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Post-harvesting silvicultural treatments in canopy logging gaps: Medium-term responses of commercial tree species under tending and enrichment planting

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ABSTRACT

Technical and scientific information on medium-term effects of post-logging silvicultural interventions on the recovery of harvestable growing stocks are hardly available. To mitigate uncertainties about these effects our study aimed to answer the following question: "What is the medium-term effect of post-harvest silvicultural treatments on mortality, growth, and the structure of commercial tree species in canopy logging gaps under tending and enrichment planting?" we study individuals planted and naturally regenerated in 72 logging gaps opened tree felling during reduced-impact logging among different silvicultural treatments: (1) natural regeneration tending (TNER); (2) enrichment planting in logging gaps (EP1); (3) enrichment planting in logging gaps previously cleaned of harvesting residuals (EP2). Mortality increased through time, EP1 presented the highest mortality rates of all treatments in the first, sixth and 11th year, TNER had the lowest at the same period. TNER and EP2 presented the highest basal area and EP2 the highest periodic annual increment. Effects of the silvicultural treatment TNER were positive, since it presented the highest survival and a high mean basal area of the initial trees. The medium-term effects of silvicultural treatments applied over individuals of commercial trees in logging gaps indicate higher survival and growth that reflected in the structure of treated individuals when compared to standard procedures of reduced impact-logging, these results bring positive outcomes to reach more sustainable future cutting cycles in the Brazilian Amazon and other tropical forests worldwide.

1. Introduction

The fate of tropical forests has been guided by anthropic activities (Lewis and Maslin, 2015; Putz et al., 2012). Species richness simplification in tropical environments has been observed where species have been lost due to a combination of rapid climate change, natural populations isolation in fragmented landscapes, competition against invasive species, and the impact of increasing disturbances due to land use changes (Lewis et al., 2015; Lewis and Maslin, 2015). To conciliate the conservation of forest biodiversity as well as other ecosystem services with economic interests is a big challenge for nations, especially those developing countries with large tropical forests (Chaudhary et al., 2016).

Reduced-impact logging (RIL) has been applied in tropical forests as an important tool to mitigate destructive impacts of conventional logging in order to conserve biodiversity and other ecosystem services as well to reduce deforestation rates (Putz et al., 2012; Schwartz et al., 2012). Although its several benefits, other studies have shown that tree mortality increases after harvesting following all RIL requirements (Bladon et al., 2008; Hautala and Vanha-Majamaa, 2006; Lavoie et al., 2012). Even after the application of RIL, mortality rates increase in response to disturbance effects that can remain up to 11 years after harvesting (Dionisio et al., 2017).

Besides the increased mortality, simulations of future scenarios indicate that the current technological advances in tropical forest management do not guarantee the same volume yields of wood for further harvesting cycles (Avila et al., 2017; Dauber et al., 2005; Dionisio et al., 2017; Hawthorne et al., 2012; Putz et al., 2012; Sist and Ferreira, 2007;

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Table 1
Initial conditions (2006–2007) of the four post-harvesting silvicultural treatments tested (mean ± SD) for seedlings and saplings naturally present or planted in logging gaps in Jari Florestal, Brazil (adapted from Schwartz et al., 2016).

Variable	Standard RIL (SRIL)	Tending of natural regeneration (TNER)	Enrichment planting 1 (EP1)	Enrichment planting 2 (EP2)
Number of seedlings and saplings	436	396	1520	645
Density (number of individuals/m^2)(mean ± SD)	0.070 ± 0.017	0.056 ± 0.015	0.110 ± 0.035	0.109 ± 0.020
Number of species	34	39	10	5
Number of logging gaps	15	15	34	8
Size of logging gaps (m^2) (mean ± SD)	395.1 ± 86.3	478.4 ± 200.4	418.7 ± 97.6	754.9 ± 237.7
Age of logging gaps at the beginning of the experiment (years)	2	2	2	1
Logging compartment	2004	2004	2004*	2006**
Logging residuals removed from gaps	No	No	No	Yes
Silvicultural treatment	No treatment	Tending the natural regeneration	Enrichment planting and tending	Enrichment planting and tending

* Species planted in 2006.
** Species planted in 2007.

