Revista
ÁRVORE
ISSN 1806 – 9088

Scientific Article

CHANGE IN A TERRA FIRME DENSE OMBROPHILOUS FOREST AFTER LOGGING IN THE BRAZILIAN AMAZON (2006-2016)

Jorge Luis Reategui-Betancourt[2*], Alba Valéria Rezende[2], Guido Briceño[3], Carlos Magno Moreira de Oliveira[2], Tatiana Dias Gaui[2], Salman Khan[5], Axa Emanuelle Simões Figueiredo[2] and Lucas José Mazzei de Freitas[4]

1 Received on 16.07.2023 accepted for publication on 05.06.2024.

2 Universidade de Brasília, Departamento de Engenhria Florestal, Brasília, DF, Brasil. E-mail: <jorgereategui91@gmail.com>, <alba.rezende@gmail.com>, <cmagnoliveira@hotmail.com>, <tatiana.gaui@gmail.com> and <axafigueiredo@gmail.com>.
3 CIRAD, Forêts et Sociétés, Montpellier, France. E-mail: <guidobricas@gmail.com>.
4 EMBRAPA Amazônia Oriental, Belém, Pará, Brasil. E-mail: <lucas.mazzei@embrapa.br>.
5 School of Architecture Planning and Environmental Policy University College Dublin, Dublin, Ireland . E-mail: <salman.khan@cirad.fr>.
*Corresponding author.

ABSTRACT

The effective management of disturbed forests requires adequate knowledge of forest dynamics. In this study, we assessed the changes in a managed forest using 18 permanent 1 ha plots located in a 'terra firme' tropical rainforest in the Eastern Amazon (Paragominas, Brazil). All individuals with a diameter at breast height (DBH) ≥ 20 cm were evaluated in two separate assessments conducted in 2006 and 2016. The results show that, ten years after logging, the managed forest exhibits an imbalance between recruitment (1.54% per year) and mortality (2.23% per year) rates, indicating that it is still in the process of recovering its structure. Nevertheless, biomass tended to increase after logging (28.49 tons per hectare). The characteristics of these changes suggest that the forest is undergoing a silvigenetic process driven by the effects of logging. Furthermore, our observations indicate that the forest remains active and has sufficient potential for new timber production at the end of the cutting cycle, considering the same species and tree sizes.

Keywords: Mortality; Recruitment; Biomass; Forest management.

How to cite:
Reategui-Betancourt, J. L., Rezende, A. V., Briceño, G., Oliveira, C. M. M. de, Gaui, T. D., Khan, S., Figueiredo, A. E. S., & Freitas, L. J. M. de. (2024). Change in a terra firme dense ombrophilous forest after logging in the brazilian Amazon (2006-2016). *Revista Árvore*, *48*(1). https://doi.org/10.53661/1806-9088202448263679. Retrieved from https://www.revistaarvore.ufv.br/rarv/article/view/263679

MUDANÇA EM UMA FLORESTA OMBRÓFILA DENSA DE TERRA FIRME APÓS EXPLORAÇÃO MADEIREIRA NA AMAZÔNIA BRASILEIRA (2006-2016)

RESUMO – O manejo eficaz de florestas perturbadas requer um conhecimento adequado da dinâmica florestal. Neste estudo, avaliamos a mudança de uma floresta manejada em 18 parcelas permanentes de 1 hectare localizadas na floresta tropical de terra firme no leste da Amazônia (Brasil, Paragominas). Todos os indivíduos com diâmetro à altura do peito (DAP) ≥ 20 cm foram avaliados em duas avaliações separadas realizadas em 2006 e 2016. Os resultados indicam que, dez anos após a exploração, a floresta manejada apresenta um desequilíbrio nas taxas de recrutamento (1,54% ao ano) e mortalidade (2,23% ao ano), sugerindo que a floresta ainda está em processo de recuperação estrutural. No entanto, a biomassa mostrou um aumento após a exploração, atingindo 28,49 toneladas por hectare. As características das mudanças indicam que a floresta está em um processo silvigenético impulsionado pela exploração madeireira. Além disso, observamos que a floresta permanece ativa e possui potencial suficiente para uma nova produção de madeira no final do ciclo de corte, considerando as mesmas espécies e tamanhos de árvores.

Palavras-Chave: Mortalidade; Recrutamento; Biomassa; Manejo florestal.

1. INTRODUCTION

The Brazilian Amazon encompasses the largest biome in Brazil, with the widest quantity and diversity of trees. The Amazon is estimated to host over 15,000 tree species (Ter Steege et al., 2020) with 5,482 species reported in the Brazilian region alone (Castuera-Oliveira et al., 2020). Tropical forests play a crucial role in global carbon storage, accounting for ~40% of the terrestrial carbon (Bonan, 2008). In addition, there are also selectively logged forests in the Amazon region, which are disturbed to varying degrees and used extensively for timber production (Asner et al., 2002; Tritsch et al., 2016). To better understand their development and ensure their sustainability for future use, it is imperative to accurately monitor these logged forests.

In the tropical forests of Africa, Asia and Lantin America, low-impact logging practices aimed at optimizing the use of forest resources are widespread (D'Oliveira et al., 2017). Forests that are sustainably managed can maintain characteristics similar to those of an undisturbed forest (Oliveira et al., 2019). Moreover, proper logging planning is also important to minimize the damage caused to tree species (D'Arace et al., 2019) and safeguard their long-term sustainability. Competition among trees is an important driver of community structure and dynamics in tropical forests mainly through effects on individual tree growth (Rozendaal et al., 2020). An accurate assessment of these dynamics is essential to understand the mechanisms by which a species can gain dominance and resist environmental change (Marimon et al., 2020).

Reduced impact logging guarantees the conservation of biodiversity values and the provision of ecosystem services in these managed forests, there by preserving natural resources for future generations (Gibson et al., 2011; Putz et al., 2012). Nonetheless, forest managers and decision-makers still lack sufficient information to define sustainable harvest intensities and cutting rotations (Rutishauser et al., 2015). Therefore, there is a need for continuous monitoring of forests impacted by logging.

In this study, we used continuous inventory measurements in a forest management area to address the following research question: How have mortality, recruitment, and species diversity values changed after 10 years of selective logging in an Amazonian forest? The aim of this study is to provide information on forest changes in a native forest in northern Brazil using mortality, recruitment, and growth parameters.

