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Mortality of stocking commercial trees after reduced impact logging in eastern Amazonia

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ABSTRACT

Forest harvest causes disturbances in the forest and affects the mortality of residual trees. The effects of this activity on trees of the residual stocking for future felling cycles are poorly known in post-harvest situations. Detecting mortality patterns and comprehending the factors that rule the post-harvest tree mortality may offer important subsidies for future sustainable harvests. In this study, the mortality of trees under Reduced Impact Logging (RIL) was assessed in a chronosequence of 13 years in logging areas (2002–2015) in eastern Amazonia. The data were collected in five Units of Annual Production (UAP) and in a control plot. In each UAP, a Working Unit (WU) of 100 ha was divided into 20 plots of 50 m $\times$ 1000 m (5 ha). Trees $\geq$ 45 cm DBH were inventoried one year before forest harvest and again in 2015. The mortality rates were calculated and compared among: (a) ecological groups; (b) different logging intensities and (c) diameter classes. The mortality rate is higher in the first five years (5.87%) and the effects of RIL are perceived up to seven years post-harvest (3.18%). The logging intensity, 3–40 $m^3\ ha^{-1}$, did not affect the mortality of trees $\geq$ 45 cm DBH. Pioneer species are more susceptible to impacts of forest harvest than species of other ecological groups. In RIL plots, as well as in the non-logged plot, the mortality rate was not influenced by the size of trees $\geq$ 45 cm DBH.

1. Introduction

Tree mortality is a fundamental ecological and demographic process that governs the dynamic of forests (Chao et al., 2009). However, comprehending tree mortality patterns remains a challenging task, since it demands long-term stock studies. Tree mortality is related to environmental factors (soil, climate, winds, drought, and high temperatures) and echophysiological features of each species (Hurst et al., 2011). Comprehending and predicting tree mortality is, therefore, indispensable for knowledge and modeling of dynamics and diversity of forest ecosystems (Purves and Pacala, 2008). Unlike the aspects regarding their growth, tree mortality causes are still unknown in more detail (Holzwarth et al., 2013). In this way, questions about randomness and preponderant factors in tree mortality remain without consistent answers.

In the study of tree mortality, the different causes or forms of mortality should be firstly separated and categorized (Larson and Franklin, 2010). Treefalls caused by wind and tipping of neighboring trees are among the main causes (Larson and Franklin, 2010) as well as fire-caused mortality (Dunn and Bailey, 2016). Several studies address the effect of climate change on mortality, in particular, the combination of drought and high temperatures (Allen et al., 2010, 2015; Mcdowell and Allen, 2015). In periods of drought, higher temperatures increase the chances of death directly linked to physiological stress (Mcdowell et al., 2008; Adams et al., 2015) or indirectly linked to the effects of pests or pathogens attacks (Weed et al., 2013; Das et al., 2016).

The form of mortality (standing dead or fallen dead) varies among different tree species (Bladon et al., 2008). Moreover, the size (diameter and height) and the tree shape may also influence on their survival (Scott and Mitchell, 2005; Lavoie et al., 2012; Hämäläinen et al., 2016; Wu et al., 2017).

In addition to natural causes, mortality in post-harvest situations is also poorly understood. In general, tree mortality increases after the end of logging operations (Hautala and Vanha-Majamaa, 2006; Bladon et al., 2008; Lavoie et al., 2012). In logged forests, the residual trees location is also a determinant of mortality. Trees near logging gaps, at the surrounding forest edge and in clearings for infrastructure (roads, skid trails, and log decks) are at a greater risk of death (Scott and Mitchell, 2005; Gray et al., 2012).

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Understanding the factors governing post-harvest tree mortality may provide strategies to increase survival and indicate possibilities of utilization of dead trees or trees at high-risk of death.

In the Brazilian Amazon, logging in managed forests follows a polycyclic silvicultural system, which aims at the continuous timber production and protection of the ecosystem and its goods and services. This polycyclic silvicultural system has been substantially improved over the past decades, especially after the adoption of Reduced Impact Logging (RIL) techniques (Schwartz et al., 2016). RIL is a set of techniques aimed at maintaining the structure and functions of the harvested forest as similar as possible to its original condition (Zarin et al., 2007). This makes RIL an important tool for biodiversity conservation in areas under forest management and for reduction of deforestation rates (Putz et al., 2012; Schwartz et al., 2012).