Valle et al., 2007). The scarcity of natural regeneration of commercial species in harvested tropical forests (Park et al., 2005; Schwartz et al., 2017a; Van Rheenen et al., 2004), the large amount of timber volume removal per harvest cycle, and the volume of wood lost due to increased post-harvest mortality are crucial factors to prevent successful future harvesting cycles. Evidences show that the current cutting cycle of 25–35 years employed in the Brazilian Amazonian forests with a maximum harvesting volume of 30 m^3 ha^{-1} (SEMAS, 2015) cannot be sufficient to allow the recovery of harvested timber volumes (Avila et al., 2017; Dionisio et al., 2018, 2017; Schwartz et al., 2013; Sist and Ferreira, 2007). Non-logged commercial species, however, could be harvested in further cutting cycles to ensure the same forest yields.

Some of the possible alternatives to mitigate this issue includes: (a) to change the set of harvested species to lighter wood species (Reis et al., 2010); and (b) to apply post-harvesting silvicultural treatments (Dauber et al., 2005) such as tending the natural regeneration and planting commercial species in canopy gaps created by tree felling during harvesting operations (Schwartz et al., 2017b). Silvicultural treatments increase timber production in tropical forests and favor the establishment of natural regeneration and the growth of seedlings potentially able to replace harvested individuals (Avila et al., 2017; Inada et al., 2017; Schwartz et al., 2017b, 2017a, 2013; Vieira et al., 2018; Villegas et al., 2009), but there is a need to assess the costs of silvicultural treatments.

Technical and scientific information on medium-term effects of post-logging silvicultural interventions on the recovery of harvestable growing stocks are hardly available (Petrokofsky et al., 2015) and are empirical or based simply on simulations. In this sense, it becomes necessary a non-empirical silvicultural system for the sustainable management of tropical forest resources (Jardim, 2015). To mitigate uncertainties about the effects of post-harvest silvicultural treatments (Gomes et al., 2019; Lopes et al., 2008; Schwartz et al., 2013; Souza et al., 2015; Taffarel et al., 2014; Vieira et al., 2018) our study aimed to respond the following questions: What is the medium-term effect of post-harvest silvicultural treatments on survival, growth, and the structure of commercial tree species in canopy logging gaps under tending and enrichment planting?

2. Materials and methods

2.1. Study area and sampling design

Data were obtained from a field experiment carried out in the forest management area of the forestry company Jari Florestal SA under the project 'Logging Gaps Management' coordinated by Embrapa Eastern Amazon in cooperation with Jari Florestal. The study area is located in the Jari valley, Almeirim municipality (1°9′S, 52°38′W), Pará state, Brazil. Average annual precipitation is 2200 mm and the annual average temperature is 26 °C. The vegetation is mainly ombrophilous dense forest over yellow latossols (Azevedo, 2006).

Jari Florestal has a total area of 545,535 ha under forest management where harvesting operations follow RIL techniques. A total of 2997 seedlings and saplings naturally present or planted in 72 gaps created by tree felling due to RIL operations were assigned to assess treatments as follows: (1) standard procedures of RIL (SRIL), (2) tending of the naturally established regeneration (TNER), (3) enrichment planting 1 (EP1), and (4) enrichment planting 2 (EP2).

The experiment was established in 2006 and 2007 in the logging compartments harvested in 2004 and 2006. In SRIL, which served as control, marked individuals were only monitored, with no additional silvicultural treatments, according to the current forest management regulations for forest monitoring in the Brazilian Amazon. In the other three treatments, silvicultural procedures were applied in addition to all steps required to employ RIL.

Tending consisted in the liberation of target individuals against competing tree species and lianas, it was applied over seedlings and saplings of commercial tree species naturally established (TNER) and planted (EP1 and EP2) in all measurement years. In the enrichment planting treatments, all seedlings were planted in a spacing of 2.5 m × 2.5 m using commercial tree species of different ecological groups. EP1 and EP2 differed in terms of planted species, logging compartments, gap ages and removal of logging residuals. EP1 was established in 2-year gaps where no logging residual was removed while EP2 was established in 1-year gaps with complete logging residual removal for further energy production by the forestry company (Table 1).

