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Effects of reduced impact logging on population dynamics of *Pseudopiptadenia suaveolens* in Eastern Amazon, Brazil

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ABSTRACT: Knowing the dynamics of the species natural populations is a strategy to improve its timber production and conservation, mainly through the effects caused by the reduced impact logging (RIL). Thus, the question is: what is the effect of RIL on the dynamics of *Pseudopiptadenia suaveolens* over time? The effect of RIL on the dynamics of *P. suaveolens* was evaluated based on survival, growth, recruitment, basal area and density of individuals ≥ 45 cm from Diameter to Breast Height (DBH at 1.30 m from the ground) in a thirteen-year chronosequence. Five Annual Production Units (APU) were inventoried, where four were harvested in different years (2002; 2004; 2008 and 2010) and one not harvested. The highest mortality rate occurred at five (6.6% year^{-1}) and seven (5.2% year^{-1}) years after RIL. At eleven (2.4% year^{-1}) and thirteen (1.0 % year^{-1}) years, mortality rates did not differ significantly between themselves and in relation to the control area (not harvested). The recruitment rate was significantly higher seven years after logging (7.7% year^{-1}) when compared to the other years. In logged areas, trees with DBH ≥ 75 cm account for the majority of deaths, although there was no significant difference between diameter classes, which were minimally influenced by RIL. Mortality and growth rates of *P. suaveolens* by diametric class did not show significant difference, however, they were minimally influenced by the RIL.

Key words: forest dynamics; forest logging; species density; Timborana

Efeitos da exploração de impacto reduzido na dinâmica populacional de Pseudopiptadenia suaveolens na Amazônia Oriental, Brasil

RESUMO: Conhecer a dinâmica de populações naturais da espécie é estratégia para melhorar sua produção madeireira e conservação, principalmente mediante os efeitos causados pela exploração de impacto reduzido (EIR). Desta maneira, questiona-se: qual o efeito da EIR na dinâmica de *Pseudopiptadenia suaveolens* ao longo do tempo? O efeito da EIR na dinâmica de *P. suaveolens* foi avaliada com base na sobrevivência, crescimento, recrutamento, área basal e densidade de indivíduos ≥ 45 cm de diâmetro a altura do peito (DAP a 1,30 m do solo) em uma cronossequência de treze anos. Foi inventariado cinco Unidades de Produção Anual (UPAs), quatro exploradas em diferentes anos (2002; 2004; 2008 e 2010) e uma não explorada. A maior taxa de mortalidade ocorreu aos cinco (6,6% ano^{-1}) e sete (5,2% ano^{-1}) anos após a EIR. Aos onze (2,4% ano^{-1}) e treze (1,0% ano^{-1}) anos as taxas de mortalidade não apresentaram diferenças significativas entre si e em relação à área controle (não explorada). A taxa de recrutamento foi significativamente superior aos sete anos após a exploração (7,7 % ano^{-1}) quando comparado aos demais anos. Em áreas exploradas, as árvores com DAP ≥ 75 cm respondem pela maioria das mortes, embora não houve diferença significativa entre as classes diamétricas, as quais foram minimamente influenciadas pela EIR. As taxas de mortalidade e crescimento de *P. suaveolens* por classe diamétrica não apresentaram diferença significativa, entretanto foram minimamente influenciados pela EIR.

Palavras-chave: dinâmica florestal; exploração florestal; densidade de espécies; Timborana

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Introduction

In the Brazilian Amazon, logging activities must be carried out in accordance with the reduced impact logging (RIL) guidelines, which negative impacts are minimized, as the adoption of good management practices is recommended for the best use and yield of the forest raw material. On the other hand, favorable conditions for the natural regeneration of the forest must be maintained. RIL consists of a series of guidelines implemented pre- and post-harvest, designed to protect existing natural regeneration, ensure future regeneration of the forest, minimize damage to the soil, avoid damage to remaining species, to keep the forest structure as similar as possible to the natural conditions.

The management of forest resources is important for the economic development of the Amazon region (Braz & Mattos, 2015). The practice of forest logging is provided for by Law No. 12,651, of May 25, 2012 and by Normative Instruction No. 5, of December 11, 2006, which govern the technical aspects and requirements of the inspection body to enable forestry and, consequently, the implementation of the Sustainable Forest Management Plan (PMFS) (Brasil, 2012).

Thus, it is important to know the dynamics of populations of forest species in their characteristics of recruitment, growth and mortality rates. This knowledge helps in the management of forests after logging, in the establishment of minimum cut diameter (MCD) per species (Araújo et al., 2016), cutting intensity and analysis of the effect of logging on species populations (Dionisio, 2020).

The studies of the dynamics in the Amazon forest are still insufficient to promote silvicultural practices applied to the set of native forest species, as well as the knowledge of the particularity of each population. Thus, the study of the dynamics of tree species in the Amazon is of interest to forestry companies and of great relevance to the understanding of ecology, silviculture and conservation of tree species.

