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AGRONOMY AND FORESTRY | ORIGINAL ARTICLE

Goupia glabra does not recover its timber stock after a 35-year logging cycle in the Brazilian Amazon: evidence from long-term multi-area monitoring

Sabrina Benmuyal VIEIRA[1]*, Ademir Roberto RUSCHEL[2], Joice Nunes FERREIRA[2], Lucas José MAZZEI de Freitas[2], Cintia Rodrigues de SOUZA[3], Fabiano EMMERT[4], Rodrigo Geroni Mendes NASCIMENTO[4]

[1] Universidade Federal do Pará, Instituto de Geociências. Belém, Pará, Brazil

[2] Embrapa Amazônia Oriental, Belém, Pará, Brazil

[3] Embrapa Amazônia Ocidental, Manaus, Amazonas, Brazil

[4] Universidade Federal Rural da Amazônia, Instituto de Ciências Agrárias, Belém, Pará, Brazil

*Corresponding author: sabrina_benmuyal@hotmail.com

ABSTRACT

Single-rule management is often adopted for various tropical forest timber species due to limited knowledge on species-specific growth and the relationship between logging intensity and recovery time. This study provides information to support sustainable management of *Goupia glabra* by simulating its wood stock recovery over a 35-year period following logging using data from six areas in the Brazilian Amazon. Monitoring periods after the first harvest cycle varyed from 16 to 29 years, and logging intensity from 0.000 to 0.696 m^2 ha^{-1}. Tree density of *G. glabra* varied from 0 to 22 trees ha^{-1} and dominance from 0.00 to 7.39 m^2 ha^{-1}. Frequency of tree diameters was almost evenly distributed across diameter classes, slightly higher in the first (20–30 cm) class. These parameters generated estimations of recovery rate from 12 to 85%, showing that 35 years is insufficient for trees with DBH ≥ 20 cm in all study areas to grow and replace the stock of trees with DBH ≥ 50 cm harvested during the first cycle. Minimum recovery periods from 48 to 83 years were estimated to guarantee the recovery of the wood stock in the study areas. These findings reinforce the need to adapt management rules according to the population dynamics of each timber species and each logging area, and suggest the need for changes in the current legal requirements that define forest management in the Amazon.

KEYWORDS: recovery rate, sustainable harvest, species-specific management, tropical timber

Goupia glabra não recupera seu estoque de madeira após um ciclo de corte de 35 anos na Amazônia brasileira: evidências de monitoramento de longo prazo em múltiplas áreas

RESUMO

Manejo de regra única é frequentemente adotado para várias espécies madeireiras de floresta tropical devido ao conhecimento limitado sobre o crescimento e a relação entre intensidade de exploração e tempo de recuperação de cada espécie. Este estudo fornece informações para subsidiar o manejo sustentável de *Goupia glabra* por meio da simulação da recuperação do estoque de madeira em um período de 35 anos usando dados de seis áreas na Amazônia brasileira. Períodos de monitoramento após o primeiro ciclo de colheita variaram de 16 a 29 anos e intensidades de exploração de 0.000 a 0.696 m^2 ha^{-1}. A densidade arbórea de *G. glabra* variou de 0 a 22 árvores ha^{-1} e a dominância de 0,00 a 7,39 m^2 ha^{-1}. A frequência de diâmetros das árvores se distribuiu homogeneamente entre as classes diamétricas, com maior concentração na primeira classe (20-30 cm). Esses parâmetros geraram estimativas de taxa de recuperação de 12 a 85%, mostrando que 35 anos é insuficiente para árvores com DAP ≥ 20 cm recuperarem o estoque de árvores com DAP ≥ 50 cm colhidas no primeiro ciclo de colheita em todas as áreas. Prazos mínimos de recuperação de 48 a 83 anos foram estimados para garantir a recuperação do estoque de madeira nas áreas de estudo. Os resultados reforçam que as regras de manejo necessitam ser adaptadas à dinâmica populacional de cada espécie madeireira em cada local de exploração e sugerem a necessidade de mudar as exigências legais vigentes que definem o manejo florestal na Amazônia.

PALAVRAS-CHAVE: taxa de recuperação, colheita sustentada, manejo por espécie, madeira tropical.

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INTRODUCTION

Management of tropical forest timber species in Asia, Africa, and the Americas essentially involves selective logging systems which utilize the same diameter limit for harvesting and cutting cycles for all species (Brasil 2006; 2009; Degen et al. 2006; Ashton and Hall 2011; Martin et al. 2015). Yet widespread application of a single system for all species is believed to degrade the growing forest stock (Sist et al. 2003; Sebbenn et al. 2008). Several studies have shown that such management does not ensure continuous production of slow-growing species, even when reduced-impact logging is implemented (Castro and Carvalho 2014; Braz and Mattos 2015; Vinson et al. 2015; Andrade et al. 2017; David et al. 2019). Each species responds differently to disturbances in the forest canopy (Free et al. 2014; Fernandez-Vega et al. 2017), variation in site conditions and stage of forest succession (Rozendaal et al. 2006). For this reason, silvicultural practices and strategies must be implemented in accordance with species-specific ecological needs (Putz et al. 2000; Klenner et al. 2009; Rist and Moen 2013; Navarrete-Segueda et al. 2017).

Forest management in Brazil involves logging cycles of 25–35 years, a 50-cm diameter limit for cutting, and a maximum harvest time of 35 years (Brasil 2006; 2009). Simulations involving *Dipteryx odorata* Aubl. Willd. and *Manilkara elata* (Allemão ex Miq.), both widely commercialized in Brazil, have shown that they require at least 160 and 601 years to recover, respectively (Vinson et al. 2015; Ferreira et al. 2020). On the other hand, fast-growing species such as those of the genus *Cecropia* require less time to recover than the 35 years established in management regulations for the Brazilian Amazon (Pereira 2015). Therefore the use of standardized rules to manage different species is not an ideal strategy to guarantee the sustainable use of forests (Schulze et al. 2008; Sist and Ferreira 2007) and studies on the spatial variation of the ecological responses of timber species to logging are essential to support management systems.

Brazilian forest management regulations simultaneously attempt to establish sustained wood production and protect biodiversity, namely tree populations (Avila et al. 2015; MacDicken et al. 2015; Roopsind et al. 2017; Ruslandi et al. 2017). However, forest management practices over time have had an impact on the sustainability of tree species, suggesting that current regulations are insufficient to guarantee long-term sustainability (Stone 1998). This is principally the result of a lack of knowledge about timber species regarding species-specific growth, autecology, and impact of logging intensity and cutting cycle (Schulze et al. 2008; Valkonen et al. 2017; Ferreira et al. 2020). Although some recent studies have focused on the recovery of certain groups of species after logging (Sist and Ferreira 2007; Nascimento et al. 2014), important knowledge gaps still remain for many species that are commonly logged in the Amazon. One such species is *Goupia glabra* Aubl. (Goupiaceae), which is one of the five most widely traded species within the states that comprise the Brazilian Amazon (Semas 2016; Ribeiro et al. 2016; Zaque et al. 2019). Its wood is dense (0.87 g cm^{-3}), workable and strong, which earned it wide acceptance in domestic and international markets (Silva 2016; Mendoza et al. 2017).

In this study, we assessed the recovery of wood stocks of *G. glabra* across six long-term study areas of wood harvest in the Brazilian Amazon by monitoring population dynamics after logging. We analyzed whether the natural remaining population of *G. glabra* with diameter at breast height (DBH) ≥ 20 cm at each area is expected to recover the population structure of wood stock within a simulated period of 35 years after logging. We also estimated the minimum time needed for each population to recover.

MATERIAL AND METHODS

Studied species

Goupia glabra is known in Brazil as *cupiúba*, *kabukalli* or *copie* (Camargos 1996; Lorenzi 1998). It occurs in the Amazon region of Brazil, Colombia, French Guiana, Peru, Suriname and Venezuela, as well as in Panama (Comvalius 2001; Ferreira and Tonini 2004; Ashton and Hall 2011). It is classified as a heliophilous species (Oliveira et al. 2017), flowering over a long period of the year, bears fruit during the transition between the dry and rainy periods, with fruit ripening taking place at the end of the dry period (Freitas et al. 2015; Santos et al. 2018; Aleixo et al. 2023). It displays aggregate spatial distribution (Jesus et al. 2014), generally reaching 40 m in height and up to 1.2 m in diameter (Ferreira and Tonini 2004).