2. MATERIAL AND METHODS

2.1 Study area

The study area is located on the Rio Capim farm, in the forest management unit belonging to the company CKBV Florestal Ltd. of the Cikel Group (3° 39′ 28″ S and 48° 49′60″ W), located in the municipality of Paragominas, Pará state, Brazil (Figure 1). The Rio Capim

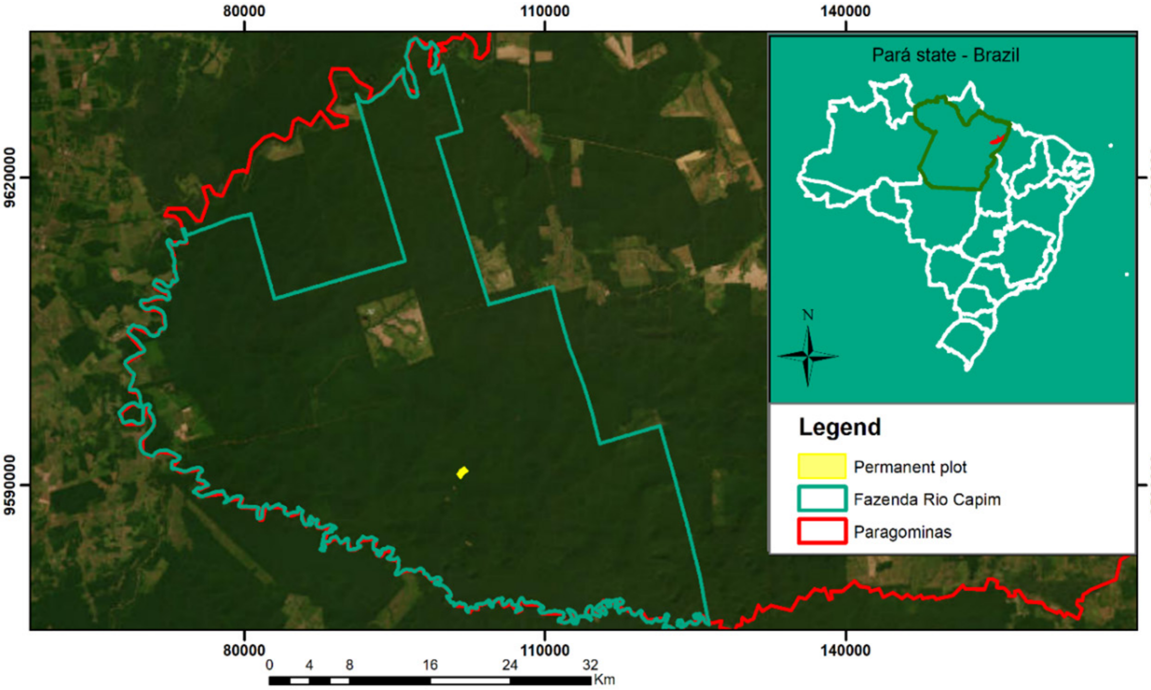

Figure 1. Location of the Forest Management area, Fazenda Rio Capim, in the municipality of Paragominas, Pará state – Brazil.

Figura 1. Localização da área de manejo florestal, Fazenda Rio Capim, no município de Paragominas, estado do Pará – Brasil.

farm has a total area of 140,000 ha, where 121,000 ha are under Forest Stewardship Council (FSC) certified forest management. The forest formation is described as Submontane Dense Ombrophylous Forest (IBGE, 2012). According to the Köppen classification, the climate is of type “Aw”, characterized as rainy tropical with average annual rainfall of 1,800 mm, with a well-defined dry season from July to September, with an average annual temperature of 26.3°C and relative humidity of 81% (Alvares et al., 2013). The dominant soil type in the study area is Belterra clay (Laurent et al., 2017).

The forest management unit at Rio Capim farm consists of 35 Annual Production Units (APUs), subdivided into Work Units (WUs). The data collected were from APU (7,585 ha), which are divided into 73 Working Units (WUs). This area is part of a network 18 permanent plots of one hectare each (100 x 100m) was selected for this study (Cesario et al., 2022). These plots were grouped into two transects with 9 plots in each group. In the plots, all trees with DBH (diameter at 1.30 m from the ground) $\geq$ 20 cm were inventoried. Each permanent plot was divided into sixteen 25 m x 25 m subplots, and two contiguous subplots were drawn to measure trees between 10 cm $\leq$ DBH < 20 cm, totaling 36 subplots (Ferreira, 2005).

Over ten years, a series of continuous inventory measurements were conducted. The first measurement took place in 2004, prior to logging, while subsequent measurements were taken in the years 2005, 2006, 2008, 2010, 2012, 2014 and 2016. For this study, however, we focused on the data collected from the year 2006 through 2016 covering a 10-year period. The logging was conducted in July 2004 where approximately 34 commercial species were extracted, corresponding to an average of 7 trees ha^{-1}, equivalent to an average volume of 21.3 m^3 ha^{-1} of roundwood or 51.4 m^3 ha^{-1} of the standing volume of the plots (Ferreira, 2005; Sist and Ferreira, 2007). The average diameter of felled trees was 79.5 cm and for each tree harvested 3.4 m^3 of roundwood were obtained. The average felling rate in the plots was 67.7% (Sist and Ferreira, 2007).

2.2 Data analysis

We first analyzed and described the horizontal structure of the forest community of trees ≥20 cm DBH in 2016, including trees <20 cm in 2006 that entered the first class at the end of the analysis period, using phytosociological parameters such as Relative Frequency (RF), Relative Density (RD) and Relative Dominance (DoR) and Importance Value Index (IVI) as recommended by Souza and Soares (2013).

With data from the years 2006 to 2016 of trees ≥20cm DBH, the dynamics of different variables over 10 years of forest development were determined. The periodic annual increment (PAI) was also calculated. For the mortality (M) and recruitment (R) rates equations 1 and 2 were applied (Sheil et al., 1995; Sheil and May, 1996), while for the basal area loss (L) and gain (G) equations 3 and 4 were used (Souza Werneck and Franceschinelli, 2004).

$$M = \left\{1 - \left[\frac{No - m}{No}\right]^{\frac{1}{t}}\right\}100 \qquad \textit{(Eq.1)}$$

$$R = \left\{1 - [1 - \frac{Nr}{Nt}]^{1/t}\right\}100 \qquad \textit{(Eq.2)}$$

$$P = \left\{1 - \left[\frac{Go - Gm + Gd}{Go}\right]^{\frac{1}{t}}\right\}100 \qquad \textit{(Eq.3)}$$

$$G = \left\{1 - [1 - \frac{Gr + Gg}{Gt}]\right\}100 \qquad \textit{(Eq.4)}$$

‘t’ represents the time elapsed between two measurements, ‘No’ and ‘Nt’ denote the initial and final tree counts, ‘m’ and ‘r’ correspond to the number of dead trees and recruits respectively, ‘Go’ and ‘Gt’ indicate the initial and final basal areas, ‘Gm’ and ‘Gr’ represent the basal areas of dead individuals and recruits respectively, ‘Gd’ denotes the increment resulting from breakage or partial trunk loss, and ‘Gg’ signifies the increment in basal area of surviving trees.