The logging gaps used in this experiment were set in terms of size, according to the classification of Jardim et al. (2007) in: 27 small size gaps (200–400 m^2), 30 medium size gaps (401–600 m^2), and 11 large size gaps (> 600 m^2). EP2 has the largest logging gaps with a significant statistical difference of the other three treatments, whose did not differ among them (SRIL, TNER, and EP1) in size. The tending silvicultural treatments on TNER, EP1, and EP2 were applied annually from 2006 to 2010, 2012, 2017, and 2018. In 2018 the treatments SRIL, TNER, EP1, and EP2 presented 203, 248, 461, and 276 trees, respectively, which remained alive since the experiment beginning (henceforth "Initials"). At the 2017 measurement, new individuals ≥ 300 cm in height that grew naturally inside the monitored logging gaps (henceforth "Complementary") were included and monitored in the experiment. All species of the study are commercial but not necessarily were harvested by the forestry company. The total number of new individuals included in SRIL, TNER, EP1, and EP2 were 51, 44, 129, and 20, respectively (Table 2).

Table 2
Current conditions (2017–2018) of the four post-harvesting silvicultural treatments tested for initial and complementary individuals in logging gaps in Jari Florestal, Brazil.

Variable	Standard RIL (SRIL)	Tending of natural regeneration (TNER)	Enrichment planting 1 (EP1)	Enrichment planting 2 (EP2)
Number of alive trees ≥ 300 cm in height since the experiment beginning	203	248	462	274
Number of complementary trees, included in 2017	51	44	129	20
Total number of trees in the experiment	254	292	591	294
Number of species included in 2017	0	0	15	8
Current total number of species	29	34	24	13
Current number of logging gaps	15	13	32	8
Total area of logging gaps (m^2)	5926.61	6587.13	13325.85	6038.93

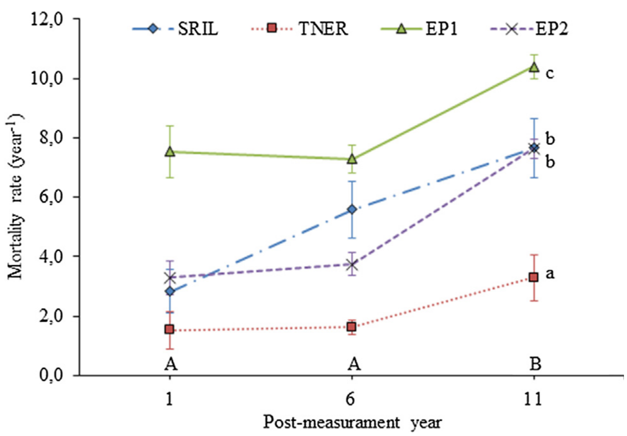

Fig. 1. Mean (± SE) of mortality rates of standard procedures of reduced-impact logging (SRIL), tending of the naturally established regeneration (TNER), enrichment planting 1 (EP1), and enrichment planting 2 (EP2) treatments by one, six, and 11 years in logging gaps in the managed forests of Jari company, Pará state, Brazil. Lowercase letters are treatment comparisons and uppercase letters are time comparisons in the GLM repeated measures ANOVA and post-hoc Tukey's pairwise test.

2.2. Data analysis

Only individuals with height ≥ 300 cm were used in the analyses carried out in this study. This means that every planted or naturally regenerated seedling that did not reach minimum height of 300 cm by 2010 was not considered in this study. Mortality, diameter at breast height (DBH) at 1.3 m from the soil, periodic annual increment (PAI), basal area, and diameter classes were calculated based on the measurements of the years 2017 for SRIL, TNER, and EP1 and 2018 for EP2, so in this way all treatments were analyzed under the same measurement ages.

