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Natural regeneration of tree species in the Eastern Amazon: Short-term responses after reduced-impact logging

Gustavo Schwartz [a,b,*], Vanessa Falkowski [a], Marielos Peña-Claros [a]

[a] Forest Ecology and Forest Management Group, Wageningen University and Research, P.O. Box 47, 6700 AA Wageningen, The Netherlands
[b] Embrapa Eastern Amazon, P.O. Box 48, 66095-100 Belém, PA, Brazil

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ABSTRACT

Forest management for timber production has improved in tropical forests with the adoption of a polycyclic silvicultural system (PSS) where harvesting is carried out using reduced-impact logging (RIL). In this study, the natural regeneration of forests harvested under RIL restrictions was assessed in three different sites of the Eastern Amazon two years after logging. A total of 7987 seedlings and saplings belonging to 197 species were sampled through 951 plots of 2×2 m in 11 different natural and logging created environments. Light-demanding commercial species presented their highest density in logging environments such as logging gaps, skid trails, and borders of log decks. Shade-tolerant commercial species were more common in natural and logging gaps. Regarding the densities of harvested species in the three study sites, only 26.3% were represented by $\geqslant 5$ individuals and 28.1% were completely absent in the surveys two years after logging. These results suggest a lack of natural regeneration of the current commercial tree species in the Eastern Amazon. Therefore, post-harvesting silvicultural treatments as enrichment planting and the tending of the natural regeneration in logging gaps should be applied to ensure the regeneration of these species.

1. Introduction

Long-term management of tropical forests through sustainable polycyclic silvicultural systems (PSS) for timber production is only possible if the harvested species have a continuous and abundant regeneration (Fredericksen and Mostacedo, 2000). The natural regeneration of harvested species can be related to their ecological requirements and to how these species are managed, which includes among other aspects the ways how logging is carried out (Pereira et al., 2002).

Reduced-impact logging (RIL) is a set of techniques applied under a PSS aimed to avoid destructive impacts over remaining trees to be harvested in further cutting cycles. RIL has been widely accepted by managers and certifiers as an environmental-friendly way of harvesting primary tropical forests (e.g., Johns et al., 1996; Pinard and Putz, 1996; Putz et al., 2008). Among the practices composing RIL, there are directional felling and mapping of harvestable trees, water courses, and topography (Dykstra, 2002; Pereira et al., 2002; Zarin et al., 2007). Many studies show that RIL does not cause negative effects on several groups of animal species (Bicknell and Peres, 2010) such as birds (Wunderle et al., 2006), bats (Castro-Arellano et al., 2009), other mammals (Azevedo-Ramos et al., 2006), and butterflies (Ribeiro and Freitas, 2012). RIL also does not interfere on the genetic diversity of the harvested tree species (Cloutier et al., 2007; Sebbenn et al., 2008). Despite of its environmental advantages, the effects RIL on the natural regeneration of commercial tree species is still poorly understood. More detailed knowledge about effects of RIL on the natural regeneration of the current commercial tree species is needed to reach ecologically and economically productive harvesting cycles as well as the conservation of these species within their natural environments (Guariguata and Pinard, 1998; Schwartz et al., 2012; Karsten et al., 2014; Schwartz et al., 2014).

During logging operations, different forest environments are created due to tree falls and machinery's movements. These environments vary in their characteristics from those with high levels of forest ground illumination and high soil compaction (log decks) to those environments similar to natural gaps (logging gaps). Moreover, log decks, natural and logging gaps are not homogeneous environments; sunlight incidence decreases from the center towards the border of these environments (Park et al., 2005). These differences in sunlight incidence are likely to be reflected in the species composition found in each environment. Additionally, such variations in environmental conditions interfere on the survival

* Corresponding author at: Embrapa Eastern Amazon, P.O. Box 48, 66095-100 Belém, PA, Brazil.
E-mail address: Gustavo.Schwartz@embrapa.br (G. Schwartz).

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chances and consequent seedling establishment of tree species (Hattori et al., 2013). It can be expected that, after logging, seedlings and saplings of tree species will differ in their density and distribution according to their regeneration requirements. Some tree species may even face reduction in their populations due to logging and its associated disturbances. In extreme cases, species with low natural densities may even disappear from managed forests due to lack of natural regeneration (Schulze et al., 2008; Darrigo et al., 2016). Hence, an adequate management of the logging created environments can strongly contribute to the conservation of the current commercial tree species (Mostacedo and Fredericksen, 1999).

