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Growth, mortality, and recruitment of tree species in an Amazonian rainforest over 13 years of reduced impact logging

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ABSTRACT

Forest harvesting causes disturbances in the forest, affecting the dynamics of tree species. In this study, growth, mortality, and recruitment of trees ≥45 cm DBH were assessed in different forests logged along 13 years (2002–2015) in the Eastern Amazon. The data were collected in a control unlogged forest and in four 100-ha working units divided into 20 plots of 5 ha (total of 100 plots in 500 ha sampled) and inventoried at 100% one year before harvesting and again in 2015. A total of 49 species were analyzed in the study. The highest mortality rate occurred in the first five years after harvesting (5.6%), with a reduction from the seventh year (3.2% $year^{-1}$), a period in which recruitment rate significantly increased for species from all ecological groups. Harvesting reduced both the number of individuals and species in the first five years after logging. Logged areas presented the highest growth rates five and seven years and only stabilized eleven years after logging. Within the range of 3–40 $m^3 ha^{-1}$ of logging intensity no differences were observed in growth rates of remaining trees ≥45 cm DBH. Pioneer, light-demanding, and shade-tolerant species presented higher growth rates in the first five years after logging. From seven years after harvesting, light-demanding presented a higher growth when compared to the shade-tolerant species. Larger diameter classes presented the highest relative growth rates (RGR). All diameter classes increased RGR up to 11 years after logging.

1. Introduction

Forest dynamics results from mechanisms that promote constant recruitment and establishment of new individuals and species in the community (De Avila et al., 2013) even under changes in the environment that can be caused by natural or man-made disturbances (Marchesini et al., 2009). In this sense, knowledge on forest dynamics, including the factors determining tree growth, mortality, and growth rates in managed tropical forests is crucial for their conservation and prediction on their future production. Precise information about forest dynamics and species composition shifts gives to the manager a much clearer picture on the recovery capacity of a given harvested forest.

Harvesting over Amazonian forests in Brazil, as well as other tropical forests worldwide, has been carried out through selective logging of a few high value tree species. Selective logging of large trees (DBH ≥ 50 cm) through reduced-impact logging (RIL) has clear effects on forest dynamics (De Avila et al., 2017) with higher mortality rates of remaining stand individuals left for future harvesting cycles (Dionisio et al., 2017). RIL is a set of techniques and methods addressed to maintain the structure and ecological functions of harvested forests as similar as possible of the original conditions (Zarin et al., 2007; Hirai et al., 2012). RIL is based on operations planning, personnel training, and investments on forest management, thus harvesting through RIL must: (a) minimize environmental damage, (b) diminish operation cost by increasing work efficiency, and (c) reduce operational waste.

Environmental changes resulting from selective logging are determinant in forest dynamics, especially by increasing individuals' growth due to more light reaching the forest floor (Baraloto et al., 2005; Duah-Gyamfi et al., 2014; Schwartz et al., 2012). However, there are still controversies on the effects of selective cutting through RIL over tropical forests. More information is necessary on the potentially destructive RIL effects on the structure, composition, and dynamics of managed tropical forests (Gourlet-Fleury et al., 2013). In addition, biodiversity maintenance (Burivalova et al., 2014) and sustainability of timber production (Hawthorne et al., 2012) may not be guaranteed after selective logging under RIL. Forests in this condition are a mosaic that includes places directly affected by logging and undisturbed areas (Darrigo et al., 2016), causing different impacts on the natural

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regeneration of commercial species (Schwartz et al., 2014). Thus, it is important to assess RIL effects on the ecological dynamics of large trees (DBH ≥ 45 cm) to understand post-logging processes and to determine the need of further interventions. These steps are essential to ensure future yields, since large trees are part of the stock for the next harvesting cycle.

Studies about the effects of RIL on the dynamics of commercial tree species in tropical forests have mostly focused on individuals < 45 cm in diameter (Bertault and Sist, 1997; Herault et al., 2010; Schwartz et al., 2012; Duah-Gyamfi et al., 2014) whereas studies assessing growth, mortality, and recruitment of tree species with DBH ≥ 45 cm are scarce. In this study, the effects of harvesting on growth, mortality, and recruitment of remaining trees were assessed in different areas of a managed forest submitted to RIL along 13 years (2002–2015) in order to answer the following questions: (a) Does RIL affect mortality and recruitment and, consequently, density of individuals and commercial species? (b) In what extent growth rates of trees ≥45 cm are driven by time after logging and logging intensity? (c) What are the effects of RIL on growth rates in each ecological group and diameter class in harvested tropical forests?

2. Material and methods

2.1. Study area

This study was carried out in the forest management area of Rio Capim farm, belonging to the company CKBV Florestal Ltda. (3°39′28″S and 48°49′60″W) located in Paragominas municipality, Pará state, Brazil (Fig. 1). Rio Capim farm has a total area of 140,000 ha, where 121,000 ha have been under forest management certified by the Forest Stewardship Council (FSC) since 2001 (Dionisio et al., 2017).