In the present study, the species *Pseudopipitadenia suaveolens* (Miq.) J. W. Grimes was assessed in terms of mortality rate, recruitment and growth, basal area and density of individuals over 13 years of RIL to better understand its dynamics in forests subject to logging.

The study of the dynamics of the forest and its systems can generate important data on the balance between the number of individuals that enter the forest with the number of removed individuals, wood productive potential and the distribution of individuals by diameter class. This knowledge helps in choosing the most appropriate management practice for *P. suaveolens*. The objective of this study was to evaluate the dynamics of the species *P. suaveolens* in the Eastern Amazon over 13 years of RIL.

Material and Methods

Study area

The study area is located on the Rio Capim farm, belonging to the Keilla Group (formerly CIKEL), located in the municipality of Paragominas (03°39'28.16"S and 48°49'59.73"W), state of Pará, Brazil (Figure 1). The Rio Capim farm has a total area of 140,000 ha, of which 121,000 ha are under forest management certified by the Forest Stewardship Council (FSC) since 2001.

The ecosystem characteristic of the region is of the Dense Ombrophilous Forest type, also called Equatorial Humid Forest of *terra firme* (IBGE, 2012). According to the Köppen classification, the climate of the region is of the "Awi" type, i.e., tropical rainy with average annual rainfall of 1,800 mm, average annual temperature of 26.3 °C and relative humidity of 81% (Alvares et al., 2013). The altitude of the study area is 20 m in flat to slightly undulating relief (Sist & Ferreira, 2007). Yellow Latosols, Yellow Ultisols, Plintosols, Gleysols and Neosols are the main soil types in the region (Rodrigues et al., 2003).

Forty-nine commercial species were selected, which were monitored over thirteen years (from 2002 to 2015). Of the commercial species harvested in Rio Capim farm, the chosen species was *Pseudopiptadenia suaveolens* for the present study.

Popularly known as timborana (Morim, 2020), *P. suaveolens* belongs to the ecological group of light-demanding species (Norden et al., 2009) and is an important commercial species in the Amazon due to the multiple uses of its wood. *P. suaveolens* wood is used in civil construction as rafters, slats, boards, canes, sheets for plywood and turned parts; can also be applied to parts of boats and pieces of musical instruments (Santini Junior et al., 2021). It has a basic wood density of 760 kg m^{-3} and an average price of sawn wood ranging from R$ 550.00 to R$ 700.00 respectively in the informal and formal market of Santarém, Pará (Ribeiro et al., 2019).

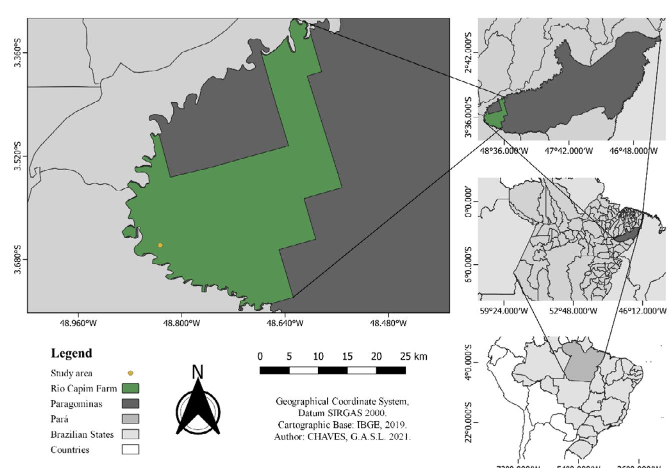

Figure 1. Location of the Rio Capim farm, in the municipality of Paragominas, Pará, Brazil.

Sampling design

For the evaluation of the chosen variables, five Annual Production Units (APUs) were selected, four operated in different years of logging (2002; 2004; 2008 and 2010) and one not logged and monitored since 2006. In each APU, one Work Unit (WU) of 100 ha was selected and divided into 10 plots of 10 ha (100 × 1,000 m) (Figure 2).

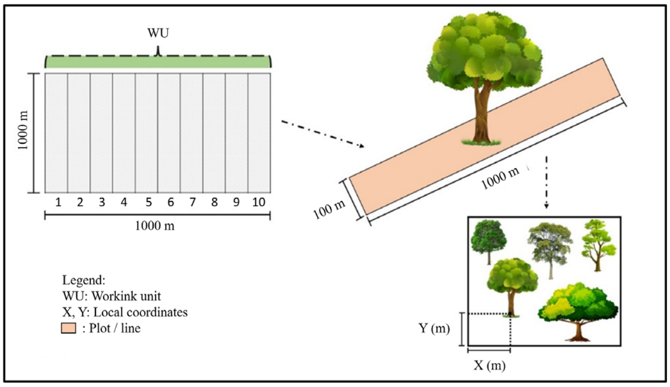

Figure 2. Scheme of the 10 plots of 100 × 1,000 m in each work unit, Rio Capim farm, municipality of Paragominas, Pará, Brazil (Adapted from Dionisio et al. (2018)).