In the present study, two main questions were addressed: (1) Do the density of commercial tree species and individuals vary among different natural and logging created environments? (2) What is the density of seedlings and saplings of harvested tree species two years after harvesting under RIL techniques?

2. Materials and methods

2.1. Study sites

This study was carried out in three sites with managed primary forests (Tapajós, Jari, and Rio Capim), in the Eastern Amazon, Pará state, Brazil. Forest management in these sites follows the Brazilian environmental regulations and the FSC requirements. Harvestings are done through RIL in cycles of 30–35 years within a PSS (Table 1). The Tapajós site is in the concession area of Coomflona, a cooperative for community forest management. This concession encompasses part of the Tapajós National Forest, a 549,000-ha conservation unit for sustainable production of timber and non-timber products. The Jari site is in the Almeirim municipality with 545,535 ha of forests managed by the company Jari Florestal S.A that is certified under the FSC scheme since 2003. Rio Capim is in the Paragominas municipality with 209,130 ha of forests managed by the company Cikel Brasil Verde Madeiras Ltda and is certified under the FSC scheme since 2001. These sites represent some of the most important regions where good forest management practices have been applied in the Brazilian Amazon (Pereira et al., 2010).

All sites have similar biophysical characteristics (Table 1) with forests classified as ombrophilous dense, lowland moist forest, or as *terra firme* forest, depending on the classification system and author (e.g. Eva et al., 2004; IBGE, 2004). Most of the Brazilian forest management plans for production of native timber under a PSS and harvestings with RIL are applied over this type of forest.

2.2. Sampling

Data were collected from September to December 2010, specifically in logging compartments harvested in 2008 under RIL. To assess the short-term responses of the natural regeneration of tree species to RIL, five natural and logging created environments typically present in logging compartments were sampled: (a) unlogged forest: portion of forest not disturbed by logging activities, (b) natural gaps: formed by fallen trees due to natural causes, (c) skid trails: paths used by skidders to bring logs from the forest to log decks, (d) logging gaps: created by felled trees during harvesting operations, and (e) log decks: open areas along main logging roads used to storage logs.

Only natural gaps with estimated ages of two years were sampled in order to be comparable with logging gaps. Age estimations were based on the rotting degree of the fallen trunk and on the development of the within and surrounding vegetation. Only the middle of primary and secondary skid trails, i.e., >1 m from the path borders was sampled. Samples were placed at least 50 m away from each other to avoid edge effects. Plots on natural gaps and unlogged forest were placed in the same logging compartment where the logging created environments were sampled. The sampling effort covered the whole logging compartment of 2008, sizing nearly 100 ha per site.

Natural gaps, logging gaps, and log decks were sub-divided in other three environments: border, intermediate, and center: (a) one plot randomly placed in the gap-forest or log deck-forest border, (b) one plot randomly placed in-between the border and the gap/log deck's center, and (c) a third plot in the gap/log deck's center (Table 2). Counting the subdivisions of natural gaps, logging gaps, and log decks, the total number of natural and logging created environments assessed in this research was 11. Therefore, the assessed environments, from the least disturbed to the most disturbed, were (with abbreviation in parentheses): (1) Forest (FOR), (2) Natural Gap Border (NGB), (3) Natural Gap Intermediate (NGI), (4) Natural Gap Center (NGC), (5) Skid Trail (STR), (6) Logging Gap Border (LGB), (7) Logging Gap Intermediate (LGI), (8) Logging Gap Center (LGC), (9) Log Deck Border (LDB), (10) Log Deck Intermediate (LDI); (11) Log Deck Center (LDC). To sample the natural regeneration of tree species, 30 plots of 2×2 m were established in each environment of the three study sites, except log decks in Tapajós. Only 17 log decks were opened in the logging compartment of 2008 in Tapajós, which were all sampled (Table 2).

Individuals of all commercial and non-commercial tree species $\geqslant$30 cm in height up to 20 cm in DBH found in the plots were identified to the lowest possible taxonomic level, counted, and measured. Height was measured in individuals <300 cm, while DBH (at 1.30 m from the ground) was measured in individuals $\geqslant$300 cm in height. The identification was done by a tree spotter with 30 years of experience in the Eastern Amazon. A cumulative curve of species-area to indicate sufficiency in sampling effort was done for each site.