Study area

We used data from 185 permanent plots (total area 102 ha) in six study areas which are part of the Amazon Forest Dynamics Monitoring Network (REDEFLOR in its acronym in Portuguese) in the Brazilian Amazon, in the municipalities of Vitória do Jari, Amapá state (AP-Jari) (40 plots), Belterra, (PA-FN Tapajós) (60), Moju, (PA-Moju) (22) and Paragominas (PA-Cikel) (36), all three in the state of Pará, and Itacoatiara, Amazonas state (AM-Mil1 and AM-Mil 2) (27) (Figure 1).

A detailed description of the climate, soils, and vegetation types at each study area is in Tables 1 and 2. The climate in the study areas is Köppen type Am and Af (Amazonas and Pará) and Am (Amapá), both featuring tropical monsoon (Alvares et al. 2013), annual average temperature from 25.0 to 27.2ºC, relative humidity from 86 to 92%, and annual precipitation from 1,500 to 3,300 mm (Watrin and Rocha 1992; Silva et al. 2001; Lopes et al. 2001; Carvalho 2002; Andrade 2023; Moraes et al. 2005; Giuliatti et al. 2019; Orellana et al. 2020). The predominant soil type across the study areas is dystrophic yellow latosol (IBGE 2008; 2010; Santos et al. 2018), and vegetation types are lowland and submontane ombrophilous dense forest (MMA 2006; IBGE 2012).

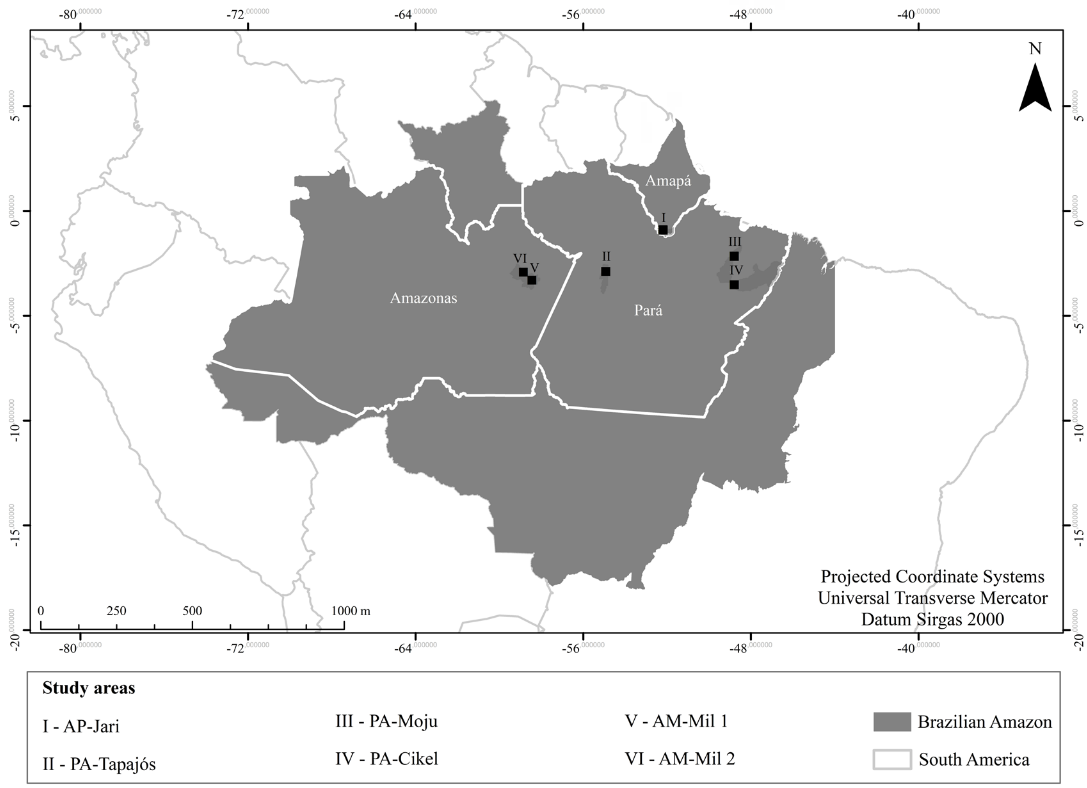

Figure 1. Location of the six study areas in the Brazilian Amazon. I-AP-JARI: municipality of Vitória do Jari, Amapá state; II-PA-Tapajós: municipality of Belterra, Pará state; III-PA-Moju: municipality of Moju, Pará state; IV-PA-Cikel: municipality of Paragominas, Pará state; V-AM-Mil 1, VI-AM-Mil 2: municipality of Itacoatiara, Amazonas state.

Table 1. Descriptive parameters of the six experimental areas of forest management in different regions of the Brazilian Amazon where recovery of *Goupia glabra* was monitored. PP = permanent plots; APU = annual production unit.

Identification	I- AP-Jari	II- PA-Tapajós	III- PA-Moju	IV- PA-Cikel	V- AM-Mil 1	VI- AM-Mil 2
Experimental area	Jari Florestal	Flona Tapajós	Campo Moju	Cikel Group	Mil Madeiras APU-B	Mil Madeiras APU-C
Municipality	Vitória do Jari	Belterra	Moju	Paragominas	Itacoatiara	Itacoatiara
State	Amapá	Pará	Pará	Pará	Amazonas	Amazonas
Vegetation (MMA 2006; IBGE 2012)	Alluvial dense ombrophilous forest	Alluvial dense ombrophilous forest	Lowland dense ombrophilous forest	Dense submontane rainforest	Alluvial dense ombrophilous forest	Alluvial dense ombrophilous forest
Predominant soil (IBGE 2008)	Dystrophic red-yellow latosol	Dystrophic yellow latosol and ortic quartzarenic neossol	Dystrophic yellow latosol with clay texture	Dystrophic yellow latosol	Dystrophic yellow latosol	Dystrophic yellow latosol
Climate (Alvares et al. 2013)	Am	Am	Af	Aw	Af	Af
Average annual temperature (ºC)	26.5	25.0	26.0	27.2	25.5	25.5
Annual rainfall (mm)	1,850 – 2,550	2,300 - 2,800	1,500 – 3,300	1,800 – 2,300	2.000 - 2.500	2.000 - 2.500
Average annual humidity (%)	92	86	85	81	85	85
Total number of plots	40	60	22	36	14	13
Total area of plots (ha)	40	15	11	9	14	13
Plot size (m x m)	100 x 100	50 x 50	50 x 100	50 x 50	100 x 100	100 x 100
Logging year	1985	1982	1995	2003	1996/1997	1997
Monitoring years	1984; 1986; 1988; 1990; 1994; 1996 2004; 2011	1981; 1983; 1987; 1989; 1995; 2003; 2008; 2012	1995; 1998; 2004 2010; 2015	2003; 2004; 2005; 2007; 2008; 2011; 2018; 2023	1996; 1998; 2001; 2014	1997; 2001; 2014
Overall monitoring time (years)	26.6	31.1	20.1	20.6	17.2	16.6

Table 2. Descriptive parameters of the continuous forest inventory for all trees with a DBH ≥ 20 cm in the six experimental areas of forest management in different regions of the Brazilian Amazon where recovery of *Goupia glabra* was monitored. Data are presented for the whole community of monitored timber species and for *G. glabra* in particular. MCD = minimum cutting diameter; MID = minimum inclusion diameter; LI = logging intensity shown in tree density, basal area and volume; % Logging = percentage of stand suitable for logging.