In each WU, a 100% forest inventory was carried out for trees with DBH ≥ 45 cm. The inventory took place one year before logging and later in 2015. The areas had different logging ages, thus forming a chronosequence of 13 years of logging (Table 1). The five sampled areas are under the same soil and climate characteristics.

Data analysis

Density and basal area of the individuals (pre- and post-harvest), mortality rate (% year^{-1}), recruitment (% year^{-1}) and growth (cm year^{-1}) were determined by year of logging and by classes of diameter of individuals of the species *P. suaveolens* with DBH ≥ 45 cm.

Mortality and recruitment rate were calculated for each harvested area and for the control area. In this way, the annualized rates of mortality and recruitment of the individuals remaining after logging in the period of 13 years were calculated using Equations 1 and 2, respectively:

$$m = 1 - \left(\frac{N_{t2}}{N_{t1}}\right)^{\left(\frac{1}{t}\right)} \quad (1)$$

$$r = \left(1 - \left(1 - \left(\frac{I}{N_{t2}}\right)^{\left(\frac{1}{t}\right)}\right)\right) \times 100 \quad (2)$$

where, m = annual mortality rate, r = annual recruitment rate, N_{t1} = number of trees alive in the initial sampling, N_{t2} = number of trees that survived until the second sampling, I = numbers of trees recruited, and t = years between the first and second sampling (Sheil et al., 1995; Sheil & May, 1996).

Mortality rate was calculated using live trees in the first measurement and the remaining live trees in the 2015 remeasurement. Recruitment rate was calculated from new trees, not present in the first measurement, with DBH ≥ 45 cm in the second measurement.

The growth rate was calculated by the difference between the diameter measurements of the trees in the periods 2002-2015, 2004-2015, 2006-2015, 2008-2015 and 2010-2015 $(DBH_{final} - DBH_{initial}) / (time_{final} - time_{initial})$.

For the analysis of density, basal area, mortality rate and growth by diameter class, individuals were divided into six classes based on DBH (45 - 54.9 cm; 55 - 64.9 cm; 65 - 74, 9 cm; 75 - 84.9 cm, 85 - 94.9 cm and ≥ 95 cm).

For statistical analysis of mortality and recruitment and growth rates, each 10 ha plot was considered a repetition. Data were analyzed using analysis of variance (ANOVA). In case of significant difference between treatments, Tukey's post-hoc test was used to compare the means. All forest dynamics parameters and statistical analyses were performed in the R program, version 4.0.2 (R Core Team, 2020), at a significance level of $p < 0.05$.

Results and Discussion

Mortality and recruitment rate

A higher mortality rate was observed in *Pseudopiptadenia suaveolens* individuals with DBH ≥ 45 cm at five years (6.6 ± 2.9% year^{-1}) and seven years after logging (5.2 ± 2.0% year^{-1}) ($F_{4; 45}$ = 15.45, p = 0.001) (Figure 3A). At 11 years (2.4 ± 1.4%) and 13 years (1.0 ± 0.9%), the mortality rates did not show significant differences between them and in relation to the control area, which was 2.4% year^{-1} in all monitoring years. The recruitment rate was significantly higher at seven years after logging compared to the other years (7.7 ± 2.4% year^{-1}, $F_{4;45}$ = 7.768, p = 0.001) and, in all subsequent years, the recruitment rates did not show significant differences between them and in relation to the control area (3.1 ± 2.1%) (Figure 3B).

Despite having minimal impacts on the forest, reduced impact logging (RIL) contributed to increasing mortality and recruitment rates (Dionisio et al., 2018), with mortality rates higher at five and seven years after logging, demonstrating that the population of *P. suaveolens* was affected by the disturbances. However, rates tend to decrease over time. In studies by De Graaf (1986), the stabilization of the

Table 1. Sampled Annual Production Units (APU) and Working Units (WU) inventoried between 2002 and 2010 and remeasured in 2015, Rio Capim farm, PA, Brazil.

Year of harvesting/ evaluation period	Years after harvesting	WU area (ha)	Average volume harvested ± SD (m³ ha^{-1})	Density	Dead trees	Recruits
					(Ind ha^{-1})	
2006-215	Control	100	---	24.18	4.38	7.62
2010-215	5	100	29.07 ± 2.10	29.92	5.22	2.68
2008-215	7	100	29.13 ± 1.94	30.62	5.04	13.38
2004-215	11	100	28.93 ± 1.75	32.46	5.30	11.06
2002-215	13	100	26.42 ± 2.53	18.75	2.91	14.25