Table 1
Biophysical characteristics of the areas under forest management (Tapajós, Jari, and Rio Capim) in the Eastern Amazon (Brazil) sampled in this study.

	Tapajós	Jari	Rio Capim
Location	3°02′S–54°56′W	1°09′S–52°38′W	3°32′S –48°35′W
Mean altitude (masl)	175	150	120
Annual mean temperature	25 °C	26 °C	25 °C
Annual rainfall	1900 mm	2200 mm	1700 mm
Main type of soil	Yellow latosols	Yellow latosols	Yellow latosols
Type of forest	Ombrophilous dense	Ombrophilous dense	Ombrophilous dense

Table 2
Number of plots sampled per environment and site to assess the natural regeneration of tree species two years after harvesting using reduced-impact logging in the Eastern Amazon (Brazil). The total number of plots and sampled area (m^2) in each habitat are also given.

Habitat	Plots per site	Total number and total area of plots sampled
Unlogged forest	1 × 30 replicates = 30	90 (360 m^2)
Natural gaps	3 (center, border, intermediate) × 30 replicates = 90	270 (1080 m^2)
Skid trails	1 × 30 replicates = 30	90 (360 m^2)
Logging gaps	3 (center, border, intermediate) × 30 replicates = 90	270 (1080 m^2)
Log decks	3 (center, border, intermediate) × 30 replicates = 90	231 (924 m^2)[a]

[a] The Tapajós site had only 17 log decks sampled.

Log decks had length and width measured while natural and logging gaps had major and perpendicular axes measured to calculate their areas. Gap size was considered the projection of the canopy opening on the ground, obtained through the ellipse formula = πLW, where L is the radius of the major axis and W is the radius of the perpendicular axis that crosses the major axis. Percentage of the total area of each environment covered by liana and vines (hereafter, liana cover) was estimated visually for natural gaps, logging gaps, and log decks.

2.3. Natural regeneration of harvested tree species two years after logging

For each site, the list of the species harvested in the logging compartment of 2008 was used to check if the species harvested in 2008 appeared in the natural regeneration as seedlings or saplings two years later. Due to the limited botanical information from the harvested species from the companies, there were cases where the identification at the species level was impossible. Some of the sampled seedlings and saplings were identified only at the genus level (11 morpho-species, representing 5.6% of the species and 8.2% of the individuals sampled). Botanical identification doubts arose regarding some of the harvested species in 2008. Hence, groups of 2–4 species identified in the samplings of 2010 were grouped in a single genus to be comparable with the lists of the species harvested in 2008. This procedure was used only for the complex genera *Lecythis*, *Nectandra*, *Ocotea*, and *Protium*. The species were also assigned in the functional groups of light-demanding and shade-tolerant according to Pinheiro et al. (2007), Do Amaral et al. (2009) and Condé and Tonini (2013).

2.4. Data analysis

Data on the area and percentage of liana cover of natural gaps, logging gaps, and log decks were not normally distributed, even after Ln (x + 1) transformations. Thus, non-parametric tests were used to compare these variables among the three environments (Kruskal-Wallis) and between natural and logging gaps (Mann-Whitney). Species density (number of species per plot) and the density of individuals (number of individuals per plot) in the 11 environments were analyzed using one-way ANOVA. Data were Ln (x + 1) transformed prior to the analyses to meet the homogeneity of variance. The univariate analyses were performed with the IBM SPSS 17.0 (New York, USA) software. Statistical differences were significant at $p < 0.05$.

To assess differences in the overall species composition in each environment, a cluster analysis was performed. The clustering method of UPGMA (Unweighted Pair Group Method using Arithmetic Averages) with the Euclidean similarities distances was used. The analysis was also performed including separately the light-demanding and the shade-tolerant commercial species harvested in 2008 and present in the natural regeneration in 2010. The software used for multivariate analyses was MVSP (Pentraeth, UK).

3. Results

3.1. Natural regeneration of tree species in natural and logging created environments

A total of 7987 individuals were sampled, in which 437 were ⩾300 cm in height and <10 cm in DBH. Twelve individuals were 10–20 cm in DBH. Tapajós showed the highest species richness (152 species) and the highest abundance (3298 individuals) (Table 3). In a graphic interpretation of the cumulative curve of species-area, the species accumulation stabilized between the 200th and the 250th plot surveyed in each site (Fig. 1). This indicates a sufficient sampling effort to the investigated sites.

