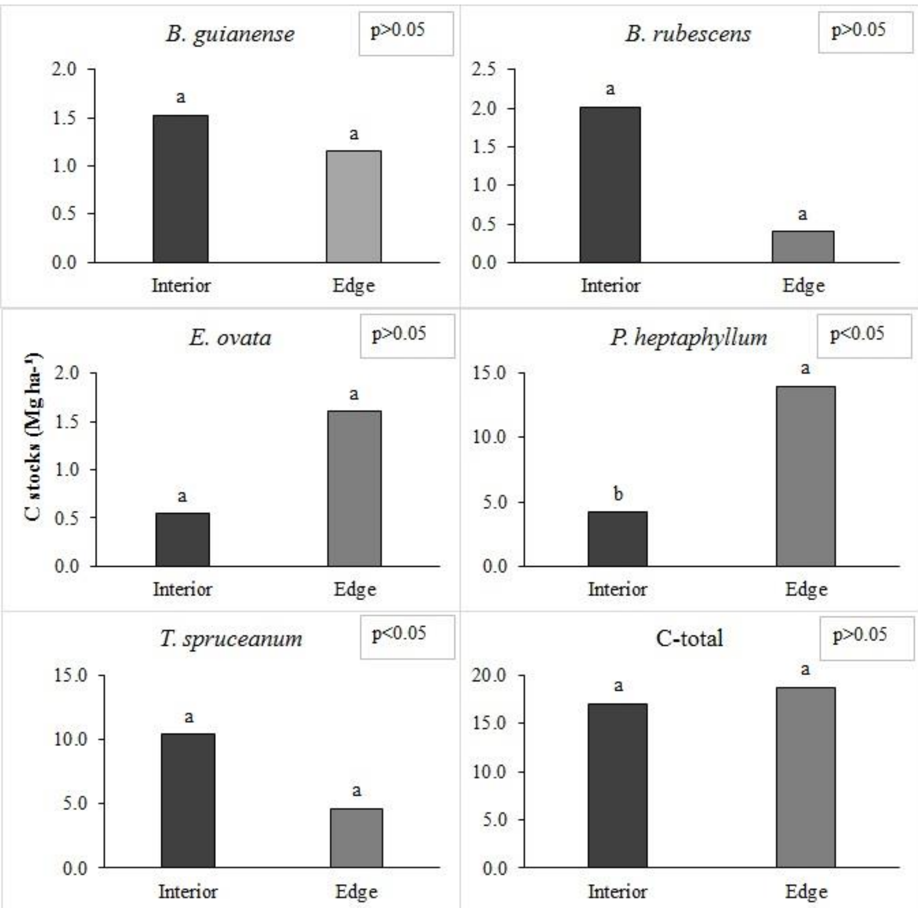

Fig 4. C stocks by species in Atlantic Forest (edge and interior), equal letters do not differ statistically by Student's t-test at 5% probability.

factors such as 50% are not appropriate due to the under-or over-estimation of the carbon content. In this aspect, Watzlawick et al. (2014) reported C levels of 36.16-46.67%, finding that the conversion factor of 0.5 overestimated the C by an average of 14.27%. The values for the C content in the leaf compartment have been reported as the primary (majority) in many studies, which is not consistent with the data observed in the present work with species from the Atlantic Forest in Northeastern Brazil.

Litter carbon content

Litter C contents did not show significant differences by Student's t-test ($t = -0.804$, $df = 17.34$, $p > 0.05$) in relation to edge and interior environments. At the edge, the plots presented C contents with an average of 436.76 g kg^{-1}, while in the forest interior, 440.66 g kg^{-1}. Chiti et al. (2016) detected a variation of 431±20 to 494±18 g kg^{-1} in the mean C contents of accumulated litter, values consistent with those obtained in our study.

Overall, the carbon contents of litter were similar to those reported in other studies in tropical forests; in addition, few studies have addressed the issue of determining the concentrations of C in the litter reservoir in tropical rainforest, especially in fragments of the Atlantic Forest.

Carbon stocks

C-AGB stocks were not significantly different (ANOVA, p>0.05) between the other areas: edge and interior (Table 2). D'Albertas et al. (2018) concluded that interior plots did not have a higher C stock but only taller trees, suggesting that edge effects in the Atlantic Forest may differ from those observed in more recently fragmented tropical forests.