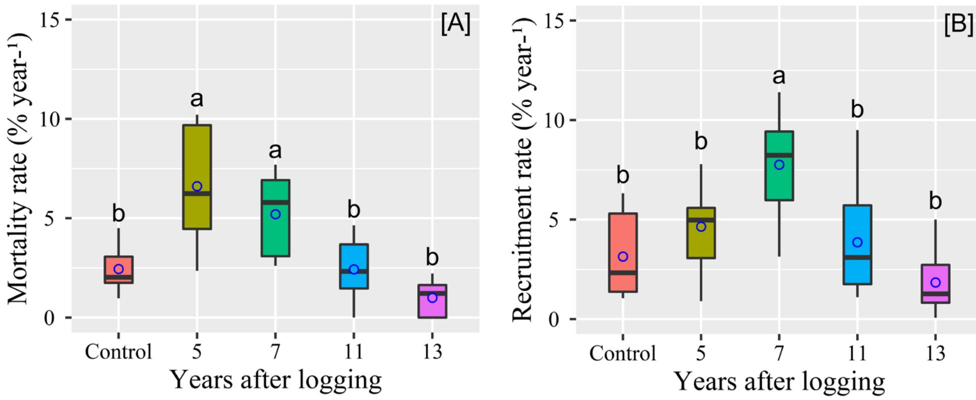

Figure 3. Boxplot with mortality (A) and recruitment (B) rates of individuals of the species *Pseudopiptadenia suaveolens* with DBH ≥ 45 cm in the management area. The thicker horizontal line represents the median, the box the interquartile range and the dashed lines the extreme values, respectively. Letters indicate statistically significant differences (p = 0.05) in ANOVA with Tukey's post-hoc test.

mortality rate of post-harvest trees occurred after 10 years of disturbance. Thus, depending on the management adopted in the forest, the effects of selective logging can often last for decades after its occurrence.

Swaine et al. (1987), from 18 studies conducted in unlogged natural tropical forests in Southeast Asia, Africa and America, found mortality rates between 1% and 2% year^{-1}. Silva et al. (1995) found mortality rates in the Tapajós National Forest of 2.6, 2.4, and 2.2% year^{-1} for five, six, and 11 years after harvest, respectively. The authors also comment that five years may not be a sufficient period to assess the mortality and the time of forest resilience regarding the rebalancing of mortality rates.

Dionisio (2020) evaluating the mortality rates of *Manilkara huberi* in the same area of the present study found a mortality rate of 9.6% year^{-1} at five years and of 7.2% year^{-1} seven years after logging. The authors report that from 11 years onwards, mortality rates did not show significant differences from the control area, suggesting stability in these rates. The authors also found a higher rate of recruitment at seven years after logging (11.3% year^{-1}) and recruitment rates did not show significant differences between them and in relation to the area without logging in all subsequent years.

Growth rate

A higher growth rate was observed five years (2.56 ± 1.22 cm year^{-1}, $F_{4; 100}$ = 8.595, p = 0.001) after logging in relation to the other logged and the control areas (Figure 4). After seven years (1.26 ± 1.20 cm year^{-1}), the forest stabilized its growth, showing no significant differences from the control area (1.21 ± 0.72 cm year^{-1}) (p = 0.999).

Even presenting reduction in growth rates, 13 years after logging, *P. suaveolens* still shows satisfactory and superior growth when compared to studies in the Brazilian Amazon for other forest species. Costa et al. (2008), studying the growth dynamics of forest species in the Tapajós National Forest, found that light-demanding species presented significantly higher diameter growth than shade-tolerant species, with

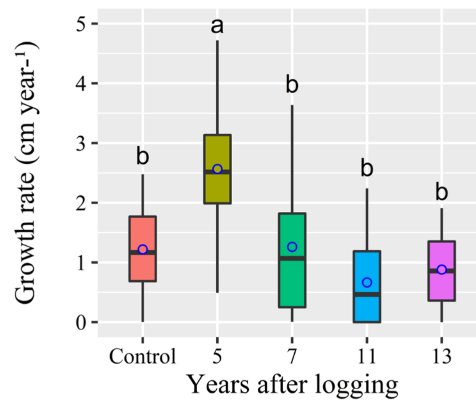

Figure 4. Boxplot with growth rate of individuals of the species *Pseudopiptadenia suaveolens* with DBH ≥ 45 cm from the logging and control areas. The thicker horizontal line represents the median, the box the interquartile range and the dashed lines the extreme values. Letters indicate statistically significant differences (p = 0.05) in ANOVA with Tukey's post-hoc test.

averages of 0.60 cm year^{-1} and 0.23 cm year^{-1}, respectively. Dionisio (2020), evaluating the growth rates of *Manilkara huberi* in the same area of the present study, found a growth rate of 0.51 cm year^{-1}.

The beneficial effect of canopy opening on tree development lasted until five years after logging, when the average growth in diameter started decreasing. This is explained by the proximity to the forest canopy and increased competition among the remaining trees. As there was no post-harvest treatment to stimulate growth of remaining trees and potential recruits, it is natural the growth rate to decrease until reaching the level of an unlogged forest. The logging of trees can be considered a silvicultural treatment, as it removes part of the commercial trees, opening canopy gaps in the forest, which increases the incidence of light inside of it. The increase in light incidence after logging positively influences the growth rates of remaining trees (Silva et al., 1995; Souza et al., 2015), but the effect remains shortly after the interventions (Dionisio et al., 2018).