The area of the environments were significantly different (Kruskall-Wallis, $p < 0.001$), with log decks presenting the largest area (mean = 576.8 ± 22.5 m^2 SE; median = 506.0 m^2). Logging gaps (mean = 167.3 ± 8.1 m^2 SE; median = 144.1 m^2) were larger in area (Mann-Whitney, $p < 0.001$) than natural gaps (mean = 123.6 ± 6.0 m^2 SE; median = 110.0 m^2). The percentage of liana cover also differed significantly among these environments (Kruskall-Wallis, $p < 0.001$). Logging gaps presented the highest liana cover (mean = 28.1 ± 3.3% SE; median = 15.0%) followed by natural gaps (mean = 18.1 ± 2.9% SE; median = 5.0%), and log decks (mean = 12.1 ± 3.2% SE; median = 5.0%). Logging gaps had as well significantly higher percentage of liana cover than natural gaps (Mann-Whitney, $p = 0.004$).

The sampled environments differed in species density (ANOVA, $F_{10,\ 940} = 75.2$, $p < 0.001$), with NGB and LGB showing the highest and LDI and LDC the lowest averages. Density of individuals also

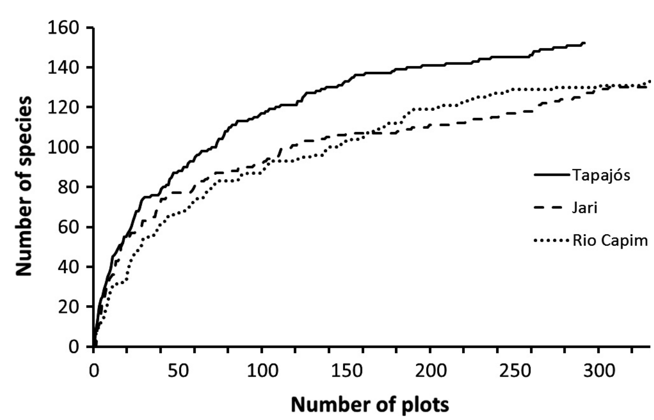

Fig. 1. Cumulative species-area curve based on 2 × 2 m plots to sample the natural regeneration of tree species in natural and logging created environments of managed forests in Tapajós, Jari, and Rio Capim (Eastern Amazon, Brazil). For total number of plots per site see Table 2.

Table 3
Cutting cycles, harvested volume, number of species harvested in 2008, species richness and abundance (in parentheses) of the natural regeneration of tree species sampled in 2010 in Tapajós, Jari, and Rio Capim (Eastern Amazon, Brazil). The number of timber species harvested in 2008 and absent in 2010, and the number of species harvested in 2008 and represented by equal or more than one and five individuals in at least one area are given.

	Tapajós	Jari	Rio Capim	Total
Cutting cycle (years)	30	30	35	–
Harvested volume in 2008 ($m^3\ ha^{-1}$)	11.3	25.5	12.3	–
Number of species harvested in 2008	21	22	42	57
Total number of species (individuals) sampled in 2010	152 (3298)	130 (2469)	133 (2220)	197 (7987)
Species harvested in 2008 and absent in samples of 2010	7	8	22	17
Species (individuals) harvested in 2008 and sampled in 2010 with N ⩾ 1	14 (176)	14 (258)	20 (355)	35 (789)
Species (individuals) harvested in 2008 and sampled in 2010 with N ⩾ 5	4 (157)	8 (245)	13 (340)	18 (736)