Mortality rates were calculated with logging gaps as the sampling units. The annualized mortality rates were calculated using the formula "$m = 1 - (N_{t2}/N_{t1})^{(1/t)}$", where N_{t1} = Number of live trees in the first sampling, N_{t2} = number of trees that survived until the second sampling and t = years between first and second sampling (Sheil et al., 1995). Mortality rates did not follow a normal distribution, thus they were analyzed through a general linear model (GLM) repeated measures ANOVA, with time and treatment as factors and mortality rates as the dependent variable and compared by post-hoc Tukey's pairwise test.

The logging gap area was calculated by the ellipse formula. Logging gap was also the sampling unit to calculate basal area, which was the sum of tree cross sections of each logging gap. Each tree cross section was obtained with the formula $g = \pi * (DBH/2)^2$ in square meters per hectare, where DBH = diameter at breast height. Basal area for the initial, complementary, and the sum of initial and complementary individuals (henceforth "Overall") in each logging gap per treatment were calculated. Once applied the Shapiro-Wilk test, the data on both initial, complementary, and overall trees did not present a normal distribution, which required a Box-Cox transformation, before running ANOVA and the post-hoc Tukey's pairwise test.

Periodic annual diameter (PAI) measured from DBH of each individual was calculated using the formula $PAI = ((DBH_{t2} - DBH_{t1})/n)*365)$, where DBH_{t1} = individual's diameter at the initial sampling, DBH_{t2} = individual's diameter at the final sampling, and n = days between first and second sampling. Individual PAI was the sampling unit, ANOVA ($p < 0.05$ significance level) was performed and compared by the post-hoc Tukey's pairwise test. All analyses were performed using the R version 3.0.2 (2016).

The number of individuals (initial, complementary, and overall trees), in percentages, were set in five diameter classes ranging 5 cm in DBH from 0 up to 25 cm. In addition, the basal area was also set in each of these five diameter classes.

3. Results

Mortality increased through time. In the first, sixth and 11th year, EP1 presented the highest mortality rates of all treatments, 7.5, 7.3, and 10.4% $year^{-1}$, respectively. TNER had the lowest mortality rate observed at the same period, with 1.5, 1.6, and 3.3% $year^{-1}$, respectively. There was a significant statistical difference among treatments (repeated measures ANOVA, $p < 0.001$) and time (repeated measures ANOVA, $p < 0.001$), with no significant interaction between treatment and time (repeated measures ANOVA, $p = 0.063$). SRIL and EP2 treatments presented statistical similarity ($p = 0.93$ significance level; Fig. 1).

In terms of basal area of the initial trees 11 years after the experiment started, EP2 presented the highest value (2.47 $m^2 ha^{-1}$) and SRIL the lowest (1.12 $m^2 ha^{-1}$). However, for the complementary trees, the highest basal area was observed in SRIL (0.90 $m^2 ha^{-1}$) and the lowest in the EP2 treatment (0.25 $m^2 ha^{-1}$). The sum of initial and complementary basal area resulted in TNER (3.14 $m^2 ha^{-1}$) as having the highest basal area, and SRIL with the lowest (2.01 $m^2 ha^{-1}$; Fig. 2). Comparisons among initial trees presented statistical significant difference ($p < 0.001$) among treatments, except between TNER (2.33 $m^2 ha^{-1}$) versus EP2 (2.47 $m^2 ha^{-1}$) and SRIL (1.19 $m^2 ha^{-1}$) versus EP1 (1.18 $m^2 ha^{-1}$) that had no statistical differences. No statistical significant differences were found among treatments in the mean basal area of the complementary and overall trees (Fig. 2).

The lowest mean of PAI were observed in the natural regeneration treatments, where SRIL presented half (0.20 cm $year^{-1}$) of the PAI mean observed in TNER (0.41 cm $year^{-1}$). EP2 presented the highest PAI mean (0.84 cm $year^{-1}$), four times more than SRIL ($p < 0.05$). Statistical differences were found in all treatments ($p < 0.05$, Fig. 3).