Additionally, from this same group of data of trees ≥20cm DBH, with equations 5, 6 and 7 the rate of net change of tree density (RCTD), basal area (RCG) and the tree replacement rate (R) were calculated. After defining the half-life time (T1/2), we used equation 8, which corresponds to the time required for the community to reduce its size by half; and the doubling time (T2), equation 9, which is the time required for the community to double its size while maintaining the current rate of inflow. To assess individual turnover rate (TR), we employed equation 10, and for basal area turnover rate (TG), we used formula equation 11. Finally, the stability of the tree community (E) was determined with equation 12, with a value closer to zero indicating a more stable forest. Moreover, a smaller value of replacement indicates a more dynamic tree community (Korning and Balslev, 1994).

$$\mathrm{RCT}_i = \left\{\left[\frac{Nt}{No}\right]^{\frac{1}{t}} - 1\right\}100 \qquad \textit{(Eq.5)}$$

$$\mathrm{RC}_G = \left\{\left[\frac{Gt}{Go}\right]^{\frac{1}{t}} - 1\right\}100 \qquad \textit{(Eq.6)}$$

$$\mathrm{R} = [\mathrm{T}_{1/2} + \mathrm{T}_2]/2 \qquad \textit{(Eq.7)}$$

$$\mathrm{T}_{1/2} = [(\ln 0.5)/\ln[(No - m)/No]^{\frac{1}{t}} \qquad \textit{(Eq.8)}$$

$$\mathrm{T}_2 = [(\ln 2)/\ln[(No + r)/No]^{\frac{1}{t}} \qquad \textit{(Eq.9)}$$

$$\mathrm{T}_R = (M + R)/2) \qquad \textit{(Eq.10)}$$

$$\mathrm{T}_G = (P + G)/2) \qquad \textit{(Eq.11)}$$

$$\mathrm{E} = (\mathrm{T}_{1/2} - \mathrm{T}_2) \qquad \textit{(Eq.12)}$$

For above ground biomass estimation, equation 13 developed by Chave et al. (2014) was used. The biomass was estimated for three diameter classes (20 - 40 cm, 40 - 60 cm and >60 cm) and was compared for the two periods using the Wilcoxon non-parametric alternative test. The analyses were done in R version 4.02.3 software.

$$\begin{aligned} ABG = {} & \exp[-1.803 - 0.976 * E + 0.976 * \ln(\rho) \\ & + 2.673 * \ln(\mathrm{dbh}) - 0.0299 * [\ln(dbh]^2]) \end{aligned} \qquad \textit{(Eq.13)}$$

Where: ABG is aboveground biomass, E is the site-specific bioclimatic stress variable, ρ is wood density (in g cm^{-3}), and dbh is diameter at breast height (in cm).

3. RESULTS

During the 10-year monitoring period, it was observed that 11 out of 20 species maintained their ecological importance by retaining their position on the Importance Value Index (IVI). However, the remaining species exhibited slight variations in their position on the IVI, indicating some changes

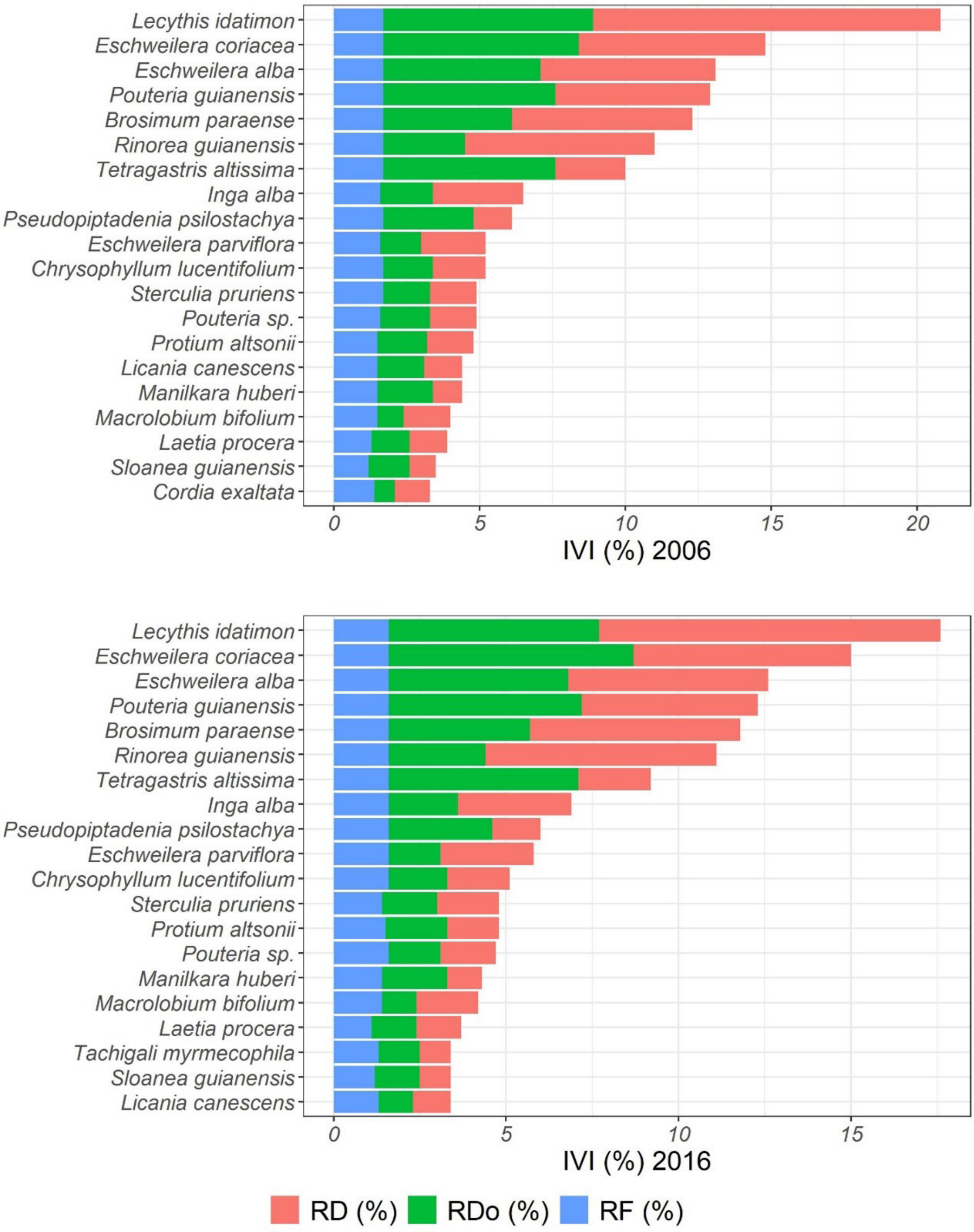

Figure 2. Ranking of the 20 species with the highest Importance Value Index (IVI). Relative Frequency (RF), Relative Density (RD) and Relative Dominance (RDo) parameters for the years 2006 and 2016.