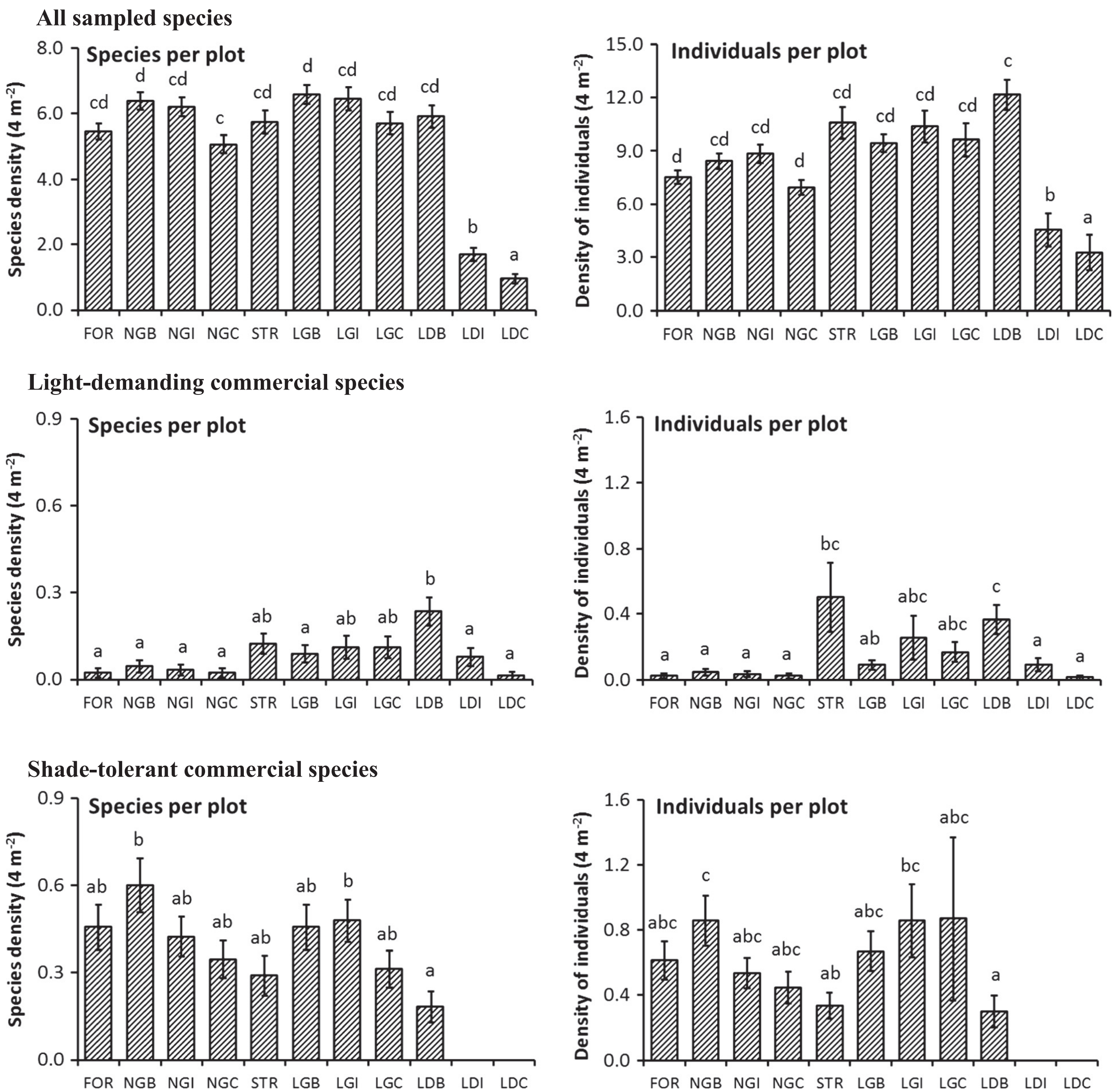

Fig. 2. Species density (mean number of species per plot ± SE) and density of individuals (mean number of individuals per plot ± SE) of all sampled tree species, light-demanding commercial species, and shade-tolerant commercial species in 11 natural and logging created environments sampled in Tapajós, Jari, and Rio Capim (Eastern Amazon, Brazil) two years after logging. Letters indicate statistical differences (One-way ANOVA and the Tukey post hoc test) among the environments with $p < 0.05$. Forest (FOR), Natural gap border (NGB), Natural gap intermediate (NGI), Natural gap center (NGC) Skid trail (STR), Logging gap border (LGB), Logging gap intermediate (LGI), Logging gap center (LGC), Log deck border (LDB), Log deck intermediate (LDI), and Log deck center (LDC). Note a different scale in graphs showing the species density and density of individuals of "All sampled species".

differed (ANOVA, $F_{10,\,940} = 43.9$, $p < 0.001$), with LDB presenting the highest and LDC the lowest averages (Fig. 2). A total of 35 commercial species harvested in the logging compartments of the three sites in 2008 were found in the samplings of 2010 (Table 3). These species were distributed in: 10 light-demanding, 15 shade-tolerant, and 10 not defined in a functional group. Shade tolerant commercial species had higher species density and density of individuals than light demanding species (Fig. 2). In the case of the light demanding commercial species, species density (ANOVA, $F_{10,\,940} = 4.7$, $p < 0.001$) and density of individuals per plot (ANOVA, $F_{10,\,940} = 5.0$, $p < 0.001$) varied among the different environments, with skid trails and borders of log decks presenting the highest averages. Similarly, shade-tolerant commercial species also differed in species density (ANOVA, $F_{10,\,940} = 8.6$, $p < 0.001$) and density of individuals (ANOVA, $F_{10,\,940} = 7.7$, $p < 0.001$) among environments, with natural and logging gaps presenting the highest averages (Fig. 2).