Over 11 years the 0–5 and 5–10 classes presented the highest percentage of the initial trees in all treatments. Meantime the 5–10 and 10–15 classes presented the highest percentage of the complementary trees. Among treatments, SRIL 0–5 cm diameter class presented the

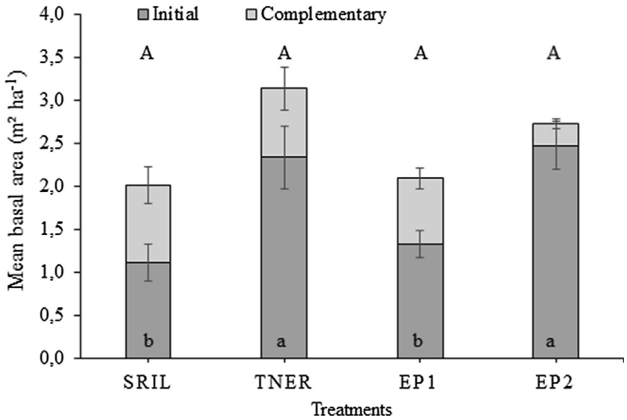

Fig. 2. Mean (± SE) of basal area (m^2 ha^{-1}) of standard procedures of reduced-impact logging (SRIL), tending of the naturally established regeneration (TNER), enrichment planting 1 (EP1), and enrichment planting 2 (EP2) treatments from the initial trees, complementary and the overall individuals (sum of initial and complementary individuals) in logging gaps in the managed forests of Jari company, Pará state, Brazil. Lowercase letters are to comparisons between the initial mean basal areal of treatments and uppercase letter are to mean basal area of complementary and overall in the ANOVA and post-hoc Tukey's pairwise test.

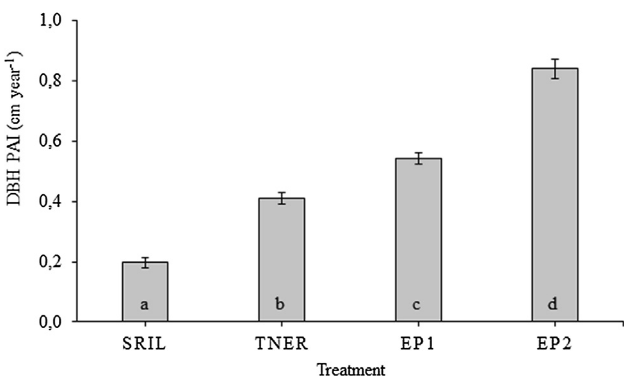

Fig. 3. Mean (± SE) of periodic annual increment (PAI) of reduced-impact logging (SRIL), tending of the naturally established regeneration (TNER), enrichment planting 1 (EP1), and enrichment planting 2 (EP2) treatments in logging gaps in the managed forests of Jari company, Pará state, Brazil. Lowercase letters are treatment comparisons in ANOVA with post-hoc Tukey's pairwise test.

highest number of individulas. On the other hand, EP1 showed the highest concentration of individuals in class 5–10 cm of the complementary individuals. The basal area presented a paraboloid tendency for all treatments. However, the classes with the highest concentration of basal area are in the range of 5–15 cm (Fig. 4).

4. Discussion

Effects of the silvicultural treatment TNER were positive, since it presented the highest survival and a high mean basal area of the trees. Furthermore, TNER presented twofold PAI value when compared to SRIL, which is the treatment that reflects the current procedures of reduced impact logging (RIL) legally adopted in the Brazilian Amazon. Tending treatment applied to natural regeneration and enrichment planting in logging gaps are financially profitable options for forest managers and investors (Schwartz et al., 2016) to minimize post-logging losses due to increased mortality observed in managed forests (Dionisio et al., 2017). These silvicultural treatments also help to mitigate the non-recovery of species diversity after logging observed in selectively logged forests (Shima et al., 2018).

The highest TNER survival is probably due to the fact that sampled individuals were already established before the silvicultural treatments had started. Besides this, tending begun to be applied to avoid competition for light against other arboreal individuals and lianas (Schwartz et al., 2016). In this study, TNER was shown to be effective to increase survival of individuals when compared to the other treatments tested. Higher mortality in enrichment planting, like EP1 and EP2, in relation to natural regeneration, like SRIL and TNER is probably due to the rustification phase (Adenesky-Filho et al., 2017).