Figura 2. Ranking das 20 espécies com o maior Índice de Valor de Importância (IVI). Parâmetros de frequência relativa (FR), densidade relativa (DR) e dominância relativa (DoR) para os anos de 2006 e 2016.

in their relative ecological importance (Figure 2).

In terms of relative density (RD), the species *Lecythis idatimon* Aubl. and *Rinorea guianensis* Aubl., had the greatest contribution in terms of number of individuals presenting the highest values for the years 2006 and 2016. As for the relative dominance (RDo), a parameter related to the basal area, *Lecythis idatimon* Aubl. and *Eschweilera coriacea* (DC.) S.A. Mori contributed significantly in both periods (Figure 2).

After the first year of exploration, 2006, 3104 tree individuals (172.4 ind ha^{-1}), and richness of 195 species (10.83 ssp ha^{-1}) were found. In the year 2016, 10 years after the exploitation, 3332 individuals), belonging to 194 species (10.77 ssp ha^{-1}), were recorded 185.1 ind ha^{-1}.

During the 10-year monitoring period, the forest showed a mortality of 446 individuals (24.7 ind ha^{-1}) with an average tree mortality rate of 1.54% year^{-1}, indicating a net loss rates of 0.71% and 1.08% of individuals and basal area, respectively, (Table 1). The recruitment of 674 trees (37.4 ind ha^{-1}) was observed, representing a recruitment rate of 2.23% year-on-year (Table 1). The PAI of the forest between the years 2006 and 2016, an 11-year period, was 0.32 cm year^{-1}. The rates of basal area loss and gain were 1.44% and 2.48% respectively, indicating a high level of dynamism in relation to recruitment and

Table 1. Change of a tree community after selective logging a submontane dense ombrophilous forest in southeastern Pará state over an 10-year period

Tabela 1. Mudança de uma comunidade de árvores após o corte seletivo de uma floresta ombrófila densa submontana no sudeste do estado do Pará em um período de 10 anos.

Characteristics	Total
Number of individuals 2006 (ind. ha^{-1})	172 ±1
Number of individuals 2016 (ind. ha^{-1})	185 ±1
Species richness 2006 (N° ssp.)	195
Species richness 2016 (N° ssp.)	194
Periodic increase of diameter (cm ano^{-1} ha^{-1})	0,32
Mortality rate (% year^{-1})	1.54
Recruitment rate (% year $^{-1}$)	2.23
Basal area loss rate (% year $^{-1}$)	1.44
Basal area gain rate (% year $^{-1}$)	2.48
Net change rate of individuals (% year^{-1})	0.71
Net change rate of basal area (% year^{-1})	1.08
Replacement time for individuals (years)	43.98
Basal area replacement time (years)	72.90
Half-life time (years)	49.16
Duplication time (years)	38.80
Turnover rate of individuals (% year^{-1})	1.89
Basal area turnover rate (% year^{-1})	1.96
Individual stability (years)	10,35
Basal area stability (years)	38.15
Total biomass 2006 (ton ha^{-1})	262.71±2.1
Total biomass 2016 (ton ha^{-1})	291.21±2.1

mortality processes.

In the studied forest, after logging, the half-life of trees was determined to be 49.16 years, while the doubling time was estimated as 38.80 years. The replacement time for individuals, however, was estimated to be 43.98 years. Additionally, a replacement time of 72.90 years was observed for the basal area. With a tree turnover rate of 1.89% per year and a basal area turnover rate of 1.96% per year, the forest composition exhibited an individual tree stability of 10.35 and a basal area stability of 38.15. Regarding aboveground biomass, the study observed a significant increase in biomass stockpiling ten years after logging. Specifically, the amount of aboveground biomass stock increased from 262.71+/- 2.1 ton ha^{-1} in 2006 to 291.21+/- 2.1 ton ha^{-1} in 2016, highlighting a notable recovery and accumulation of biomass during this time period (Table 1).

The gains and losses in tree biomass exhibited significant variations between different diametric classes and between monitoring periods ($p<0.05$). Within the smallest diametric class (20 to 40 cm), there was gain in biomass of 47% throughout the monitoring period (66.02±0.51 ton ha^{-1} in 2006 to 97.12±0.65 ton ha^{-1} in 2016). In contrast, the larger diametric classes showed less gain in tree biomass, with a 23% increase observed for the 40 to 60 cm class (66.75 +/- 0.75 ton ha^{-1} in 2006 and 82.15 +/- 0.81 ton ha^{-1} in 2016). The biomass of individual trees with a diameter larger than 60 cm experienced a gain of 14%, rising from 98.06 +/- 1.98 ton ha^{-1} in 2006 to 111.96 +/- 2.07 ton ha^{-1} in 2016. (Figure 3).