In the multivariate cluster analysis, the resulting dendrogram for all species (Fig. 3) showed two main clusters following disturbance gradient from FOR (no disturbance) to LDC (highest disturbance). The first cluster included the least and the intermediate disturbed environments (natural environments and logging gaps). A second main cluster contained the four most disturbed environments, namely those created by the infrastructure required for timber extracting (i.e., skid trails and log decks; Fig. 3). The dendrogram including only shade-tolerant commercial species was similar to the dendrogram with all sampled species. For

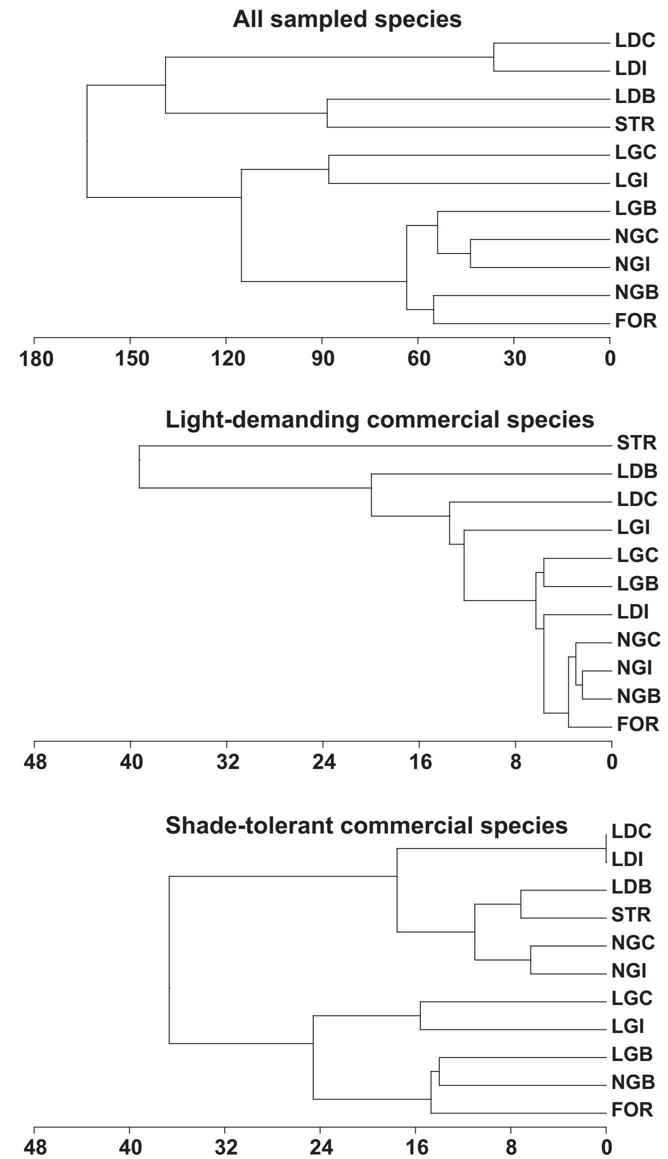

Fig. 3. Cluster analysis with Euclidean distances of 11 natural and logging created environments two years after harvesting in Tapajós, Jari, and Rio Capim (Eastern Amazon, Brazil) for all sampled species, light-demanding commercial species, and shade-tolerant commercial species. Forest (FOR), Natural gap border (NGB), Natural gap intermediate (NGI), Natural gap center (NGC) Skid trail (STR), Logging gap border (LGB), Logging gap intermediate (LGI), Logging gap center (LGC), Log deck border (LDB), Log deck intermediate (LDI), and Log deck center (LDC). Note the different scale in the "All sampled species" dendrogram.

light-demanding commercial species, the dendrogram showed STR, LDB, and LDC as the most distant from the main cluster formed by all the remaining environments (Fig. 3).