Although the rustification phase, EP2 and SRIL did not present significant statistical difference in mortality, which can figure as a positive treatment effect of cleaning potential competitors for light and nutrients in enrichment planting. The higher mortality of enrichment planting treatments in relation to tending may be a result of the low quality many planted seedlings. The availability of high quality seedlings of native commercial species is a serious bottleneck for enrichment planting in the Brazilian Amazon. For the success of enrichment planting in logging gaps, it is recommended a rigorous seedling production, with fertilizers, as well as annual cleanings once seedlings planted in the field normally face strong competition (Gomes et al., 2019).

The highest complementary mean basal area in SRIL can be explained by the absence of any silvicultural treatment, which permitted new individuals of commercial species to get established. The fact that there was no tending over the monitored individuals of commercial species (initials) could have allowed competing individuals to over compete them inside logging gaps (Avila et al., 2017; Jardim, 2015). Results on basal area found in this study corroborate Inada et al., (2017), in a comparison among RIL + Line Planting/Slashing (LP/S) of tree species versus conventional logging and versus RIL. After 10 years, stocks were marginally higher in RIL + LP/S plots, with no statistical difference among treatments.

SRIL, TNER, and EP2 presented a similar total area of logging gaps (m^2), but the basal area of the initial trees of TNER and EP2 were twice higher than SRIL. The tending treatment benefits both natural regeneration and enrichment planting and may be influenced by gap sizes, since in larger gaps more light illuminates the forest floor, stimulating tree growth (Vatraz et al., 2016). In an experiment with *Cedrela odorata* planted in logging gaps, Vieira et al. (2018) found after five years that tending silvicultural treatment provided higher growth in height of seedlings planted in larger logging gaps (> 600 m^2).

The canopy height formed by trees that surround a logging gap is crucial for the success of individuals of tree species under any silvicultural treatment. Foresters can also enlarge logging gaps in order to improve success of survival and growth rates of planted or tended individuals of tree species. For example, two gaps with the same area but different surrounding canopy heights will have different sunlight incidence, which will necessarily have effects on the individual performances. *S. parahyba* planted in small gaps (200 m^2) can thrive since the surrounding canopy height is not so tall. And this is the case of Schwartz et al. (2017b) where *S. parahyba* was managed in logging gaps surrounded by a short canopy height.

Low densities or absence of the regeneration of commercial species found in three managed forests sampled by Schwartz et al., (2017a) suggest that commercial species are having poor post-harvesting capacity to regenerate in the Eastern Amazon. The enrichment planting in gaps is defined by Schwartz and Lopes (2015) as a type of assisted densification. This means that tree species have their densities increased in their own natural habitats, which can work both for conservation and timber production, as it can increase artificial density up to 60 times compared to the natural densities of many commercial species. Mahogany is an example of rare commercial species that can have its natural densities increased (Lopes et al., 2008).

EP1 started with 10 species in 2006 and reached 24 in 2017, even though one of the planted species had 100% of mortality rate in the period. The high mortality of EP1 trees and the application of cleaning