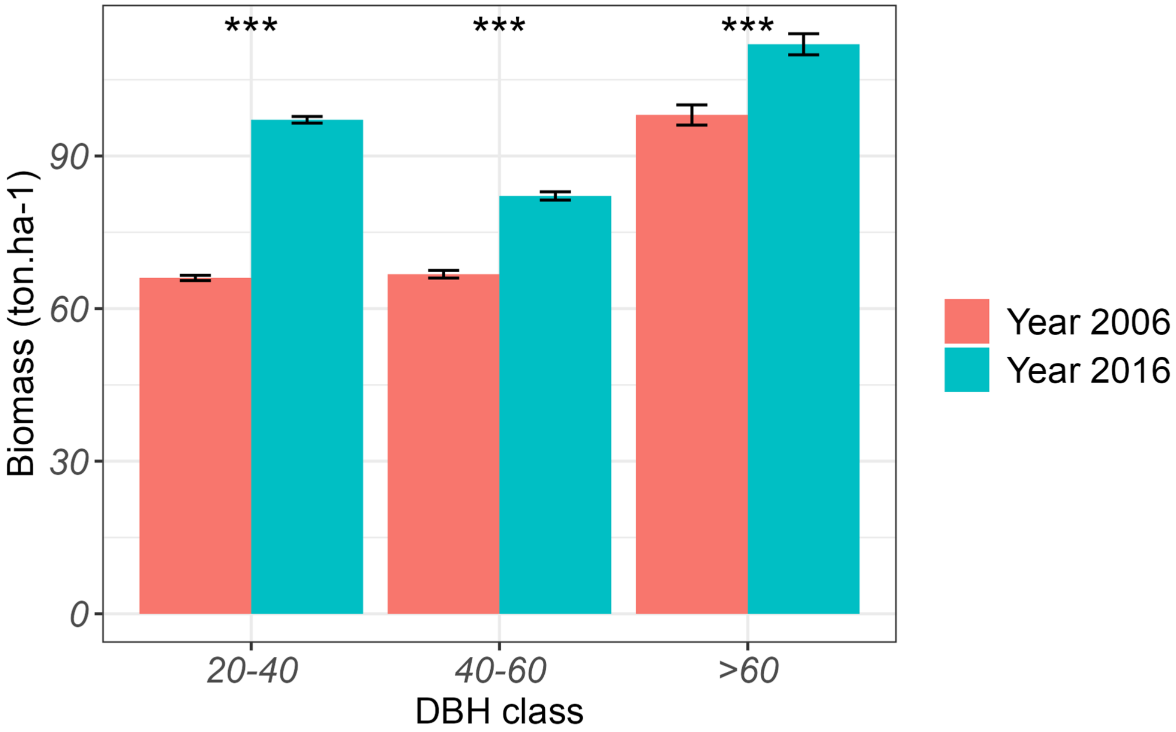

Figure 3. Biomass by diametric class of an Amazonian Forest in Northwestern Brazil

Figura 3. Biomassa por classe diamétrica de uma Floresta Amazônica no Noroeste do Brasil

4. DISCUSSION

4.1 Ecological impacts and recovery change following selective logging

The forest under study was cleared from 2004 onwards, and the effects of logging continued until 2006. These activities resulted in significant losses of trees that were damaged during the logging process. Similar findings were reported by Oliveira et al. (2019) and Rutishauser et al. (2015), highlighting the ongoing impacts of logging on forests. It is common for managed forests to experience a reduction in basal area and volume as large trees are harvested and other trees dies from felling and log dragging (Rutishauser et al., 2015). In addition, the width of the secondary track can exacerbate these impacts of ecological disturbance (D'Arace et al., 2019).

In our analysis we found a significant increase in the number of individuals 228 (12.6 ind ha^{-1}) in the 10 years (2006-2016) after logging, but the richness in the entire forest decreased from 195 to 194 species. These species richness values are significantly lower than those observed in other tropical forests that were not affected by severe ecological disturbance. For instance, the number of tree species with a DBH ≥ 10 cm in Brazil was reported to be 250 species per hectare (Carneiro, 2004; Marra et al., 2014) and can reach up to 300 species on a single hectare (Valencia et al., 1994; Cerqueira et al., 2021). Nonetheless, it is pertinent to mention that in our study the minimum diameter for a tree to be included in the inventory was 20 cm. Despite the apparent low richness of tree species observed, these fluctuations in the number of species were relatively insignificant during the monitored interval.

The PAI of the forest, considering only the individuals that remained alive during the 10-year period, showed an increment of 0.32 cm year^{-1}. This value is consistent with previous studies carried out in neotropical forests, which reported a growth rate of 0.25 to 0.6 cm year^{-1} (Higuchi et al., 1997; Gourlet-Fleury et al., 2004; Oliveira et al., 2005). Other studies reported a mean diameter increment for trees ≥ 5 cm DBH over an eight-year period of 0.37 cm year^{-1} after logging trees of ≥ 45 cm DBH and 0.36 cm year^{-1} after logging trees with a DBH of ≥ 55 cm (Carvalho et al., 2004). By reducing the logging intensity to 3-4 trees per hectare (10-14 m^3 per hectare) and implementing silvicultural treatments, the annual increment could potentially improve from 0.40 - 0.50 cm/year. With this approach, we could guarantee a sustainable cutting cycle of 40 years (Sist and Ferreira, 2007), guaranteeing the growth and survival probability of the remaining trees after logging (Reategui-Betancourt et al., 2023).

The forest exhibited an average tree mortality rate of 1.54% per year, with a net change in both individuals and basal area amounting to 0.71% and 1.08%, respectively. This observed tree mortality rate aligns closely with findings from other studies conducted in relatively undisturbed tropical forests (Phillips et al., 2004; Teixeira et al., 2007; Phillips et al., 2008; Phillips et al., 2010; Johnson et al., 2016). It is worth noting that mortality rates may vary significantly depending on the specific site and monitoring intervals, as demonstrated by modeling data covering up to 25 and 50 years (Lewis et al., 2004; Phillips et al., 2004, 2010). In the present study, the observed mortality rate is approximately 21% lower than the average value reported for the entire Amazon basin, when a longer time interval of 14 years is considered.

However, these higher mortality rates observed, corroborate with other studies that investigated forest dynamics after selective logging (Azevedo et al., 2008; Amaral et al., 2019). In particular, in a study in an experimental management area in the Manaus region, Amaral et al., (2019) observed mortality rates between 2.4% at low exploitation intensity and 4.6% at high intensity during the 25-year monitoring period. Selective logging causes damage to 24.5% of the remaining trees (Martins et al., 1997). Therefore, these higher mortality rates observed after selective logging should be related to the detrimental effects on the surviving individuals in the logged forest.

In the study area, the forest showed a recruitment rate of 2.23% year-^{1}. This recruitment rate is also substantially higher than what is typically observed in undisturbed tropical forests, where values range between 0.9% and 1.8% per year (Lieberman and Lieberman, 1987; Phillips et al., 2004; Lewis et al., 2004). Although these rates observed in the present study are higher than values found in tropical forests free of anthropogenic disturbance (Phillips et al., 2004), they corroborate the existence of a balance in the entry and exit of individuals in tropical forests, suggesting stability in the abundance of trees in the forest after logging. These higher recruitment rates in selective logging areas can be attributed to the creation of clearings, an immediate consequence of tree felling and high tree mortality from damage in subsequent years (Amaral et al., 2019).

The opening of clearings alters microclimatic conditions, making the environment more favorable for the establishment of pioneer species and altering tree recruitment rates (Denslow et al., 1987; Espírito Santo et al., 2014; Soamandaugh et al., 2017). However, it is important to note that recruitment rates, similar to mortality rates, are sensitive to monitoring intervals as instances of tree mortality and recruitment may go unrecorded during longer monitoring censuses (Lewis et al., 2004; Talbot et al., 2014). Therefore, caution should be exercised while conducting long-term studies and performing cross-area comparisons. For our study, the monitoring interval had a periodicity of 10 years.