3.2. Natural regeneration of harvested tree species two years after logging

Amongst the sampled timber species, 57 of them were harvested in at least one site and 23 were common in at least two sites harvested in 2008 (Table 3). Five species (*Bagassa guianensis*, *Diplotropis* sp., *Hymenaea courbaril*, *Manilkara* sp., and *Vochysia maxima*) were harvested in the three study sites. From the 57 species harvested in 2008 in the three sites, 28.1% had no individuals sampled in 2010, and 7.0% were represented by a single individual (Table 4). Only 26.3% of the harvested species were represented by five or more individuals in at least one site in the sampling of seedlings and saplings done in 2010.

4. Discussion

4.1. Natural regeneration of tree species in natural and logging created environments

Logging activities result in new environments with different environmental conditions where the regeneration of tree species may take place (Johns et al., 1996; Karsten et al., 2014; Schwartz et al., 2014). For example, it has been found that soils of logging gaps, skid trails and borders of log decks are less disturbed than soils in the intermediate and central positions of log decks (Hattori et al., 2013). These differences in soil compaction were reflected in the species density and density of individuals of all species and of each functional group (Fig. 2), and ultimately in species composition (Fig. 3). Our results are similar to the ones found in the Peruvian Amazon (Karsten et al., 2014). The authors suggest that lower levels of soil disturbances promote high diversity, while excessive soil disturbances result in low diversity of timber species. Moreover, borders of log decks are subjected to a large sunlight incidence, which offers great conditions for growing and survival of seedlings and saplings.

Light-demanding commercial species can benefit from resources availability and conditions offered by the artificially created logging environments. These species take advantage from soil disturbances and the highly increased light availability in the places opened by logging operations (Fredericksen and Mostacedo, 2000; Peña-Claros et al., 2008). In this study, light-demanding species had the highest species density and highest density of individuals in logging environments such as logging gaps, skid trails, and borders of log decks, while the lowest values were observed in the least disturbed environments (Fig. 2). On the other hand, shade-tolerant commercial species were not found in the intermediate and central positions of log decks (Fig. 2). This can be related to soil compaction, a consequence of intensive movement of heavy machinery as bulldozers and skidders. Soil compaction reduces possibilities of seedlings establishment, growth, and survival of shade-tolerant species (Guariguata and Pinard, 1998; Fredericksen and Pariona, 2002; Alameda and Villar, 2009).

Most of commercial species depend on natural gaps to regenerate. These gaps are crucial to trigger germination of light-demanding and promote growth of shade-tolerant species (Felton et al., 2006; Yamamoto, 2000; Kukkonen et al., 2008; Zhu et al., 2014). Within canopy gaps, the high availability of light provides the ideal environmental conditions for germination and growth of seedlings and saplings. Under these conditions, germination of light-demanding species from seed banks can be triggered and growth of shade-tolerant species from seedling banks enhanced. Logging gaps, as showed in this study, tend to be larger than natural gaps, which may increase establishment chances of seedlings belonging to valuable timber species.

4.2. Natural regeneration of harvested tree species two years after logging

Low seedling and sapling numbers may reduce substantially chances of a given species having individuals in reproductive size by the following cutting cycles (Grogan et al., 2008). The results found in this work, therefore, reinforce evidences of a poor regeneration of commercial species in the Eastern Amazon. Poor natural regeneration of tree species within managed forests has also been observed in other tropical forests, as in Bolivia (Mostacedo and

Table 4
Timber species harvested in 2008 with one or lesser individuals found in the whole sample of 2010, encompassing Tapajós, Jari, and Rio Capim (Eastern Amazon, Brazil). Species with no information about their functional groups are classified as "unknown". Species identified at the genus level are indicated as "not applicable (na)".