Identification	I- AP-Jari	II- PA-Tapajós	III- PA-Moju	IV- PA-Cikel	V- AM-Mil 1	VI- AM-Mil 2
Study areas	Jari Florestal	Flona Tapajós	Campo Moju	Cikel Group	Mil Madeiras APU-B	Mil Madeiras APU-C
MCD (cm)	50	45	50	50	50	50
MID (cm)	20	20	20	20	20	20
Tree density (trees ha-^{1})	177.48 ± 0.35	145.33 ± 4.19	186.55 ± 1.22	183.89 ± 0.55	207.50 ± 1.18	216.31 ± 1.62
Basal area (m^2 ha-^{1})	22.79 ± 0.05	19.88 ± 0.54	20.74 ± 0.20	22.04 ± 0.13	24.82 ± 0.21	23.08 ± 0,50
LI (trees ha-^{1})	4.89	11.83	2.91	4.17	6.93	3.00
LI *G. glabra* (trees ha-^{1})	1.47	0.67	0.09	0.00	0.29	0.07
LI (m^2 ha-^{1})	2.64	4.87	1.53	1.14	2.65	0.145
LI *G. glabra* (m^2 ha-^{1})	0.696	0.327	0.055	0.000	0.123	0.007
LI (m^3 ha-^{1})	43.43	66.60	15.99	15.57	35.09	2.123
% Logging *G. glabra*	43.16	97.98	17.10	0.00	24.54	2.64

The total stand density and basal area for *G. glabra* trees with DBH ≥ 20 cm in the six study areas prior to logging ranged from 145.3 to 216.3 trees ha^{-1} and 19.8 to 24.8 m² ha^{-1}, respectively (Table 2). All areas were monitored up to one year before logging, and at intervals of one to eight years after logging, over total periods of 17 to 31 years (three to eight monitoring occasions per area) (Table 2). The PA-Cikel area was logged for other timber species, but not for *G. glabra* due to the low abundance. We included this area in the analyses for the purpose of comparison (Table 2).

Data processing and analysis

Permanent plot monitoring was carried out according to the guidelines by Silva et al. (2005). The monitored parameters for the natural population for *G. glabra* were tree density (trees ha^{-1}); dominance (m^2 ha^{-1}); diametric distribution; recovery rate; and recovery time. Tree density by study area was compared only in the first measurement and was obtained through equation [1].

$$d = \frac{N}{A} \quad [1]$$

where N = total number of trees; and A = area in hectares, calculated according to the number of plots by study area.

We chose to use dominance-related basal area in our analyses because basal area serves as a highly reliable proxy for individual volume. Estimating volume directly would require height measurements with lower accuracy and higher uncertainty in the estimates (Clarck and Clarck 2000; Sist et al 2014). Dominance also defines population basal area and was obtained through equation [2]. It was also compared among study areas only in the first monitoring.

$$\Sigma g = \frac{\left(\frac{\pi \times DBH^2}{4}\right)}{A} \quad [2]$$

where π = constant; and DBH = diameter at breast height (1.30 m).

The diametric distribution was defined using nine diameter classes with an amplitude of 10 cm, presented by their respective class centers: 25, 35, 45, 55, 65, 75, 85, 95, and ≥ 100 cm. The distribution was determined in tree density (trees ha^{-1}) for the first (before logging) and last measurements in each study area.

The recovery rate estimates the percentage of the tree population under the diameter limit for cutting (DLC), in this case trees with DBH = 20.0–49.9 cm (measured after logging), which reaches DLC (DBH ≥ 50) after a defined time span *P*. In this study, *P* was 35 years, which represents the cutting cycle defined in Brazilian legislation (Brasil 2006; 2009). The recovery rate of *G. glabra* was calculated for all areas using equation [3] proposed by Durrieu de Madron and Forni (1997) and adapted by Sist and Ferreira (2007).

$$R(\%) = \left(\frac{N_a \times (1-m)^P}{N_i}\right) \times 100 \quad [3]$$

where $R(\%)$ = recovery rate in percentage of the number of trees of *G. glabra* which was in stock (% trees); N_i = number of trees with DBH ≥ 50 cm in the measurement before logging; N_a = number of trees remaining after logging with DBH = 20.0–49.9 cm that reached DBH ≥ 50 cm at time period *P*; *m* = mortality rate of trees with DBH = 20–49.9 cm after logging, represented as % year^{-1}, calculated according to equation [4] (Sheil and May 1996); *P* = 35 years. In the PA-Cikel area, where the species has not been logged, the equation resulted in the natural growth rate of the *G. glabra* population.

$$M = 1 - ((N_0 - m)/N_0)^P \times 100 \quad [4]$$

where M = annual mortality rate in percentage; N_0 = number of trees inventoried in the first measurement, m = number of dead trees in the measurement after logging; and P = 35 years.

The DBH value of each *G. glabra* tree was adjusted year by year based on the annual periodic diameter increase (API_d) for this species until reaching DLC at time P. API_d was calculated individually for all trees with DBH 20.0–49.9 cm, and represents the change in tree size between the beginning and end of the overall monitoring interval, divided by the number of years of the overall monitoring interval at each area. An average API_d was obtained from all individual API_d values at each area after logging. Recovery time was simulated using the API_d for each study area from a tree with DBH = 20 cm.

Tree density, dominance, and DBH of *G. glabra* were statistically compared among the areas before logging, and within area before and after logging (considering the latest measurement after logging). Each variable was tested for normality and homoscedasticity of variance using the Shapiro-Wilk and Levene tests, respectively. As these premises were not satisfied, a non-parametric Kruskall-Wallis test was used for comparisons among areas and Wilcoxon tests were used for comparison before and after logging within study areas. When the Kruskal-Wallis test indicated significant differences, post-hoc comparisons were conducted using Dunn's test to compare the experimental areas. In all cases, a significance level of 5% was used. All statistical analyses were conducted and graphs generated with R v. 4.3.0 software (R Core Team 2023).

RESULTS

Tree structure

Tree density and dominance prior to logging differed statistically among the areas. Tree density was significantly higher in AP-Jari and PA-FN-Tapajós than in PA-Moju, PA-Cikel and AM-Mil2, while dominance was significantly higher in AP-Jari and PA-FN-Tapajós than in PA-Moju and PA-Cikel. Tree density varied from 0.0 to 22.0 trees ha^{-1}, and dominance from 0.0 to 7.390 m^2 ha^{-1} (Figure 2). Diameter distribution was highest in the 25-cm class in three areas (PA-Cikel, AM-Mil1, AM-Mil2). In PA-Moju diameter distribution was highest in the 35-cm class, AP-Jari in the 75-cm class, and PA-FN-Tapajós in the 25, 75 and 95-cm classes (Figure 3).

We observed the reduction of *Goupia glabra* density was lower in all diameter classes in four areas at the end of the monitoring period (AP-Jari, PA-Tapajós, PA-Moju, AM- Mil 1) (Figure 3). Reductions in the post-logging 45 and 75-cm classes were due to logging.

No statistically significant differences were observed between the pre- and post-logging tree structure parameters in the study areas where *G. glabra* was logged (indicating that populations are recovering). In PA-Cikel over 20 years, we also observed the same structure pre- and post-logging in the area (Figure 4).

Population recovery rate

API_d for trees 20–49.9 cm DBH in the six areas ranged from 0.36 ± 0.27 to 0.62 ± 0.21 cm year^{-1}. The highest value was observed at PA-Tapajós and AM-Mil 2, with 0.62 ± 0.21 and 0.52 ± 0.21 cm year^{-1}, respectively. The annual mortality rate of trees 20–49.9 cm DBH after logging varied from 0 to 4% year^{-1}, and the highest mortality rate was observed at PA-Moju (Table 3).

The estimated recovery rate 35 years after logging (DBH ≥ 50) ranged from 12 to 85%. The highest rate of 85% occurred at AM-Mil 2, the study area with the second largest API_d, and one of the lowest mortality rates. The lowest recovery rate of 12% occurred at PA-Moju, where API_d ranked third, but the mortality rate was highest (Table 3). In PA-Cikel, where *G. glabra* was not logged, the natural population growth rate was 20% (Table 3).

The estimated time for trees with DBH = 20 cm to reach commercial stocks or the DLC of DBH = 50 cm varied from 48 to 83 years according to the API_d of each study area. This period was shortest at PA-Tapajós and longest at PA-Jari (Table 3).

Table 3. Recovery rate and time of *G. glabra* tree populations after logging in six study areas in the Brazilian Amazon after an estimated 35-year period based on the annual periodic increment (API_d) and mortality rate (M) of the remaining trees (DBH = 20.0–49.9 cm). We also show the diameter of the trees that reached the diameter limit for cutting (DBH ≥ 50 cm) in each area (DBH_m) at 35 years. LI = logging intensity. API_d and DBH_m values are the mean ± standard deviation.