In the forest studied, following logging activities, the half-life (49.16 years) was found to exceed the doubling time (38.80 years). This relationship shows that the forest is in a phase characterized by the "construction" of the silvigenetic cycle, suggesting that periods of higher mortality occurred earlier, especially in the period 2005-2006 immediately after logging. In addition, high mortality occurs mainly during the first years of forest succession giving way to new recruitment windows for more individuals and species (Van Breugel et al., 2007). It can also be attributed to the imbalance between recruitment and mortality rates, signifying that the forest is in constant recovery of its structural composition, with trees showing a long half-life and a low doubling time (Mews et al., 2011).

The replacement time of individuals and basal area, which are 43.98 and 72.90 years respectively, represents the supply time required by the forest to restore its initial values. The rate of tree turnover is 1.89% year^{-1} and of basal area 1.96% year^{-1}, presenting a stability period of 10.35 years for individuals and 38.15 years for basal area. These values are directly influenced by the exploration that occurs in the forest through the formation of clearings and the dragging of logs. Nonetheless, the recovery time heavily depends on the intensity of logging. For example, projections conducted in the same forest with different logging intensities revealed that for a low-intensity logging of 3 trees per hectare, the estimated time for above-ground biomass recovery was 15 years. In contrast, for the typical logging intensity applied in the region, which is 6 trees per hectare, the recovery time can extend up to 51 years (Mazzei et al., 2010).

In general, when considering exclusively the number of trees entering and leaving the system, there is an apparent dynamic equilibrium between the number of dead and recruited individuals, resembling the pattern observed in undisturbed forests (Lewis et al., 2004; Phillips et al., 2004; Rossi et al., 2007; Amaral et al., 2019). However, the evidence presented here demonstrates a significant balance in floristic composition. The complete replacement of dead trees by newly recruited individuals indicates that in this 10-year period of post-logging forest dynamics, silvagenesis is highly active and sufficient to ensure new timber production from the same species and tree sizes at the end of the cutting cycle.

4.2 Biomass recovery and sustainability in tropical forests after selective logging

An amount of 9.78% of the aboveground biomass stored 10 years after logging showed the slow resilience of tropical forests to anthropic interventions. These results are consistent with observation in the existing literature, which indicate that tropical forests subjected to selective logging require between 15 and over 100 years to retrieve their original biomass levels (Blanc et al., 2009; Mazzei et al., 2010; West et al., 2014). However, assessing this recovery in total biomass alone of a given area is not sufficient to evaluate the resilience of these forests and the possibility of initiating a new cutting cycle. It is also necessary to assess the recovery of the volume of commercial wood stored in the trees to ensure sustainable cycles of timber harvest while promoting the conservation of these forests.

The basal area gain rate of 2.48%, exceeding the loss rate by 1.44%, demonstrated that the forest is in the process of succession after logging, where the number of dead individuals was suppressed by recruits. This gain is less pronounced in the largest classes as selective logging was restricted to the largest diametric classes, while mortality associated with collateral damage from logging occurs in all classes. Additionally, recruitment tends to occur only in the smallest diametric class. These results reinforce the slow recovery of these forests and further highlight the lower capacity of these managed forests to sequester and store carbon.

After selective logging, the newly recruited trees belong to different species than the commercially exploited ones (Baraloto et al.

2012; Imai et al. 2012; Gaui et al., 2019). This phenomenon can potentially compromise the ecosystem functioning and the consequent provision of the associated services (Leverkus and Castro, 2017). For example, a *Licania heteromorpha* of 30 cm diameter and 20 m height stores approximately 4.14 Mg of carbon, while a *Cecropia* sp. a pioneer with the same dimensions only stores 1.47 Mg of carbon.

Considering the significant role of these forests in regulating planetary biogeochemical cycles, including annually fixing the amount of carbon emitted by the entire global human economy (Beer et al., 2010), small changes in species composition can undermine their capacity in processing and storing carbon in their biomass. Analyzing the change in species composition only is not sufficient for monitoring the response of these forests to forest management. A thorough assessment of forest dynamics, including information on mortality, recruitment, and growth rates, is crucial to understand the patterns of change and recovery of these forests post-selective logging.

However, it is important to emphasize that when drawing conclusions about the forest's ability to recover after logging, forest management actions must prioritize both the timber production of commercial species and the conservation of these forests. Simultaneously, it is crucial to ensure the long-term sustainability of these forests, as they play a vital role in providing essential ecological services

5. CONCLUSION

The ombrophilous forest, ten years after logging, shows an imbalance between mortality and recruitment, indicating an ongoing process of structural recovery. The observed characteristics of forest change reveal a silvigenetic state resulting from the effects of logging. This pattern indicates that the forest is highly dynamic and has the capacity to maintain resilience and stability within the ecosystem. These results highlight the complex renewal of the forest, reflecting differentiated responses to management interventions. This information is crucial for forest management in the Brazilian Amazon to define strategies for selecting species and trees to be harvested.

AUTHOR CONTRIBUTIONS

J.L.R.B., data analysis and text written; L.J.M. de F. and A.V.R., research supervision and text review; G.B. and C.M.M. de O., conception and data analysis, writing and editing; T.D.G¸ S.K and A.E.S.F., text review.

6. REFERENCES

Alvares CA, Stape JL, Sentelhas PC, Gonçalves JD, Sparovek G. Köppen's climate classification map for Brazil. Meteorologische zeitschrift; 2013; 22(6):711-28.

Amaral MR, Lima AJ, Higuchi FG, Dos Santos J, Higuchi N. Dynamics of tropical forest twenty-five years after experimental logging in Central Amazon mature forest. Forests; 2019; 10(2):89.

Asner GP, Keller M, Pereira Jr R, Zweede JC. Remote sensing of selective logging in Amazonia: Assessing limitations based on detailed field observations, Landsat ETM+, and textural analysis. Remote sensing of environment; 2002; 80(3):483-96.

Azevedo CP, Sanquetta CR, Silva JN, do Amaral Machado S. Efeito de diferentes níveis de exploração e de tratamentos silviculturais sobre a dinâmica da floresta remanescente. Floresta; 2008; 38(2).

Baraloto, C. et al. Contrasting Taxonomic and Functional Responses Of A Tropical Tree Community To Selective Logging. Journal of Applied Ecology; 2012; 49(4): 861–870.

Beer C, Reichstein M, Tomelleri E, Ciais P, Jung M, Carvalhais N, Rödenbeck C, Arain MA, Baldocchi D, Bonan GB, Bondeau A. Terrestrial gross carbon dioxide uptake: global distribution and covariation with climate. Science; 2010; 329(5993):834-8.

Blanc L, Echard M, Herault B, Bonal D, Marcon E, Chave J, Baraloto C. Dynamics of aboveground carbon stocks in a selectively logged tropical forest. Ecological Applications; 2009; 19(6):1397-404.