The typical region's forest ecosystem is dense ombrophilous forest (IBGE, 2012). According to the Köppen classification, climate is Awi (tropical rainy) with an average annual precipitation of 1800 mm, average annual temperature of 26.3 °C, and a relative humidity of 81% (Alvares et al., 2013). The study area's altitude is 20 m with a flat to slightly wavy relief (Sist and Ferreira, 2007). Most of the soils are classified as Yellow Latosols, Yellow Argisols, Plinthosols, Gleysols, and Neosols (Rodrigues et al., 2003).

Average pre-harvest density of trees ≥45 cm DBH at Rio Capim farm is 12.6 ind. ha^{-1}. A total of 49 commercial species were harvested in 2002, so that only those species were assessed over the study period (13 years, 2002–2015). From the 49 commercial species harvested in Rio Capim farm, only five of them currently represent more than 50% of the whole company's wood production. In order of importance, the five species are: *Manilkara huberi* (Ducke) A. Chev., *Parkia gigantocarpa* Ducke, *Sclerolobium paraense* Huber, *Pseudopiptadenia suaveolens* (Miq.) J.W. Grimes, *Astronium lecointei* Ducke.

2.2. Experimental design

Data were collected in five Working Units (WU) that were part of five Annual Production Units (APU). Four of these APU/WU were logged at different years (2002; 2004; 2008 and 2010), and one never logged APU/WU monitored since 2006 was used as a control (Table 1). The five sampled areas (four logged and one control area) have the same soil and climate characteristics described above. The minimum and maximum straight line distances between each APU are 5 km and 24 km, respectively.

In each APU, 20 plots of 50 m × 1000 m were assessed, which sums up 100 plots of 5 ha (500 ha sampled), where trees ≥45 cm DBH were inventoried (Fig. 1). Measurements on the inventoried trees occurred one year before forest harvesting and again in 2015 in each one of the four logged areas. In the control area, inventoried trees were measured in 2006 and 2015. In addition to the re-measurement of remaining trees, all recruited individuals from the 49 study species with DBH ≥ 45 were inventoried in the period between measurements of each logged and control area.

2.3. Data analysis

Density of individuals and species (pre-logging and post-logging) and growth rates of 49 commercial species were sampled in 5-ha plots from four APUs harvested in different years and a fifth APU with unlogged forest that served as a control. Data on, mortality, recruitment, and density were analyzed through repeated measures ANOVA and an ANCOVA, with time since logging as the fixed factor and harvesting intensity as the co-variate. Data on density, mortality, and recruitment were collected at the plot level, with two measurements for each plot. The 49 sampled commercial species were identified in three ecological groups (pioneer, light-demanding, and shade-tolerant) Whitmore (1989a,b) and Carvalho (1992).

Mortality and recruitment rates were calculated for each harvested APU and for a control area (never logged). For more details on mortality of commercial species in this area see Dionisio et al. (2017). Thus, the annualized mortality and recruitment rates of remaining individuals after harvesting in the 13-year period were calculated by using Eqs. (1) and (2), respectively:

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

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

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

Mortality rates were calculated including live trees during the first inventory and the remaining live trees in the re-measurement of 2015. Recruitment was calculated from new trees not present in the first measurement, with a minimum diameter of 45 cm in the second measurement. Recruitment rates were also calculated and compared separately in each ecological group.

A linear regression analysis was performed in order to assess the isolated effect (in each year of logging) of the harvested volume on the growth rate of the remaining trees. Growth rates (cm $year^{-1}$) were calculated and compared between ecological groups and harvesting intensities applying repeated measures ANOVA with an ANCOVA, with time since logging, ecological groups as the fixed factor and harvesting intensity as the co-variate. Data on ecological groups and diameter classes were collected at the plot level, with two measurements for each plot.

Growth rates were calculated by the difference between measurements of tree diameter and time $((DBH_{final} - DBH_{initial})/(t_{final} - t_{initial}))$ in the periods of 2002–2015, 2004–2015, 2006–2015, 2008–2015, and 2010–2015. Relative Growth Rate (RGR) was used to compare growth rates by diameter class of remaining trees. RGR was calculated by the formula $((\ln DBH_{final} - \ln DBH_{initial})/(t_{final} - t_{initial}))$ and represented by (cm cm^{-1} $year^{-1}$). Five diameter classes were compared where individuals were distributed according to their DBH (45–54.9, 55–64.9, 65–74.9, 75–84.9, and ≥85 cm). Statistical procedures applied to compare RGR among diameter classes were the same used for growth rates.

Mortality, recruitment, density, and growth measured in each 5-ha plot were considered as the unit to perform statistical analyses. In the case of significant difference between treatments, Tukey's post hoc test was used to compare the means. All analyses were performed in the statistical program R version 3.3.3 at $p < 0.05$ significance level.