However, Rocha et al. (2019) estimated average stocks of 45.43 Mg C ha^{-1} in the edge and 63.71 Mg C ha^{-1} in the interior. The authors concluded that edge formation significantly affected C stocks in the fragment.

Magnago et al. (2017) concluded that the edges and smaller fragments were warmer, windy, and less humid, with more fertile and less acidic soils, and the C stocks in the trees being higher in the forest interior. De Paula et al. (2011) concluded that habitat fragmentation and the consequent edge establishment reduce the capacity to retain C.

Edge carbon stocks did not differ from interior C stocks. This is probably associated with the fact that these places previously affected by forest fragmentation (over 50 years) have already recovered a large part of the C lost due to the adverse effects of the formation of edge, a much older forest degradation process, unlike what happens in fragmented areas in the Amazon region, where fragmentation is more recent (the 70s-80s).

Litter carbon stock

The carbon stocks of litter accumulated under the forest floor did not differ (t = -2.03, df = 17.38, p>0.05) between edge and interior covers (Table 2). The average C stocks ranged from 1.19 Mg C ha^{-1} at the edge and 1.59 Mg C ha^{-1} in the forest interior. In fragmented environments, Vidal et al. (2007) reported a downward trend in litter production at edges of the fragments, with more significant evidence in fragments with more extensive areas (> 10 ha). According to Bernier et al. (2008), the annual canopy foliage production and its subsequent senescence, together with the production and senescence of terminal branches, flowers and, fruits/seeds, represent a yearly critical sink for C in forest ecosystems.

Although there was no significant difference between edges and interior, litter carbon stocks showed high variability, possibly influencing no difference between environments. Besides, it is noteworthy that the litter biomass and C data can provide direct information on the annual inputs of C into the forest soil, representing a key compartment for quantification and movement (fluxes) of C in forest ecosystems.

Carbon stocks by species

Regarding C stocks by species, it was found that there was no significant difference by the t-test (p>0.05) in C stocks between edge and forest interior for the species: *Brosimum guianense*, *Brosimum rubescens*, *Eschweilera ovata* e *Thyrsodium spruceanum* (Figure 4).

The only species to show a significant difference (t-test, p<0.05) between C stocks (edge and interior) was *Protium heptaphyllum*, with higher values at the edge, 13.99 ± 1.75 Mg ha^{-1}.

On the other hand, the species with the lowest C stocks was *Brosimum rubescens*, with mean values of 0.29 ± 0.11 Mg C ha^{-1} at the edge.

Silva (2020) also identified a similar value in C stocks for the species *Dialium guianensis* (Aublet.) Sandw, with ~16 Mg C ha^{-1}, being responsible for the most extensive stocks in the area. However, the species *Protium heptaphyllum* obtained only ~2 Mg C ha^{-1}, much lower than obtained in the present study.

Silva et al. (2018) identified the most significant stocks for the species *Guarea guidonia* (L.) Sleumer, with an average of 24.11 Mg C ha^{-1} and *Artocarpus heterophyllus* Lam. with an average of 10.45 Mg C ha^{-1}, values higher than the results for C stocks by species obtained in the present study.

Azevedo et al. (2018) also quantified the C stocks in Atlantic Forest species in a reforestation area. They detected a variation of 1.05-8.87 Mg C ha^{-1}, emphasizing the species Guarea guidonia, which presented the highest stocks of C.

In forest fragments in Costa Rica, Santiago-García et al. (2019) reported a contribution of ~13.4 Mg C ha^{-1} for the species Pentaclethra macroloba, representing about 18% of the total stock of C.

Therefore, the need to improve biomass and forest C estimates is highlighted, especially regarding C contents and stocks by species in fragmented forest environments (Atlantic Forest). Most of these data are neglected in C quantification in tropical forests, as few species disproportionately contribute to C stocks in these areas.