Bonan GB. Forests and climate change: forcings, feedbacks, and the climate benefits of forests. Science; 2008; 320(5882):1444^{-1}449.

Carneiro V M. Composição florística e análise estrutural da floresta primária de terra firme na bacia do rio Cuieiras, Manaus-AM. [S.L.] Instituto Nacional De Pesquisas Da Amazônia (INPA); 2004.

Carvalho JO, Silva JN, Lopes JD. Growth rate of a terra firme rain forest in Brazilian Amazonia over an eight-year period in response to logging. Acta Amazonica; 2004; 34:209-17.

Castuera-Oliveira L, Oliveira-Filho AT, Eisenlohr PV. Emerging hotspots of tree richness in Brazil. Acta Botanica Brasilica; 2020; 34:117-34.

Cerqueira RM, Jardim MAG, Júnior LLMS, Paixão LP, Martins MB. Fitossociologia do estrato arbóreo em floresta nativa e em áreas do programa de recuperação de áreas degradadas sob influência da mineração, Paragominas, Pará, Brasil. Nature and Conservation; 2021; 14(3): 22-41.

Cesario FV, de Carvalho Balieiro F, Mazzei L. Humipedon dynamics in lowland Amazonian forests: are there Amphi humus forms even in tropical rain forests?. Geoderma; 2022; 418: 115849.

Chave J, Réjou-Méchain M, Búrquez A, Chidumayo E, Colgan MS, Delitti WB, Duque A, Eid T, Fearnside PM, Goodman RC, Henry M. Improved allometric models to estimate the aboveground biomass of tropical trees. Global change biology; 2014; 20(10):3177-90.

D'arace LMB, et al. O Manejo Florestal Como Estratégia Para Mitigar Os Impactos Da Exploração Florestal. Revista Ibero-Americana de Ciências Ambientais; 2019; 10(6):32–42.

D'Oliveira MV, Oliveira LC, Acuña MH, Braz EM. Twenty years monitoring growth dynamics of a logged tropical forest in Western Amazon. Pesquisa Florestal Brasileira; 2017; 37(92):493-502.

Denslow JS. Tropical rainforest gaps and tree species diversity. Annual review of ecology and systematics; 1987; 18(1):431-51.

Espírito-Santo FD, Gloor M, Keller M, Malhi Y, Saatchi S, Nelson B, Junior RC, Pereira C, Lloyd J, Frolking S, Palace M. Size and frequency of natural forest disturbances and the Amazon forest carbon balance. Nature communications; 2014; 5(1):1-6.

Ferreira N. Análise da sustentabilidade do manejo florestal com base na avaliação de danos causados por exploração de impacto reduzido (eir) em floresta de terra firme no município de Paragominas-PA. Dissertação [Mestrado em Manejo Florestal] - Universidade Federal Rural da Amazônia; Belém, Pará; 2005.

Gaui TD, Costa FR, de Souza FC, Amaral MR, de Carvalho DC, Reis FQ, Higuchi N. Long-term effect of selective logging on floristic composition: A 25 year experiment in the Brazilian Amazon. Forest Ecology and Management; 2019; 15(440):258-66.

Gibson L, Lee TM, Koh LP, Brook BW, Gardner TA, Barlow J, Peres CA, Bradshaw CJ, Laurance WF, Lovejoy TE, Sodhi NS. Primary forests are irreplaceable for sustaining tropical biodiversity. Nature; 2011; 478(7369):378-81.

Gourlet-Fleury S, Guehl JM, Laroussinie O. Ecology and management of a neotropical rainforest. Lessons drawn from Paracou, a long-term experimental research site in French Guiana. Paris: Elsevier; 2004.

Higuchi N, Santos JD, Ribeiro RJ, Freitas JV, Vieira G, Coic A, Biot Y. Crescimento e incremento de uma floresta amazônica de terra-firme manejada experimentalmente. BIONTE-Biomassa e Nutrientes Florestais; 1997; 1: 89-132.

Instituto Brasileiro de Geografia e Estatística (IBGE). Manual Técnico Da Vegetação Brasileira: Sistema Fitogeográfico: Inventário Das Formações Florestais e Campestris: Técnicas e Manejo de Coleções Botânicas: Procedimentos Para Mapeamento. Rio de janeiro: IBGE; 2012; 2(1):253-272.

Imai N, Seino T, Aiba SI, Takyu M, Titin J, Kitayama K. Effects of selective logging on tree species diversity and composition of Bornean tropical rain forests at different spatial scales. Plant Ecology. 2012 Sep;213:1413-24.

Johnson MO, Galbraith D, Gloor M, De Deurwaerder H, Guimberteau M, Rammig A, Thonicke K, Verbeeck H, Von Randow C, Monteagudo A, Phillips OL. Variation in stem mortality rates determines patterns of above-ground biomass in Amazonian forests: implications for dynamic global vegetation models. Global change biology; 2016; 22(12):3996-4013.

Korning J, Balslev H. Growth rates and mortality patterns of tropical lowland tree species and the relation to forest structure in Amazonian Ecuador. Journal of Tropical Ecology; 1994; 10(2):151-66.

Laurent F, Poccard-Chapuis R, Plassin S, Pimentel Martinez G. Soil texture derived from topography in North-eastern Amazonia. Journal of Maps; 2017;13(2):109-115.

Leverkus AB, Castro J. An ecosystem services approach to the ecological effects of salvage logging: valuation of seed dispersal. Ecological Applications; 2017; 27(4):1057-63.

Lewis SL, Phillips OL, Sheil D, Vinceti B, Baker TR, Brown S, Graham AW, Higuchi N, Hilbert DW, Laurance WF, Lejoly J.. Tropical forest tree mortality, recruitment and turnover rates: calculation, interpretation and comparison when census intervals vary. Journal of Ecology; 2004; 92(6):929-44.

Lieberman D, Lieberman M. Forest tree growth and dynamics at La Selva, Costa Rica (1969-1982). Journal of tropical ecology; 1987; 3(4):347-58.

Marimon BS, Oliveira-Santos C, Marimon-Junior BH, Elias F, de Oliveira EA, Morandi PS, S Prestes NC, Mariano LH, Pereira OR, Feldpausch TR, Phillips OL. Drought generates large, long-term changes in tree and liana regeneration in a monodominant Amazon forest. Plant Ecology; 2020; 221:733-47.

Marra DM, Chambers JQ, Higuchi N, Trumbore SE, Ribeiro GH, Dos Santos J, Negrón-Juárez RI, Reu B, Wirth C. Large-scale wind disturbances promote tree diversity in a Central Amazon forest. PloS one; 2014; 9(8):e103711.