Area	Recovery rate (%)	Period	Post-logging monitoring period (years)	API_d (cm year^{-1})	M (% year^{-1})	DBH_m (cm)	Recovery time (years)
I-AP-Jari	15	1986–2011	25	0.36 ± 0.27	0.96	37.5	83
II-PA-Tapajós	25	1983–2012	29	0.62 ± 0.21	0.00	28.6	48
III-PA-Moju	12	1998–2015	17	0.48 ± 0.35	4.00	33.4	63
*IV-PA-Cikel	20	2004–2023	19	0.42 ± 0.29	0.00	35.4	71
V-AM-Mil 1	14	1998–2014	16	0.36 ± 0.28	0.72	37.4	83
VI-AM-Mil 2	85	2001–2015	14	0.52 ± 0.21	0.44	31.8	58

The asterisk (*) indicates that no *G. glabra* trees were harvested in the area.

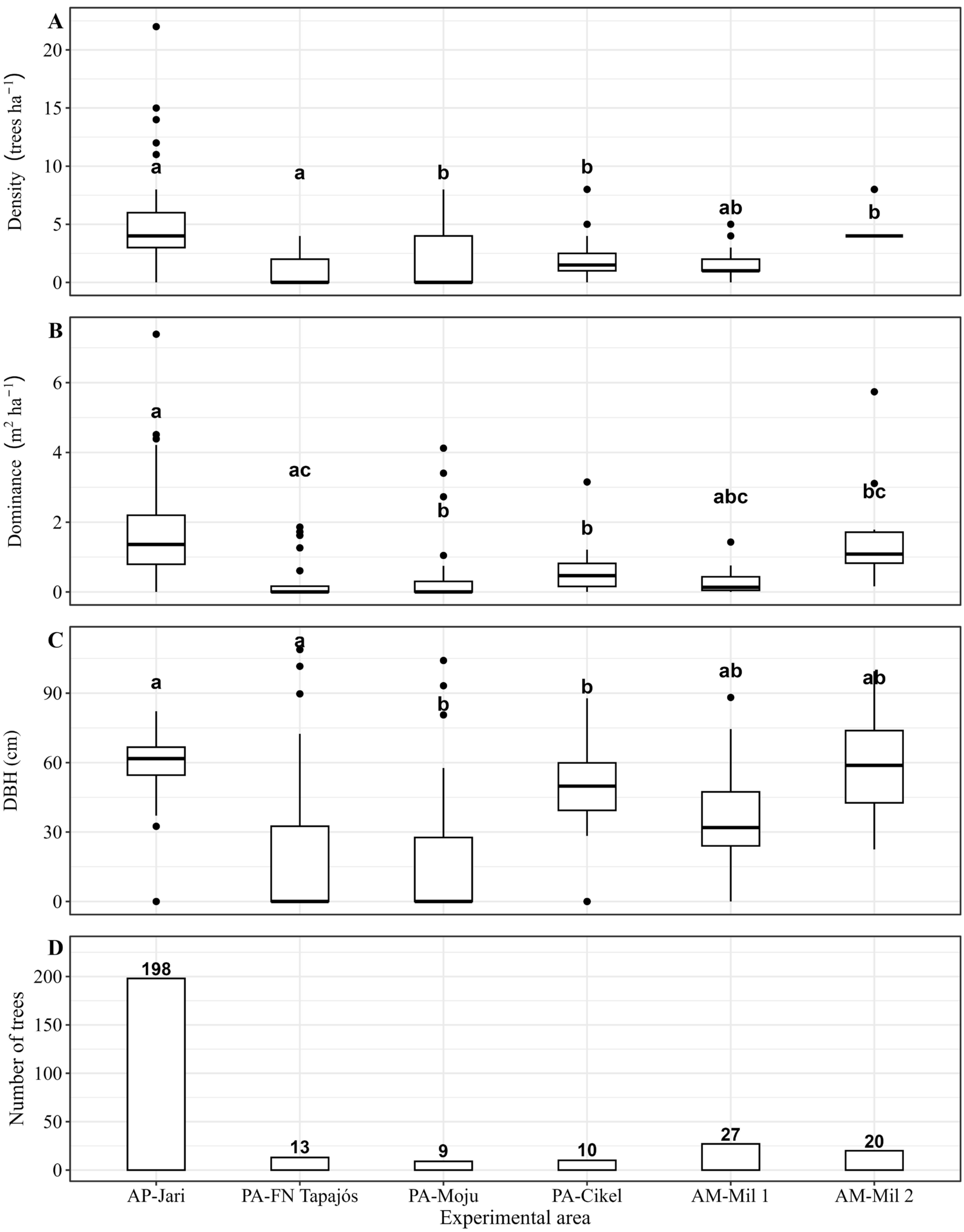

Figure 2. Tree density (A), dominance (B), DBH (C) and number of trees (D) of *Goupia glabra* with DBH (diameter at breast height) ≥ 20 cm in the pre-logging measurement in six study areas in the Brazilian Amazon. The box indicates the interquartile range; the horizontal line the median; the vertical lines the range; and the points indicate outliers. Distinct letters above the box-plots indicate a statistical difference between the areas according to a Dunn's test ($p < 0.05$). Numbers above the histograms in (D) are the number of individuals.

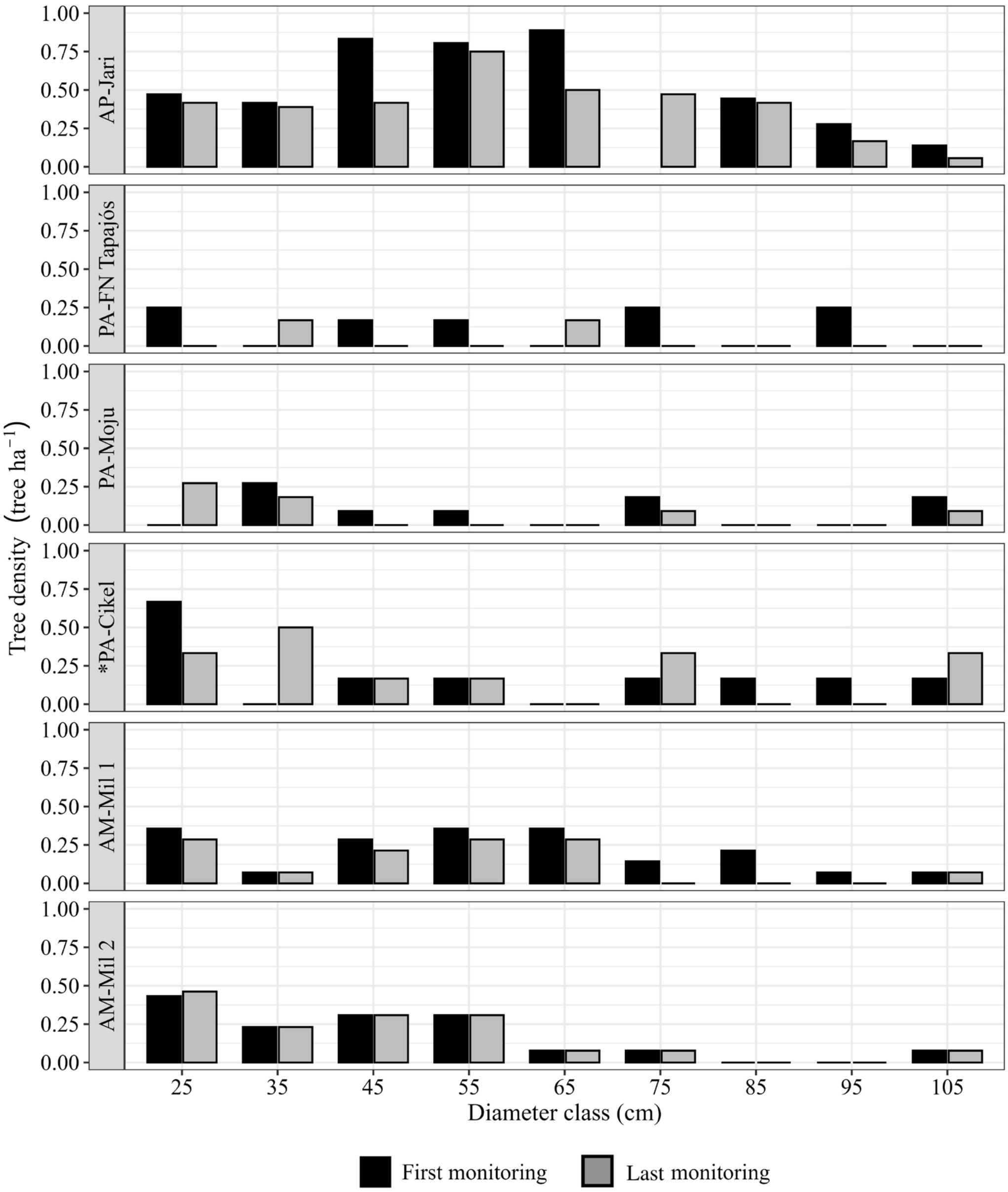

Figure 3. Tree density per diametric class of *Goupia glabra* in six study areas in the Brazilian Amazon (I-AP-Jari, II-PA-Tapajós, III-PA-Moju, IV-PA-Cikel, V-AM-Mil 1, and VI-AM-Mil 2) in the pre-logging and last post-logging monitoring period. The asterisk (*) indicates that no *G. glabra* trees were harvested in this area.