Density and basal area of individuals

The density of *P. suaveolens* individuals with DBH ≥ 45 cm decreased in all areas after logging. Five years after logging, the average density of individuals decreased from 1.74 ± 0.5 to 1.06 ± 0.3 ind. ha^{-1} and, in the 2015 inventory, this number reduced to 0.88 ± 0.3 ind. ha^{-1}, a 50% reduction from the initial value (Figure 5A). Similar results occurred in the other harvested areas, except in seven years after logging, where, due to the high recruitment rate, the area presented 0.98 ± 0.5 ind. ha^{-1} pre-logging and 0.92 ± 0.5 ind. ha^{-1} in the 2015 inventory, almost recovering the initial value of individuals (Figure 5A). Five years after logging, the basal area of the species reduced from 0.64 ± 0.2 to 0.24 ± 0.1 m^2 ha^{-1} and, in the 2015 inventory, this number increased to 0.39 ± 0.1 m^2 ha^{-1} (Figure 5B). In the other years, there was a reduction in the basal area both after logging and in the 2015 inventory. Comparing the basal area of the forest without logging (control) (0.65 ± 0.19 m^2 ha^{-1}) with the basal area 13 years after logging (0.16 ± 0.13 m^2 ha^{-1}), a reduction of 75% could be observed.

In the present study, the density of individuals and the basal area were affected in all post-logging years. This reduction was already expected in all areas due to logging and consequent tree mortality (Figure 5A and 5B). Until the 13th year of monitoring, the species *P. suaveolens* had not yet recovered the density of individuals and basal area by the growth of remaining trees and recruitment of new individuals. Since the species has a basic wood density of 0.76 g cm^{-3}, 13 years post-harvest is a relatively short time to recover the harvested stock of this species. The reduction in the density of individuals and in the basal area also occurred due to the mortality of remaining trees. Although RIL may have less impact on the forest than conventional logging, selective logging can directly alter environmental characteristics, modifying floristic composition and community structure, microclimate in the forest understory and microhabitats (Schwartz et al. al., 2017a; De Avila et al., 2017).

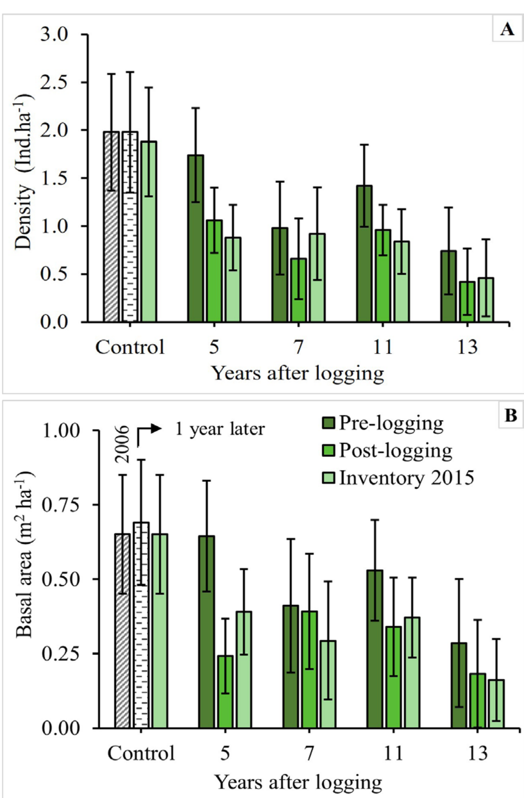

Figure 5. Average (± SD) of the individuals density (A) and basal area (B) of the species *Pseudopiptadenia suaveolens* individuals with DBH ≥ 45 from the logging and control areas, present in the pre-logging, post-logging and in the 2015 inventory.

Diameter distribution

Pseudopiptadenia suaveolens presents continuous diametric distribution, however, the distribution is not in the reverse J-shaped, indicating that this species can be light demanding. This distribution was not affected by forest logging over the 13 years of study, but it reduced the number of individuals in the 55 to 64.9 cm classes by more than 50%. As much as there is a reduction in the density of individuals, the distribution between diameter classes is similar in all years after logging (Figure 6).

In the control area (Figure 6), there was a small reduction in the number of individuals per diameter class. This reduction is associated with the natural mortality rates observed in the present study. Due to its light-demanding behavior, it is to be expected that, during the phases of intra and interspecific competition, these specimens tend to die with the advance of forest succession. During this period (2002-2015) there were some very dry years in the Amazon, which may also have implied an increase in the mortality of remaining trees.