Martins EP, Oliveira AD, Scolforo JR. Avaliação dos danos causados pela exploração florestal à vegetação remanescente, em florestas naturais. Cerne; 1997; 3(1):14-24.

Mazzei L, Sist P, Ruschel A, Putz FE, Marco P, Pena W, Ferreira JE. Above-ground biomass dynamics after reduced-impact logging in the Eastern Amazon. Forest ecology and management; 2010; 259(3):367-73.

Mews HA, Marimon BS, Pinto JR, Silvério DV. Dinâmica estrutural da comunidade lenhosa em floresta estacional semidecidual na transição cerrado-floresta amazônica, Mato Grosso, Brasil. Acta Botanica Brasilica; 2011; 25:845-57.

Oliveira EK, Rezende AV, de Freitas LJ, Júnior LS, Barros QS, da Costa LS. Monitoramento da estrutura e caracterização ecológica em floresta tropical manejada na Amazônia Brasileira. Revista Brasileira de Ciências Agrárias. 2019;14(4):1-2.

Oliveira LC, do Couto HT, Silva JN, de Carvalho JO. Efeito da exploração de madeira e tratamentos silviculturais na composição florística e diversidade de espécies em uma área de 136 ha na Floresta Nacional de Tapajós, Belterra, Pará. Scientia Forestalis/Forest Sciences; 2005; (69):63–76.

Phillips OL, Van Der Heijden G, Lewis SL, López-González G, Aragão LE, Lloyd J, Malhi Y, Monteagudo A, Almeida S, Dávila EA, Amaral I. Drought–mortality relationships for tropical forests. New Phytologist; 2010; 187(3):631-46.

Phillips OL, Baker TR, Arroyo L, Higuchi N, Killeen TJ, Laurance WA, Lewis SL, Lloyd J, Malhi Y, Monteagudo A, Neill DA. Pattern and process in Amazon tree turnover, 1976–2001. Philosophical Transactions of the Royal Society of London. Series B: Biological Sciences; 2004;359(1443):381-407.

Phillips OL, Lewis SL, Baker TR, Chao KJ, Higuchi N. The changing Amazon forest. Philosophical Transactions of the Royal Society B: Biological Sciences; 2008;363(1498):1819-27.

Putz FE, Zuidema PA, Synnott T, Peña-Claros M, Pinard MA, Sheil D, Vanclay JK, Sist P, Gourlet-Fleury S, Griscom B, Palmer J. Sustaining conservation values in selectively logged tropical forests: the attained and the attainable. Conservation Letters; 2012;5(4):296-303.

Reategui-Betancourt JL., Mazzei de Freitas LJ, Santos KRB, Briceño G, Matricardi EAT, Ruschel AR., de Faria Ferreira, NC. (2024). Timber yield of commercial tree species in the eastern Brazilian Amazon based on 33 years of inventory data. Forestry: An International Journal of Forest Research. 2023 ; 97(1), 1-10.

Rodrigues TE, Silva RD, Da Silva JM, De Oliveira Junior RC, Gama JR, Valente MA. Caracterização e classificação dos solos do município de Paragominas, Estado do Pará. 2003.

Rossi LM, Koehler HS, Arce JE, Sanquetta CR. Modelagem de recrutamento em florestas. Floresta; 2007; 37(3).

Rozendaal DM, Phillips OL, Lewis SL, Affum-Baffoe K, Alvarez-Davila E, Andrade A, Aragão LE, Araujo-Murakami A, Baker TR, Bánki O, Brienen RJ. Competition influences tree growth, but not mortality, across environmental gradients in Amazonia and tropical Africa. Ecology; 2020; 101(7):e03052.

Rutishauser E, Hérault B, Baraloto C, Blanc L, Descroix L, Sotta ED, Ferreira J, Kanashiro M, Mazzei L, d'Oliveira MV, de Oliveira LC. Rapid tree carbon stock recovery in managed Amazonian forests. Current Biology; 2015; 25(18):R787-8.

Sheil D, Burslem DF, Alder D. The interpretation and misinterpretation of mortality rate measures. Journal of Ecology; 1995; [s.n.]:331-3.

Sheil D, May RM. Mortality and recruitment rate evaluations in heterogeneous tropical forests. Journal of ecology; 1996; 91^{-} ^{1}00.

Sist P, Ferreira FN. Sustainability of reduced-impact logging in the Eastern Amazon. Forest ecology and management; 2007; 243(2-3):199-209.

Soamandaugh S. An analysis of Collateral Damage Resulting from Selective Logging in a Large Forest Concession in Guyana. Imperial Journal of Interdisciplinary Research (IJIR); 2017; 3(6):2454^{-1}362.

Souza AL & Soares CP. Florestas nativas: estrutura, dinâmica e manejo. Viçosa, MG : Ed. UFV; 2013; 322 p.

Souza Werneck M, Villaron Franceschinelli E. Dynamics of a dry forest fragment after the exclusion of human disturbance in southeastern Brazil. Plant Ecology; 2004;174:339-48.

Talbot J, Lewis SL, Lopez-Gonzalez G, Brienen RJ, Monteagudo A, Baker TR, Feldpausch TR, Malhi Y, Vanderwel M, Murakami AA, Arroyo LP. Methods to estimate aboveground wood productivity from long-term forest inventory plots. Forest Ecology and Management; 2014; 320:30-8.

Teixeira LM, Chambers JQ, Silva AR, Lima AJ, Carneiro VM, Santos JD, Higuchi N. Projeção da dinâmica da floresta natural de Terra-firme, região de Manaus-AM, com o uso da cadeia de transição probabilística de Markov. Acta Amazonica; 2007; 37:377-84.

Ter Steege H, Prado PI, Lima RA, Pos E, de Souza Coelho L, de Andrade Lima Filho D, Salomão RP, Amaral IL, de Almeida Matos FD, Castilho CV, Phillips OL. Biased-corrected richness estimates for the Amazonian tree flora. Scientific reports; 2020; 10(1):10130.

Tritsch I, Sist P, Narvaes ID, Mazzei L, Blanc L, Bourgoin C, Cornu G, Gond V. Multiple patterns of forest disturbance and logging shape forest landscapes in Paragominas, Brazil. Forests; 2016; 7(12):315.

Valencia R, Balslev H, Paz Y Miño C G. High tree alpha-diversity in Amazonian Ecuador. Biodiversity & Conservation; 1994; 3:21-8.

Van Breugel M, Bongers F, Martínez-Ramos M. Species dynamics during early secondary forest succession: recruitment, mortality and species turnover. Biotropica; 2007; 39(5):610-9.

West TA, Vidal E, Putz FE. Forest biomass recovery after conventional and reduced-impact logging in Amazonian Brazil. Forest Ecology and Management; 2014; 15(314):59-63.