DISCUSSION

According to our estimates, commercial tree populations (DBH ≥ 50) of *G. glabra* would not recover their initial density within the official Brazilian cutting cycle of 35 years after logging in any of the logged study areas. The recovery rate was estimated to reach a maximum of 85% after logging, and periods of 48 to 83 years were estimated for trees with DBH = 20 cm to recover commercial stocks.

Recovery rates of timber species populations are determined by the growth dynamics of the remaining trees. The initial density of *G. glabra* differed in the various study areas but was predominantly low, with approximately 2 trees with DBH = 20.0–49.9 cm per hectare, as was also the case in other studies in the Amazon (Hirai et al. 2007; Oliveira et al. 2008; Carim et al. 2015; Santos et al. 2018; Condé and Tonini 2013). Our findings showed that the tree structure at 35 years after logging is similar to its initial density and dominance, which means that the population is recovering, but is not yet suitable for logging. This indicates that 35-years cycles are not suitable for the management of *G. glabra*, and may only be successfully employed with short-lived species

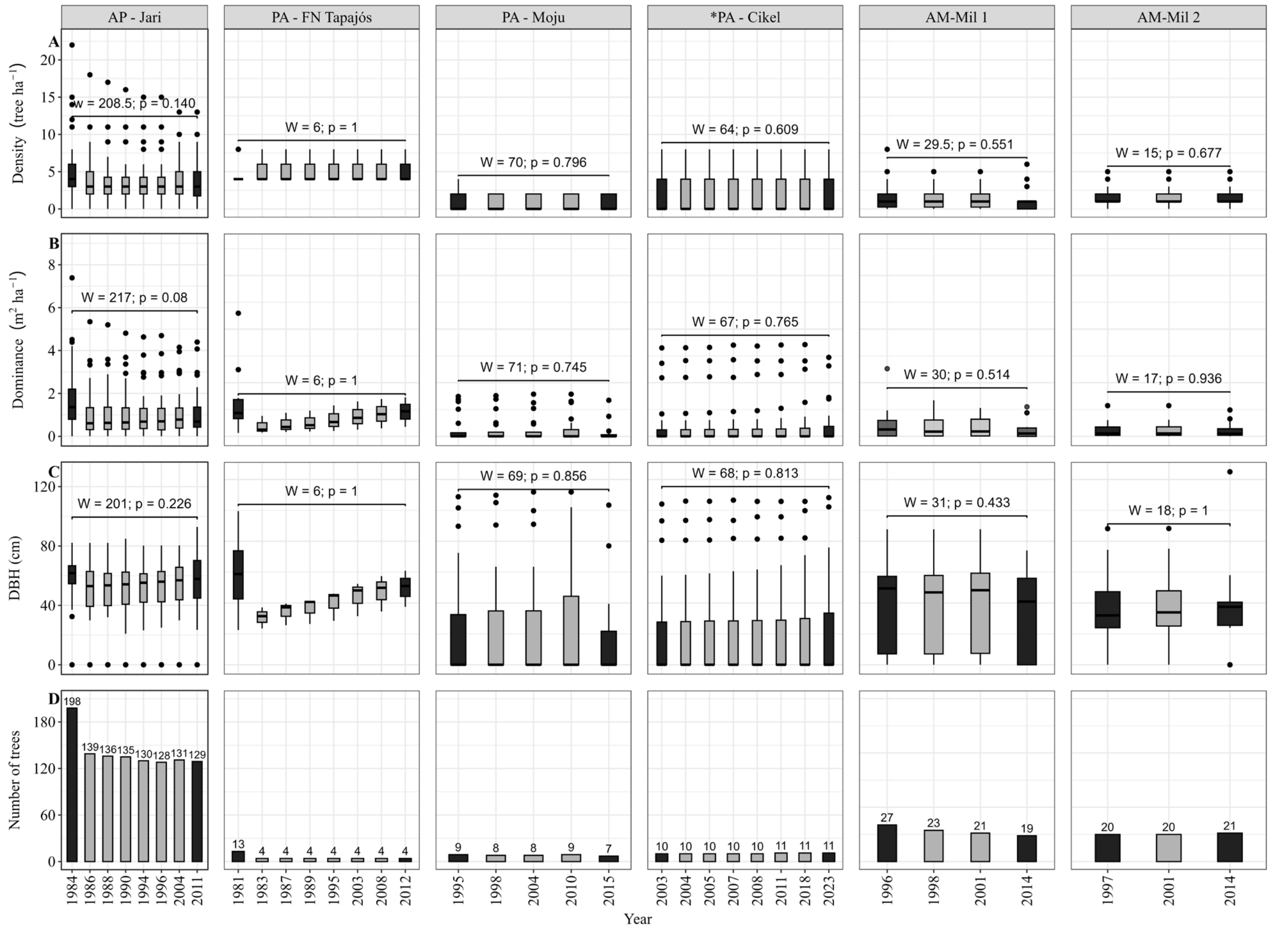

Figure 4. Tree density (A), dominance (B), DBH (diameter at breast height) (C) and number of trees (D) of *Goupia glabra* with DBH ≥ 20 cm in each measurement carried out during the monitoring period in six study areas in the Brazilian Amazon (I-AP-Jari, II-PA-Tapajós, III-PA-Moju, IV-PA-Cikel, V-AM-Mil 1 and VI-AM-Mil 2). W = value of a Wilcoxon test comparing the first and last measurement at each study area; p = significance level. The asterisk (*) indicates the area where no *G. glabra* trees were harvested. The box indicates the interquartile range; the horizontal line the median; the vertical lines the range; and the points indicate outliers. Distinct letters above the box-plots indicate a statistical difference between the areas according to a Dunn's test ($p < 0.05$). Numbers above the histograms in (D) are the number of individuals.

such as *Cecropia* spp. (Pereira 2015) and *Jacaranda copaia* (Vinson et al. 2014).

The low tree density and dominance distributed among the diameter classes, along with the moderate growth of *G. glabra,* might have influenced the low recovery rates observed. Study areas with greater dominance, represented by trees with DBH ≥ 50 cm, had a larger number of mature reproductive trees, but this was not sufficient to recover the logged population. For example, the study area with the highest dominance of *G. glabra* (AP-Jari) was also where logging intensity for the species was highest and the recovery rate was among the lowest. Generally, however, tree density is considered an important indicator to maintain genetic diversity of the species in the managed area (Jennings et al. 2001; Ratnam et al. 2014). Even in the area where *G. glabra* was not logged, the natural population growth rate was also low, which is attributed to that the population primarily consisted of smaller diameter classes, which did not reach DBH ≥ 50 cm in 35 years. This indicates that, despite remaining individuals of *G. glabra* may have suffered less competition for resources due to logging of other species in the area, this was not enough to increase their natural growth rate (Sist and Ferreira 2007; Putz et al. 2008). This result highlight the importance of understanding the natural dynamics of *G. glabra* to determine the intensity of logging.

The mortality rate, combined with low density of *G. glabra* in the five areas where the species was logged, demonstrated that the recovery of the original population structure requires longer than 35 years. Logging can have positive effects on natural ingrowth, tree density, and growth in basal area and in diameter of *G. glabra* (Silva et al. 1995; 1996; Lima et al. 2002; Francez et al. 2009; Reis et al. 2010; Rivett et al. 2016). These benefits result from reducing competition by thinning and favoring recruitment in comparison with unlogged forests (Jardim and Mory 2001), but they tend to diminish over time (Silva et al. 1995). We did not observe these positive effects on species regeneration from opening the forest canopy during logging in our study. We assume that the juvenile population of *G. glabra* (DBH < 20 cm) did not have sufficient time during the monitoring periods to grow to commercial recovery levels. For this reason, the management of the juvenile population of this species requires careful attention. Especially in areas where tree density is lower, the management protocol for the species must be reassessed and adapted (Putz et al. 2008) using conservative management strategies that enable species conservation through silvicultural treatments such as enrichment planting and promoting natural regeneration (Schwartz et al. 2013).