Reis et al. (2014), evaluating the diameter distribution of Sapotaceae 13 years after the low impact logging in the municipality of Moju, State of Pará, observed that soon after the logging, the species *Manilkara huberi* presented decreases in four of the eight diameter classes of its distribution. The authors state that there was discontinuity mainly in the 75 and 85 cm classes, which the cut of individuals was concentrated. However, the species retained the reverse J-shaped after logging. Dionisio et al. (2018) observed that the reduced impact logging did not affect the population structure of *Duguetia* spp., which in the period of 30 years after logging, maintained its natural decreasing distribution in the form of a reverse J, and the species showed a balance between mortality and recruitment rates.

In natural forests, a reverse J distribution is observed in shade-tolerant species, characterizing a typical, self-regenerating community, with a greater number of individuals in the smallest diameter classes. Species with no individuals in the smallest size classes or discontinuous distribution are considered heliophiles (Jardim, 2015). Species which diameter distribution has an intermediate form between these extremes are opportunistic, and may have large or small gaps, depending on whether they require more or less light to establish themselves.

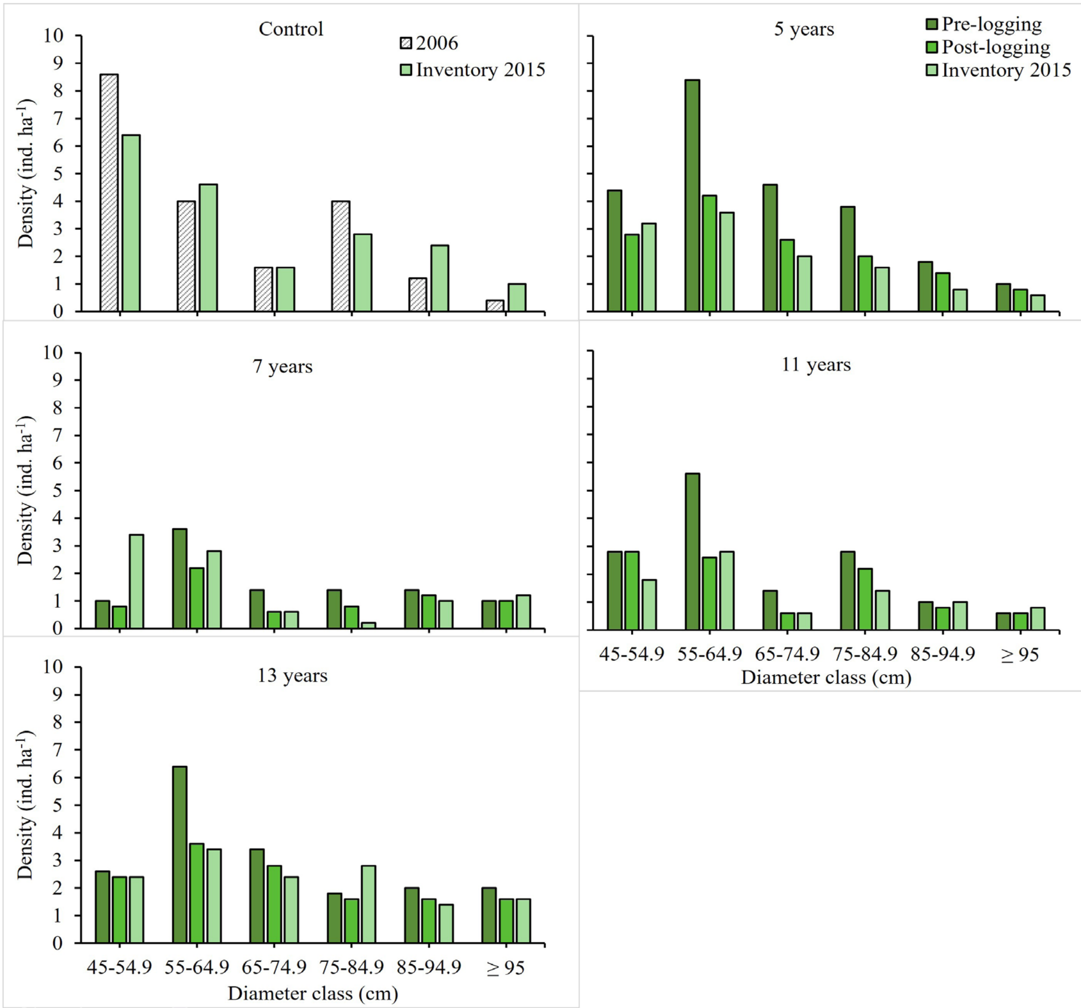

Figure 6. Diameter distribution *Pseudopiptadenia suaveolens* individuals with DBH ≥ 45 from logging and control areas, present in pre-logging, post-logging and 2015 inventory.

At the species level, however, the diameter distribution can differ greatly from the reverse J form, according to the ecophysiological behavior of the species and the changes that occur over time (Dalla Lana et al., 2013), especially after forestry logging. When trees are harvested in different diameter classes with different intensity in certain classes, it results in strong alterations in the diameter distribution and, consequently, it takes a long time to recover the usable stock of the harvested species (Reis et al., 2014).