Species	# of sites harvested	Abundance	Family	Functional group
Bagassa guianensis Aubl.	3	0	Moraceae	Light-demanding
Bombax sp.	1	0	Malvaceae	na
Buchenavia parvifolia Ducke	1	0	Combretaceae	Light-demanding
Cedrela odorata L.	2	1	Meliaceae	Light-demanding
Couratari guianensis Aubl.	2	0	Lecythidaceae	Shade-tolerant
Dinizia excelsa Ducke	2	0	Fabaceae	Shade-tolerant
Diplotropis sp.	3	0	Fabaceae	na
Dipteryx sp.	2	1	Fabaceae	na
Eperua schomburgkiana Benth.	1	1	Fabaceae	Shade-tolerant
Euxylophora paraensis Huber	1	0	Rutaceae	Light-demanding
Handroanthus sp.	2	1	Bignoniaceae	na
Micropholis sp.	2	0	Sapotaceae	na
Peltogyne lecointei Ducke	1	0	Fabaceae	Shade-tolerant
Piptadenia suaveolens Miq.	1	0	Fabaceae	Light-demanding
Qualea albiflora Warm.	2	0	Vochysiaceae	Shade-tolerant
Qualea paraensis Ducke	1	0	Vochysiaceae	Shade-tolerant
Roupala sp.	1	0	Proteaceae	na
Vatairea paraensis Ducke	1	0	Fabaceae	Unknown
Virola melinonii (Benoist) A.C. Sm.	1	0	Myristicaceae	Shade-tolerant
Zollernia paraensis Huber	1	0	Fabaceae	Unknown

Fredericksen, 1999), West Africa (Doucet et al., 2009), and West Amazon (D'Oliveira, 2000; D'Oliveira and Ribas, 2011).

The absence of seedlings and saplings of timber species two years after harvesting may be linked to the species rareness and reduction of reproductive individuals. In the Amazon, innumerous tree species are naturally distributed with extremely low densities. The density of individuals $\geqslant$45 cm in DBH of *Bagassa guianensis*, *Dipteryx odorata*, and *Symphonia globulifera* in the Tapajós National Forest are 0.15, 0.12, and 0.08 individuals per hectare, respectively (Schwartz et al., 2012). Logging of reproductive individuals of low density species tend to diminish pollen flow and seed production to ensure a constant natural regeneration (Guariguata and Pinard, 1998; Grogan et al., 2008; Schulze et al., 2008). This can be a possible cause behind the low densities and absence of seedlings and saplings of commercial species found in Tapajós, Jari, and Rio Capim.

4.3. Recommendations for management and conservation

Low densities or absence of commercial species found in three managed forests sampled in this research suggest that commercial species have poor post-harvesting capacity to regenerate in the Eastern Amazon. This increases chances that commercial species will be replaced by currently non-commercial species. Thus, managed forests of the Eastern Amazon are under the issue of a species composition change from hard-wood commercial species to light-wood non-commercial species (Reis et al., 2010; De Avila et al., 2015).

Post-harvesting silvicultural treatments are a path to improve the regeneration of commercial species in managed forests (Fredericksen and Pariona, 2002; Grogan et al., 2008; Peña-Claros et al., 2008) and decrease long-term shifts from hard-wood commercial to light-wood non-commercial species. Among these treatments, the management of logging gaps to promote the regeneration of commercial species is a feasible option, since these environments present high numbers of seedlings belonging to commercial species (Fig. 2). Canopy gaps opened by felled trees offer good microclimate conditions for seedling establishment (Lopes et al., 2008; Doucet et al., 2009). Silvicultural treatments such as enrichment planting and tending of the existing natural regeneration inside logging gaps are effective to reduce competition and maintain favorable growing conditions for seedlings of commercial species (Schwartz et al., 2013). Tending was showed to be effective when logging gaps are rich in seedlings and saplings of commercial species, while enrichment planting becomes necessary when natural regeneration of these species is poor (Schwartz et al., 2013). Nevertheless, the application of silvicultural treatments should start not later than two years after the end of logging operations as logging gaps are rapidly closed by the surrounding trees, fast-growing pioneer species, and lianas. When logging gaps are closed, a good opportunity to promote the regeneration of rare or absent commercial species is lost.

The success on conserving low density commercial species using enrichment planting in logging gaps of managed forests requires a good supply of high quality seeds. The legal requirement of the Brazilian government to maintain at least 10% of the reproductive individuals of the logged species $\geqslant$50 cm in DBH (MMA, 2006) does not seem to be enough to ensure the natural regeneration of these species. One option to overcome this problem is to identify and monitor genetically diversified sets of seed trees in the management area (or elsewhere) for seed collection.

5. Conclusion

Disturbances caused by logging and natural events increased density of commercial species, except when these disturbances were excessive, as observed in the central and intermediate positions inside log decks. Increases in density of commercial species were more pronounced among light-demanding species, especially in logging gaps, skid trails, and borders of log decks. However, two years after logging, the logged species natural regeneration was still low in the studied sites.

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