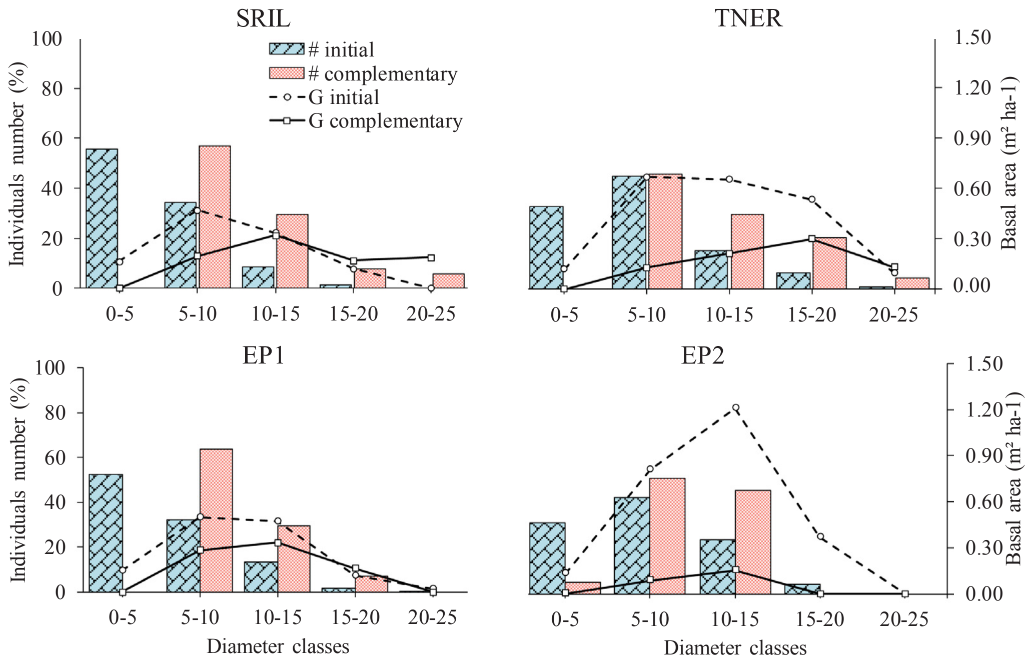

Fig. 4. Bars representing percentage of individuals per diameter class (left side y-axis) and lines showing basal area (m^2 ha^{-1}) per diameter class (right y-axis) of the standard reduced-impact logging (SRIL), tending of the naturally established regeneration (TNER), enrichment planting 1 (EP1), and enrichment planting 2 (EP2) treatments for both initial and complementary trees in logging gaps in the managed forests of Jari company, Pará state, Brazil.

opened space for new individuals of fast-growing species. This explains the entrance of the largest number of commercial species and individuals, mainly in the higher diameter classes, of EP1. This outcome of silvicultural treatment application can mitigate the sequential depletion of species (Putz et al., 2012) through the enrichment planting and augment of the regeneration with the entrance of new species and stock of the most commercial species. Most of the individuals present in higher diameter classes will probably reach the minimum cutting diameter faster than initial trees.

EP2 was the most suitable treatment for the specific purpose of timber production and/or species conservation. Furthermore, the improvement in light conditions caused by silvicultural treatments improved the increase of both growth and stock of commercial species (Inada et al., 2017). Successful enrichment planting in logging gaps confirms the results found in other experiments worldwide with enrichment planting in gaps (Doucet et al., 2009; Gomes et al., 2019, 2010; Lopes et al., 2008; Quédraogo et al., 2014; Schwartz et al., 2013; Taffarel et al., 2014; Vieira et al., 2018). These studies help to reinforce the efficiency of enrichment planting in logging gaps, which comes as a viable silvicultural alternative for managing tropical forests.

Enrichment planting in logging gaps can also work as an active germplasm bank to maintaining the genetic diversity of rare or endangered species (Lopes et al., 2008) and may have potential as seed/seedling orchard. Besides the use in old-growth managed forests, as the forest management area of the forestry company Jari Florestal, such silvicultural treatments can also be applied to recover degraded forests or to improve secondary forests, which are commonly found in the arc of deforestation (Schwartz and Lopes, 2015), a region that concentrates most of the deforestation in the Brazilian Amazon. To have this achievement, it is necessary the development of new public policies to improve the current forest management regulations in the Brazilian Amazon.

Silvicultural treatments also showed positive effects on the structure of individuals in logging gaps. Based on these results, it is hypothesized that the silvicultural treatments will shorten the time required to recover losses caused by RIL. Post-harvest silvicultural treatments could help to mitigate the delay in several tropical forests to recover harvested stocks (Shima et al., 2018).

5. Conclusion

The medium-term effects of silvicultural treatments applied over individuals of commercial trees in logging gaps indicate higher survival and growth that reflected in the structure of treated individuals when compared to standard procedures of reduced impact-logging. These results bring positive outcomes to reach more sustainable future cutting cycles in the Brazilian Amazon.

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