In our study areas, *G. glabra* did not have enough remaining structure to recover the original tree stocks 35 years after logging, demonstrating that the management framework for the species needs to be reviewed considering its area-specific tree structure dynamics and recovery rates. Our study highlights the importance of establishing cutting cycles with logging intensity in line with the remaining population structure, growth, and individual recovery capacity of each species (Braz 2010; Reis et al. 2013; Avila et al. 2018; Pires et al. 2021). Studies on other tree species in the Amazon, Asia, and Africa have shown that their ecology, dynamics, forestry, and management according to local conditions of occurrence must be considered to achieve recovery. For example, *Swietenia macrophylla* King (mahogany) and *Voucapoua americana* Aubl. (acapu) do not recover their initial stocks in cycles that consider current management legislation in the countries where they occur (Degen et al. 2006; Sebbenn et al. 2008; Ashton and Hall 2011; Grogan et al. 2014). Careful adaptation of forest management guidelines according to species-specific population recovery characteristics is essential to guarantee the long-term sustainability of forest management in the Brazilian Amazon.

CONCLUSIONS

The simulated recovery rate of the wood stock at 35 years after logging for *G. glabra* was 12 to 85%, showing that the populations did not recover the stock of timber trees. The estimated time for the population of *G. glabra* trees with DBH = 20 cm to recover their wood ranged from 48 to 83 years. These findings demonstrate the need to adopt species-specific management strategies, and to consider productivity per site to promote sustainable production and conserve timber species.

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REFERENCES

Aleixo, I.F.; Maciel, J.M.; Reis, L.Q.; Nascimento, T.; Calvi, G.P.; Norris, D.; Barbosa A.P. 2023. *Fenologia: Árvores da Amazônia*. Editora INPA, Manaus. 53p.

Alvares, C.A.; Stap, J.L.; Sentelhas, P.C.; Moraes, J.L. 2013. Köppen's climate classification map for Brazil. *Meteorologische Zeitschrift* 22: 711–728.

Andrade, C.G.C.; Silva, M.L. da; Torres, C.M.M.E.; Ruschel, A.R.; Silva, L.F. da; Andrade, D.F.C. de; et al. 2017. Crescimento diamétrico e tempo de passagem de Minquartia guianensis após manejo na Floresta Nacional do Tapajós. *Pesquisa Florestal Brasileira* 37: 299–309.

Andrade, J.S. 2023. Eventos extremos de precipitação pluvial na cidade de Itacoatiara-AM. Master´s dissertation, Universidade Federal do Amazonas (UFAM), Brazil, 102p. (https://tede.ufam.edu.br/handle/tede/9467).

Ashton, M.; Hall, J. 2011. Review the ecology, silviculture, and use of tropical wet forests with special emphasis on timber rich types. In: Gunter, S. (Ed.). *Silviculture in the Tropics.* Tropical Forestry, Berlim. p.145–192.

Avila, A.L.; Ruschel, A.R.; de Carvalho, J.O.P.; Mazzei, L.; Silva, J.N.M.; Lopes, J. do C.; et al. 2015. Medium-term dynamics of tree species composition in response to silvicultural intervention intensities in a tropical rain forest. *Biological Conservation* 191: 577–586.

Avila, A.L. de; Sande, M.T. van der; Dormann, C.F.; Claros, M.P.; Poorter, L.; Mazzei, L.; et al. 2018. Disturbance intensity is a stronger driver of biomass recovery than remaining tree-community attributes in a managed Amazonian forest. *Journal of Applied Ecology* 55: 1647–1657.

Brasil. 2006. Ministério do Meio Ambiente. Instrução Normativa nº 5, de 11 de dezembro de 2006. Diário Oficial da União, Brasília, DF, 5 mar. 2006. (https://www.legisweb.com.br/legislacao/?id=76720).

Brasil. 2009. Conselho Nacional de Meio Ambiente. Resolução nº 406, 2 de fevereiro de 2009. Diário Oficial da União, Seção 1, Brasília, 06 de fevereiro de 2009. (https://www2.cprh.pe.gov.br/wp-content/uploads/2021/02/CONAMA_RES_CONS_2009_406.pdf).

Braz, E.M. 2010. *Subsídios para o planejamento do manejo de florestas tropicais da Amazônia*. Doctoral thesis, Universidade Federal de Santa Maria (UFSM), Brazil, 236p. (http://coral.ufsm.br/ppgef/images/Teses2010/Evaldo-Munoz-Braz.pdf).

Braz, E.M.; Mattos, P.P. de. 2015. Manejo de produção em florestas naturais da Amazônia: mitos e verdades. *Nativa* 3: 292–295.

Camargos, J.A. 1996. *Catálogo de Árvores do Brasil*. MMA/IBAMA, Brasília. 887p.

Carim, M.; Guimarães, J.; Tostes, L.; Takiyama, L.; Wittmann, F. 2015. Composition, structure and floristic diversity in dense rainforest in the Eastern Amazon, Amapá, Brazil. *Acta Scientiarum. Biological Sciences* 37: 419-426.

Carvalho, J.O.P. 2002. Changes in the floristic composition of a terra firme rain forest in Brazilian Amazonia over an eight-year period in response to logging. *Acta Amazonica* 32: 277-291.

Castro, T. da C.; Carvalho, J.O.P. de. 2014. Dinâmica da população de *Manilkara elata* (Ducke) A. Chev. durante 26 anos após a exploração florestal em uma área de terra firme na Amazônia brasileira. *Ciência Florestal* 24: 161–169.

Clark, D. A.,; Clark, D. B. (2000). Landscape-scale variation in forest structure and biomass in a tropical rain forest. *Forest Ecology and Management*, 137: 185-198.

Comvalius, L.B., 2001. *Surinamese timber species: characteristics and utilization*. Celos, Paramaribo, 243p.

Condé, T.M.; Tonini, H. 2013. Fitossociologia de uma floresta ombrófila densa na Amazônia setentrional, Roraima, Brasil. *Acta Amazonica* 43: 247–259.

David, H.C.; Carvalho, J.O.P.; Pires, I.P.; Santos, L.S.; Barbosa, E.S.; Braga, N.S. 2019. A 20-year tree liberation experiment in the Amazon: Highlights for diameter growth rates and species-specific management. *Forest Ecology and Management* 453: 117584.

Degen, B.; Blanc, L.; Caron, H.; Maggia, L.; Kremer, A.; Gourlet-Fleury, S. 2006. Impact of selective logging on genetic composition and demographic structure of four tropical tree species. *Biological Conservation* 131: 386–401.

Durrieu De Madron, L.; Forni, E. 1997. Aménagement forestier dans l'Est du Cameroun. *Bois et Forêts des Tropiques* 254: 39–50.

Fernandez-Vega, J.; Covey, K.R.; Ashton, M.S. 2017. Tamm review: Large-scale infrequent disturbances and their role in regenerating shade-intolerant tree species in Mesoamerican rainforests: Implications for sustainable forest management. *Forest Ecology and Management* 395: 48–68.

Ferreira, L.M.M.; Tonini, H. 2004. *Cupiúba* (*Goupia glabra* Aublet): *Crescimento, Potencialidades e Usos*. Documentos # 4. Embrapa Roraima, Boa Vista, 29p.

Ferreira, T.M.C.; de Carvalho, J.O.P.; Emmert, F.; Ruschel, A.R.; Nascimento, R.G.M. 2020. How long does the Amazon rainforest take to grow commercially sized trees? An estimation methodology for *Manilkara elata* (Allemão ex Miq.) Monach. *Forest Ecology and Management* 473: 118333.

Francez, L.M. de B.; Carvalho, J.O.P. de; Jardim, F.C. da S.; Quanz, B.; Pinheiro, K.A.O. 2009. Efeito de duas intensidades de colheita de madeira na estrutura de uma floresta natural na região de Paragominas, Pará. *Acta Amazonica* 39: 851-864.

Free, C.M.; Landis, R.M.; Grogan, J.; Schulze, M.D.; Lentini, M.; Dunisch, O.; et al. 2014. Management implications of long-term tree growth and mortality rates: A modeling study of big-leaf mahogany (Swietenia macrophylla) in the Brazilian Amazon. *Forest Ecology and Management* 330: 46-54.