Material and methods

Study area

The study was carried out in areas with native vegetation, in a fragment of humid tropical forest (edge and forest interior) in Sirinhaém, Pernambuco, Brazil (Figure 1). The prevailing climate in the area is humid tropical (Köppen climate classification), with an average annual rainfall of approximately 1,860 mm (Oliveira et al., 2016). The average altitude in the area is 60 m, and the predominant soils are of the Yellow Oxisols and Yellow, Red-Yellow, and Gray Ultisols types (Santos et al., 2018). The dominant vegetation in the fragment is humid tropical forest, classified as Lowland Dense Ombrophilous Forest.

Vegetation sampling

This study used the phytosociological and floristic data referring to the fragment previously collected according to Lima et al. (2019). In the native forest environment, 20 plots (edge=10 and interior =10) were selected for the evaluation of AGB and C stocks of the arboreal component with a diameter at breast height (DBH ≥ 5 cm). The plots at edges were placed at least 200 meters away from the plots located in the central region of the fragment (forest interior).

To determine the C content in plant biomass, samples of leaves, bark, and thin branches (> 3 cm in diameter) were collected from three individuals of each species. We selected five priority species based on the phytosociological parameters of the community, according to work by Lima et al. (2019).

Five species of high absolute density were selected based on the phytosociological survey of adult individuals previously carried out. Species were selected based on the presence criterion in both areas of the fragment (edge and interior): *Thyrsodium spruceanum* Benth. (TS), *Protium heptaphyllum* (Aubl.) Marchand (PH), *Brosimum guianense* (Aubl.) Huber (BG), *Eschweilera ovata* (Cambess.) Miers (EO) and *Brosimum rubescens* Taub. (BR).

The litter accumulated on the forest floor (edge and interior) was sampled with the aid of a 50cm x 50cm template. Samples were collected once in each plot (n=20). Then, samples were prepared, separating possible portions of soil present in the sample, deposited in paper bags to be taken to the kiln.

Samples of plant material (leaves, bark, branches, and litter) were weighed and transferred to porcelain crucibles and taken for analysis of C contents by dry combustion in Muffle furnace at 550ºC, following the procedures of Bernier et al. (2008) and Wang et al. (2012).

Data analysis

We calculated the above-ground biomass of living trees ≥5 cm dbh using the formula developed by Chave et al. (2014) for moist tropical forests:

$$AGB = 0.0673 * (p * DBH^2 * H_t)^{0.976} \qquad \text{Eq. (1)}$$

Where: AGB = above-ground biomass (Mg), *p* = wood density (g cm^{-3}), DBH = diameter at breast height (cm), Ht = total tree height (m)

The C stock by species was obtained by multiplying the average C stock by the number of individuals per hectare. Litter carbon stock was determined according to Rügnitz et al. (2009).

We used the classes (5-15, 15-25, 25-35, and ≥ 35 cm DBH) to verify the contribution of the diametric structure of the forest community in the biomass stocks (at the edge and interior).

The normality of the data was verified using the Kolmogorov-Smirnov test (Conover, 1971), and the homogeneity of the variances was verified by Levene's test (Brown and Forsythe, 1974), both at 5% probability.

Student's t-test at 5% probability was used to compare C-AGB and the levels and C stocks of litter accumulated on the forest floor at edge and interior and compare C stocks by species.

Data from the C content between species were analyzed using ANOVA with F-test at the 5% p significance level. When significant, averages were compared using a Scott-Knott test at the level of 5% significance.

When the data set showed non-normal distribution, the AGB data and the C pools were compared using the Kruskal-Wallis test at 5% (Kendall, 2008).

Analyzes and estimates of AGB in R were performed according to the manual for tropical forests (Tanguy et al., 2016). All statistical analyzes were performed in R version 3.6.3 (R Development Core Team, 2020).

Conclusion

AGB stocks showed no difference between edge and interior environments. Large trees are key elements for the storage of biomass and C in vegetation. There was no difference in terms of litter biomass and C accumulated between edge and forest interior. As for the C contents by species, the highest values were observed for the branch compartment, highlighting the species *Eschweilera ovata*, demonstrating its potential for C fixation, not only due to the high C contents but also by the density and distribution of individuals in the area. Overall, carbon stocks by species did not differ between edge and interior; the exception was *P. heptaphyllum*, which had the highest C stocks at the edge.

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