Mortality rate by diameter class

There was no significant difference in the mortality rate by diameter class in the logged area ($p = 0.214$). In the control area, the mortality rate was significantly higher (2.65% year^{-1}) in the 45-54.9 cm class compared to the other classes ($p = 0.001$). From the 55 cm class, there was no difference in mortality rates in the control area. It was observed that there was a significant difference when comparing the mortality rate between the areas, starting from the 55 cm class. In all other classes, the mortality rate was higher in the logged area, with significant statistical difference (Figure 7).

Even adopting RIL, forests under this type of logging are significantly affected. Larger diameter trees had higher

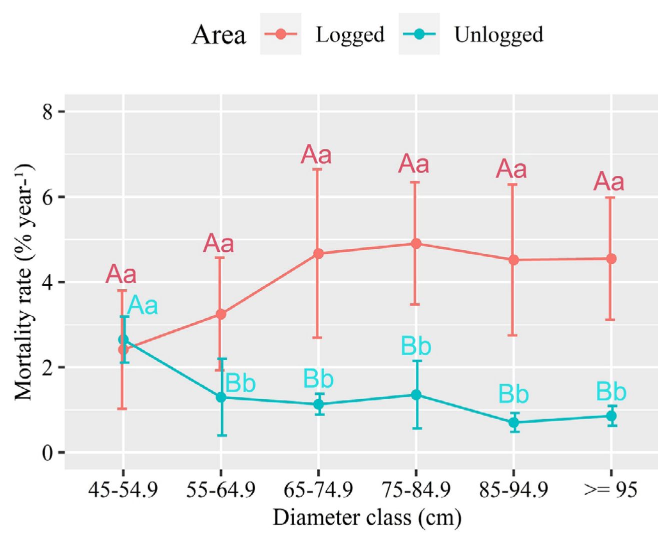

Figure 7. Average (± SD) of the mortality rate by diameter class for individuals of the species *Pseudopiptadenia suaveolens* with DBH ≥ 45 from the logged and unlogged area (control). Capital letters indicate statistically significant differences ($p < 0.05$) in ANOVA with Tukey's post-hoc test between treatment within each diameter class, and lowercase letters difference of the same treatment by classes.

mortality rates (Figure 7). In unlogged forests, it is common mortality rates to be higher in smaller diameter classes, due to high competition for nutrients and light. However, in logging areas, mortality is higher in trees with larger diameters (Dionisio, 2020). Dionisio et al. (2018), believe that the canopy opening leaves trees with larger diameters susceptible to winds, being a factor that increases probability of tree fall. At the end of the logging period (dry season), the rainy season begins. With the soil excessively wet and trees exposed to the winds the probability of of tree fall substantially increases.

Growth rate by diameter class

In the unlogged area, there was no statistical difference in growth rates in all diameter classes, with a maximum of 1.7 cm year^{-1} ($F_{5; 34}$ = 1.369, p = 0.269). Classes 85-94.9 and > 95 cm had no individuals (Figure 8A). In the logged area, there was also no significant difference for growth in the different diameter classes ($F_{5; 92}$ = 1.395, p = 0.234) (Figure 8B).

The results showed that the diameter growth of *P. suaveolens* individuals in the largest diameter classes was positively influenced by RIL. With the canopy opening, it is provided a decrease in competition and a greater incidence of light (Souza et al., 2017; Dionisio et al., 2018; Dionisio, 2020).

Implications of reduced impact logging on forest regeneration

Etymologically, regeneration means the action of generating, reproducing, rebuilding, restoring, recovering and renewing, among other actions. These terms apply to vegetation and are understood as regeneration that can be natural or artificial, depending on human involvement. The regeneration of a forest happens through different mechanisms that guarantee the forest renewal. Natural disturbances (falling of trees and branches) open canopy gaps and promote the regeneration of tropical forests. The natural regeneration of species in tropical forests has been presented in several works in the scientific literature, whether in terms of population dynamics of species or communities. In the latter case, it is interesting to evaluate the basic processes of recruitment, growth and mortality that in tropical forests are influenced by natural disturbances such as the formation of gaps (Jardim, 2015).

Despite the great advantages (less damage to the forest) compared to conventional logging, reduced impact logging (RIL) causes greater disturbances in the forest when compared to natural forests without logging. The anthropic disturbance caused by planned forest logging has positive points, such as an increase in growth rates and recruitment of tree species, mainly pioneers and light demanding, thus guaranteeing forest regeneration, but it also has disadvantages such as increased rates of mortality (Dionisio et al., 2018; Dionisio, 2020).