Freitas, J. da L.; Silva, R.B.L.E; Filho, M.N.B.; Cantuária, P. de C.; Júnior, F. de O.C. 2015. Fenologia reprodutiva de cinco espécies em ecossistemas de terra firme na Amazônia brasileira. *Biota Amazônia* 5: 38–44.

Giuliatti, N.M.; Rodrigues, A.B.M.; Jesus, E. dos S.; Junior, A.P. 2019. Variabilidade da preciptação mensal e anual no município de Paragominas-Pa. *Enciclopédia Biosfera* 16: 1716–1730.

Grogan, J.; Landis, R.; Free, C.; Schulze, M.; Lentini, M.; Ashton, M. 2014. Big-leaf mahogany Swietenia macrophylla population dynamics and implications for sustainable management. *Journal of Applied Ecology* 51: 664–674.

Hirai, E.H.; Carvalho, J.O.P. de; Pinheiro, K.A.O. 2007. Comportamento populacional de cupiúba (*Goupia glabra* Aubl.) em floresta de terra firme na Fazenda Rio Capim, Paragominas (PA). *Revista de Ciências Agrárias* 47: 89–102.

IBGE. 2008. Pedologia: Mapa esquemático de solos. Estado do Pará. Escala: 1:1.800.000. Instituto Brasileiro de Geografia e Estatística, Rio de Janeiro.

IBGE. 2010. Pedologia: Mapa Exploratório de Solos. Estado do Amazonas. Escala: 1:1.000.000. Instituto Brasileiro de Geografia e Estatística, Rio de Janeiro.

IBGE. 2012. *Manual técnico da vegetação brasileira em geociências*. 2nd ed. Instituto Brasileiro de Geografia e Estatística, Rio de Janeiro, 271p.

Jardim, F.C. da S.; Mory, A. de M. 2001. Comportamento de *Goupia glabra* Aubl. (cupiúba) em diferentes níveis de desbaste por anelamento em florestal naturais. *Revista de Ciências Agrárias* 36: 55–66.

Jennings, S.B.; Brown, N.D.; Boshier, D.H.; Whitmore, T.C.; Lopes, J. do C.A. 2001. Ecology provides a pragmatic solution to the maintenance of genetic diversity in sustainably managed tropical rain forests. *Forest Ecology and Management* 154: 1–10.

Jesus, L.M.; Souza, R.N.; Jesus, A.T.; Nicacio, M.A.; Souza, L.; Sotta, E.; Aparicio, P.S. 2014. Comportamento espacial da *Goupia glabra* Aubl. em uma floresta ombrófila densa, Amapá, Brasil. In: Ferreira, R.L.C.; Maragon, L.C (Eds.). *VIII Simpósio Brasileiro de Pós-graduação em Ciências Florestais*, UFRP, Recife. p.215–219.

Klenner, W.; Arsenault, A.; Brockerhoff, E.G.; Vyse, A. 2009. Biodiversity in forest ecosystems and landscapes: A conference to discuss future directions in biodiversity management for sustainable forestry. *Forest Ecology and Management* 258: S1–S4.

Lima, A.P.; Lima, O.P. de; Magnusson, W.E.; Higuchi, N.; Reis, F.Q. 2002. Regeneration of five commercially-valuable tree species after experimental logging in an Amazonian forest. *Revista Árvore* 26: 567–571.

Lopes, J.C.A.; Whitmore, T.C.; Brown, N.D.; Jennings, S.B. 2001. Efeito da exploração florestal nas populações de mudas em uma floresta tropical úmida no município de Moju, PA. In: Silva, J.N.M.; Carvalho, J.O.P.; Yared, J.A.G. (Eds.). *A Silvicultura na Amazônia Oriental: Contribuições do Projeto Embrapa/DFID*. Embrapa Amazônia Oriental, Belém. p.227-251.

Lorenzi, H. 1998. *Árvores brasileiras: Manual de Identificação e Cultivo de Plantas Arbóreas nativas do Brasil*, 2nd ed. Instituto Plantarrum. Nova Odessa, SP, 368p.

MacDicken, K.G.; Sola, P.; Hall, J.E.; Sabogal, C.; Tadoum, M.; de Wasseige, C. 2015. Global progress toward sustainable forest management. *Forest Ecology and Management* 352: 47–56.

Martin, P.A.; Newton, A.C.; Pfeifer, M.; Khoo, M.; Bullock, J.M. 2015. Impacts of tropical selective logging on carbon storage and tree species richness: A meta-analysis. *Forest Ecology and Management* 356: 224–233.

Mendoza, Z.M. dos S.H. de; Borges, P.H. de M.; Pierin, L.C. 2017. Coeficiente de rendimento em madeira serrada de oito espécies nativas do Mato Grosso. *Nativa* 5: 568–573.

MMA. 2006. Ministério do Meio Ambiente. Mapa de cobertura vegetal dos biomas brasileiros. Bioma Amazônia. Escala: 1:5.000.000. (https://antigo.mma.gov.br/component/k2/item/7626-mapas-de-cobertura-vegetal.html).

Moraes, B.; Costa, J.; Costa, A.; Costa, M. 2005. Variação espacial e temporal da precipitação no Estado do Pará. *Acta Amazonica* 35: 207-214.

Nascimento, R.G.M.; Machado, S. do A.; Figueiredo Filho, A.; Higuchi, N. 2014. A growth and yield projection system for a tropical rainforest in the Central Amazon, Brazil. *Forest Ecology and Management* 327: 201–208.

Navarrete-Segueda, A.; Martínez-Ramos, M.; Ibarra-Manríquez, G.; Cortés-Flores, J.; Vázquez-Selem, L.; Siebe, C. 2017. Availability and species diversity of forest products in a Neotropical rainforest landscape. *Forest Ecology and Management* 406: 242–250.

Oliveira, A.N. de; Amaral, I.L. do; Ramos, M.B.P.; Nobre, A.D.; Couto, L.B.; Sahdo, R.M. 2008. Composition and floristic-structural diversity of a hectare of terra firme dense forest in Central Amazonia, Amazonas, Brazil. *Acta Amazonica* 38: 627–641.

Oliveira, L.C.; Jardim, F.C.; Gomes, J.M.; Ramos, E.M. 2017. Classificação ecológica de espécies arbóreas por meio da análise da distribuição diamétrica. *Revista Espacios* 38: 1-20. (https://revistaespacios.com/a17v38n42/a17v38n42p03.pdf).

Orellana, J.B.P; Orellana, B.B.M.A; Segovia, J.F.O. 2020. Caracterização das condições climáticas na Amazônia. In: Segovia, J.F.O (Ed.). *Floricultura Tropical: Técnicas e Inovações Para Negócios Sustentáveis*. Embrapa, Brasília. p.33-42.

Pereira, P.C.G. 2015. Determinação do potencial silvicultural de espécies do gênero *Cecropia* na Flona Tapajós. Master´s dissertation, Universidade Federal Rural da Amazônia (UFRA), Brazil, 56p. (http://repositorio.ufra.edu.br/jspui/handle/123456789/1901).

Pires, S.A. de O.; de Mendonça, A.R.; da Silva, G.F.; d'Oliveira, M.V.N.; de Oliveira, L.C.; Silva, J.P.M.; da Silva, E.F. 2021. Growth modeling of Carapa guianensis and Tetragastris altissima for improved management in native forests in the Amazon. *Ecological Modelling* 456: 109683.

Putz, F.E.; Dykstra, D.; Heinrich, R. 2000. Why poor logging practices persist in the tropics. *Conservation Biology* 14: 951–956.

Putz, F.E.; Sist, P.; Fredericksen, T.; Dykstra, D. 2008. Reduced-impact logging: challenges and opportunities. *Forest Ecology and Management* 256: 1427-1433.

Ratnam, W.; Rajora, O.P.; Finkeldey, R.; Aravanopoulos, F.; Bouvet, J.-M.; Vaillancourt, R.E.; et al. 2014. Genetic effects of forest management practices: Global synthesis and perspectives. *Forest Ecology and Management* 333: 52–65.

R Core Team. 2023. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. (https://www.R-project.org/).

Reis, L.; Ruschel, A.; Coelho, A.; Luz, A.; Célia, R.; Martins-Da-Silva, V. 2010. Avaliação do potencial madeireiro na Floresta Nacional do Tapajós, após 28 anos da exploração florestal. *Pesquisa Florestal Brasileira* 30: 1-18. doi: 10.4336/2010.pfb.30.64.265

Reis, L.; Silva, J.; Reis, P.; Carvalho, J.; Queiroz, W.; Ruschel, A. 2013. Efeito da exploração de impacto reduzido em algumas espécies de sapotaceae no leste da Amazônia. *Floresta* 43: 395-406.

Ribeiro, E.S.; Souza, R.A.T.M. de; Paula, M.H. de; Mesquita, R.R.S. de; Moreira, E.L.; Fazion, H. 2016. Espécies florestais comercializadas pelo estado do Mato Grosso. *Biodiversidade* 15: 1–19.

Rist, L.; Moen, J. 2013. Sustainability in forest management and a new role for resilience thinking. *Forest Ecology and Management* 310: 416–427.

Rivett, S.L.; Bicknell, J.E.; Davies, Z.G. 2016. Effect of reduced-impact logging on seedling recruitment in a neotropical forest. *Forest Ecology and Management* 367: 71–79.

Roopsind, A.; Wortel, V.; Hanoeman, W.; Putz, F.E. 2017. Quantifying uncertainty about forest recovery 32-years after selective logging in Suriname. *Forest Ecology and Management* 391: 246–255.

Rozendaal, D.; Hurtado, V.; Poorter, L. 2006. Plasticity in leaf traits of 38 tropical tree species in response to light; relationships with light demand and adult stature. *Functional Ecology* 20: 207–216.

Ruslandi, R.; Cropper, W.P.; Putz, F.E. 2017. Effects of silvicultural intensification on timber yields, carbon dynamics, and tree species composition in a dipterocarp forest in Kalimantan, Indonesia: An individual-tree-based model simulation. *Forest Ecology and Management* 390: 104–118.

Santos, A.C. dos; Freitas, J. da L.; Santos, E.S. dos. 2018. Comportamento fenológico de espécies florestais com potencial madeireiro em ecossistema de terra firme, Amazônia Oriental. *Revista Brasileira de Geografia Física* 11: 924–933.

Santos, H.G. dos; Jacomine, P.K.T.; Anjos, L.H.C. dos; Oliveira, V.A.; Lumbreras, J.F.; Coelho, M.R.; Almeida, J.A. de; Araujo Filho, J.C.; Oliveira, J.B.; Cunha, T.J.F. 2018. *Sistema Brasileiro de Classificação de Solos*, 5th ed. Embrapa Solos, Brasilia, 356p.

Santos, R.O.; Carmo Lima, R.; Lima, R.; Aparício, P.; Abreu, J. 2018. Florística e estrutura de uma comunidade arbórea na floresta estadual do Amapá, Amazônia Oriental, Brasil. *Nativa* 5: 529-539.

Schulze, M.; Grogan, J.; Uhl, C.; Lentini, M.; Vidal, E. 2008. Evaluating ipê (*Tabebuia*, Bignoniaceae) logging in Amazonia: Sustainable management or catalyst for forest degradation? *Biological Conservation* 141: 2071–2085.

Schulze, M.; Grogan, J.; Landis, R.M.; Vidal, E. 2008. Management challenges posed by timber species occurring at low densities in the Brazilian Amazon. *Forest Ecology and Management* 256: 1443–1457.

Schwartz, G.; Lopes, J.C.A.; Mohren, G.M.J.; Peña-Claros, M. 2013. Post-harvesting silvicultural treatments in logging gaps: A comparison between enrichment planting and tending of natural regeneration. *Forest Ecology and Management* 293: 57–64.

Sebbenn, A.; Degen, B.; Azevedo, V.; Silva, M.; Lacerda, A.; Ciampi, A.; et al. 2008. Modelling the long-term impacts of selective logging on genetic diversity and demographic structure of four tropical tree species in the Amazon forest. *Forest Ecology and Management* 254: 335–349.

SEMAS. 2016. Sistema de Comercialização e Transporte de Produtos Florestais-Sisflora. Extração e Movimentação de Toras de Madeira Nativa. Secretaria de Meio Ambiente e Sustentabilidade, Belém, 167p.

Sheil, D.; May, R. 1996. Mortality and Recruitment Rate Evaluations in Heterogeneous Tropical Forests. *Journal of Ecology* 84: 91–100.

Silva, C.E.G. da. 2016. Influência da região de extração em propriedades físicas e mecânicas da madeira de Cupiúba (*Goupia glabra* Aubl). Master´s dissertation, Universidade Federal de São Carlos (UFSCAR), Brazil, 82p. (https://repositorio.ufscar.br/handle/ufscar/8685).

Silva, J.N.M.; Carvalho, J.O.P.; Lopes, J. do C.; de Oliveira, R.P.; de Oliveira, L.C. 1996. Growth and yield studies in the Tapajós region, Central Brazilian Amazon. *Commonwealth Forestry Review* 75: 325–329.

Silva, J.N.M.; de Carvalho, J.O.P.; Lopes, J. do C.A.; de Almeida, B.F.; Costa, D.H.M.; de Oliveira, L.C.; Vanclay, J.K.; Skovsgaard, J.P. 1995. Growth and yield of a tropical rain forest in the Brazilian Amazon 13 years after logging. *Forest Ecology and Management* 71: 267–274.

Silva, J.N.M.; Lopes, J. do C.A.; Oliveira, L.C.; Silva, S.M.A.; Carvalho, J.O.P.; Costa, D.H.M.; Melo, M.S.; Tavares, M.J.M. 2005. *Diretrizes para Instalação e Medição de Parcelas Permanentes em Florestas Naturais da Amazônia brasileira.* Embrapa Amazônia Oriental, Belém, 68p. (https://ainfo.cnptia.embrapa.br/digital/bitstream/item/205499/1/Diretrizes-para-instalacao-e-medicao-de.pdf).

Silva, S.M.A.S.; Silva, J.N.M.; Baima, A.M.V.; Lobato, N.M.; Thompson, I.S.; Costa Filho, P.P. 2001. Impacto da exploração madeireira em floresta de terra firme no município de Moju, estado do Pará. In: Silva, J.N.M; Carvalho, J.O.P.; Yared, J.A.G. (Eds.). A Silvicultura na Amazônia Oriental: Contribuições do Projeto Embrapa/DFID. Embrapa Amazônia Oriental/DFID, Belém. p.227-251.

Sist, P.; Ferreira, F.N. 2007. Sustainability of reduced-impact logging in the Eastern Amazon. *Forest Ecology and Management* 243: 199–209.

Sist, P.; Fimbel, R.; Sheil, D.; Nasi, R.; Chevallier, M. 2003. Towards sustainable management of mixed dipterocarp forests of South-east Asia: moving beyond minimum diameter cutting limits. *Environmental Conservation* 30: 364–374.

Sist, P.; Mazzei, L.F.; Blanc, L.; Rutishauser, E. 2014. Large trees as key elements of carbon storage and dynamics after selective logging in the Eastern Amazon. *Forest Ecology and Management* 318: 103-109.

Stone, S.W. 1998. Evolution of the timber industry along an aging frontier: The case of Paragominas (Pará). *World Development* 26: 719-729.

Valkonen, S.; Lappalainen, S.; Lähde, E.; Laiho, O.; Saksa, T. 2017. Tree and stand recovery after heavy diameter-limit cutting in Norway spruce stands. *Forest Ecology and Management* 389: 68–75.

Vinson, C.C.; Kanashiro, M.; Harris, S.; Boshier, D. 2014. Impacts of selective logging on inbreeding and gene flow in two Amazonian timber species with contrasting ecological and reproductive characteristics. *Molecular Ecology* 24: 38-53.

Vinson, C.C.; Kanashiro, M.; Sebbenn, A.M.; Williams, T.C.; Harris, S.A.; Boshier, D.H. 2015. Long-term impacts of selective logging on two Amazonian tree species with contrasting ecological and reproductive characteristics: inferences from Eco-gene model simulations. *Heredity* 115: 130–139.

Watrin, O.S.; Rocha, A.M.A. 1992. Levantamento de vegetação natural e uso da terra no Município de Paragominas (PA) utilizando imagens TM/Landsat. EMBRAPA-CPATU, *Boletim de Pesquisa* # 124, Belém, 40p.

Zaque, L.A. de M.; Melo, R.R. de; Stangerlin, D.M.; Junior, L.S. 2019. Diagnóstico da comercialização de madeira serrada no estado de Mato Grosso. *Nativa* 7: 607–612.

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