In forestry terms, the objective of evaluating natural regeneration is to determine whether stocks or the regeneration process are capable of ensuring that a logged species can recover its harvested stock. The concept of sustainable forest management is based on this ability to replace harvested forest products, whether timber or non-timber. The major concern among forest managers is the volume of wood yield of the species harvested, which may not recover between the first and second harvests. The growth of the remaining commercial stock must be sufficient to compensate for the volume lost during the harvesting operation. This loss comprises the volume harvested, residual parts of the felled trees and the volume of trees that die before, during and after logging that are not used and remain in the forest. Another important fact is that many commercial species in managed tropical forests lack natural regeneration (van Rheenen et al., 2004; Park et al., 2005; Schwartz et al., 2017a). The combination of these factors can result in lower yields in future cutting cycles, making forest harvesting unfeasible for many commercial species.

This does not seem to be the case for *P. suaveolens*, which presented individuals in all logging classes, stabilized its mortality rates in 11 years after logging and had positive growth five years after logging. Thus, the present study reduces the knowledge gap on the population dynamics of *P. suaveolens*.

Faced with so many factors that can alter the trajectory of forest regeneration and compromise future cutting cycles,

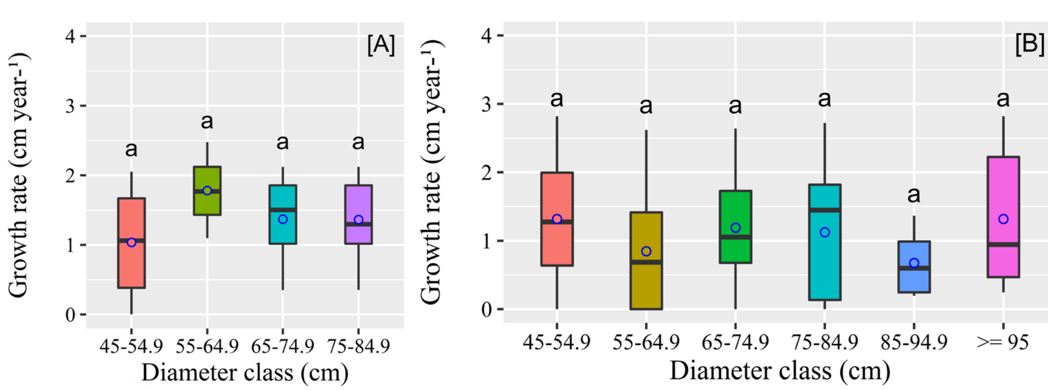

Figure 8. Boxplot of average growth rate by diameter classes of individuals of the species *Pseudopiptadenia suaveolens* with DBH ≥ 45 cm from the unlogged area (A) and from the logged areas (B). The thicker horizontal line represents the median, the box the interquartile range and the dashed lines the extreme values. Letters indicate statistically significant differences (p = 0.05) in ANOVA with Tukey's post-hoc test.

how can we intervene in the forest in order to help it recover? To balance losses in wood volume in managed tropical forests due to logging, it is believed that intensifying forestry would be an interesting alternative from an economic and environmental point of view in tropical forests. Post-harvest silvicultural practices should be adopted to increase growth and recruitment rates of commercial tree species, as well as decrease their mortality rates. Forest disturbances, including those caused by forest harvesting, resulting in canopy openings, can be used as an effective way to increase density of rare tree species (low density) and/or those that exhibit low natural regeneration and slow growth. The enrichment of gaps created by forest logging with species of commercial value, rare or locally threatened species (Sabogal et al., 2009; Schwartz & Lopes, 2015; Schwartz et al., 2017b) and the use of the volume lost due to natural or human activity become fundamental for the balance of the volume of wood harvested in managed forests. Increasing the density of individuals of these species in forest canopy gaps can work as an artificial refuge, maintaining their genetic diversity. This is possible through assisted densification (artificial increase in the number of individuals per unit area of tree species in their own natural habitats). Such a procedure can also guarantee the third cutting cycle (25-35 years) in tropical forests in the Brazilian Amazon, since commercial species naturally have low densities and suffer an increase in post-harvest mortality (Dionisio et al., 2018).

It is suggested that the volume of naturally dead trees or those that die after forest logging can be used to increase the financial profit of forestry companies without the need to increase logging intensity. The increase in total volume harvested (cut trees + dead trees) could be an interesting alternative for companies. However, studies on the economic feasibility of extracting dead trees should be carried out to corroborate the proposal presented, as well as a review of forest legislation, since there is no mention in the forestry legislation at the federal and state level about the use of trees resulting from natural fall or death.

Conclusions

Reduced impact logging (RIL) increased mortality, recruitment and growth rates of the tree species *Pseudopiptadenia suaveolens* in the first seven years post-logging.

RIL reduced by up to 50% the density and basal area of *P. suaveolens* individuals in all areas harvested. At 13 years after logging, the forest did not recover the density of individuals and basal area. Mortality and growth rates by diameter class were minimally affected by logging.

Studies with silvicultural treatments from seven years post-logging should be conducted for the population of *P. suaveolens* in order to enhance growth, recruitment and basal area of the species.

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Compliance with Ethical Standards

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