In addition to its application to the maintenance of environmental functions, RIL was introduced in tropical forest management to avoid damage to residual trees and to improve efficiency in logging operations (Putz et al., 2008; Rivett et al., 2016). Most studies in tropical forests on the effect of RIL, focuses on natural regeneration (Hirai et al., 2012; Quadros et al., 2013; Asase et al., 2014; Arevalo et al., 2016; Darrigo et al., 2016; Rivett et al., 2016), selective logging (Viana and Jardim, 2013), and disturbances caused by timber harvesting (Schwartz et al., 2014). There are still few studies on the effects of RIL on tree mortality (Sist et al., 2003). Therefore, there is a need for more detailed information on how RIL affects trees of different species and functional groups and on how individuals in the residual stocking respond to post-harvest disturbances.

In this study, the effects of forest harvest on tree mortality in natural forests under RIL were assessed to answer the following questions: (a) Does the logging intensity affect post-harvest tree mortality? (b) Is there a temporal effect of forest harvest on tree mortality? (c) Does selective logging affect mortality of commercial species in different ecological groups? and, (d) What is the relationship between the post-harvest mortality rate and the diameter of trees in natural forests under RIL?

2. Materials and methods

2.1. Study site

The Forest Management Area (FMA) of Rio Capim farm belongs to the company CKBV Florestal Ltda. and is located in the municipality of Paragominas (03°39′28.16″S and 48°49′59.73″W), state of Pará, Brazil. 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.

The typical forest ecosystem of the region is the Ombrophilous Dense Forest, also known as Dry Equatorial Forest (IBGE, 2012). Based on pre-harvesting inventories, the average density of trees was 21.3 ind. ha^{-1} (trees $\geq$ 45 DBH). Currently, more than 80 tree species are harvested in the Rio Capim farm. *Manilkara excelsa, Chrysophyllum venezuelanense, Pseudopiptadenia suaveolens, Manilkara paraensis, Astronium lecointei, Couratari guianensis, Hymenaea courbaril, Pouteria guianensis, Lecythis chartacea e Protium* spp. are the 10 most commercially important species that represent more than 50% of the total timber production in Rio Capim farm.

According to the Köppen classification, the climate of the region is "Awi", that is, rainy tropical, with a mean annual rainfall of 1800 mm, a mean annual temperature of 26.3 °C and relative humidity of 81% (Alvares et al., 2013). The study site is located at an altitude of 20 m, on a flat to slightly wavy terrain (IBGE, 2004; Sist and Ferreira, 2007). The main types of soil of the region are Yellow Latosol, Yellow Argisol, Plinthosol, Gleisol, and Neosol (Rodrigues et al., 2003).

2.2. Sampling design

The data were collected in five Units of Annual Production (UAP) logged in different years in a chronosequence of 13 years (2002–2015), and in a non-logged plot (Table 1). In each UAP, a Working Unit (WU) of 100 ha was divided into 20 plots of 50 m × 1000 m (5 ha). All 100-ha plots were 100% inventoried for trees $\geq$ 45 cm DBH one year before forest harvest and again in 2015. Moreover, the trees, which were found dead in 2015, were also inventoried and the average of the volume harvested ($m^3\ ha^{-1}$) was calculated in each WU.

The species were classified into ecological groups according to Whitmore (1989a, 1989b), Carvalho (1992), Pinheiro et al. (2007), and Condé and Tonini (2013) in: (a) pioneers, (b) light-demanding, and (c) shade-tolerant. Species were determined as commercial based on the species harvested in each logging year.

2.3. Data analyses

The annualized mortality rates of the post-harvest residual individuals were calculated using the following:

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

N_{t1} = Number of live trees in the initial sampling, N_{t2} = number of trees that survived until the second sampling and t = years between first and second sampling (Sheil et al., 1995).

Trees $\geq$ 45 cm DBH of all species were included for mortality analysis in each UAP. To evaluate the effect of logging intensity and time of operation on tree mortality, each transect of each WU (5 ha) was considered a replication of the operating year. Non-parametric data were ln(x + 1) transformed in order to increase normality. A two-way ANOVA was performed for: (a) post-harvest time (years) and (b) volume harvested (m^3), considering $p < 0.05$. A simple linear regression analysis was also performed to evaluate the isolated effect of the volume harvested on mortality.

The mortality rates were calculated and compared among: (a) ecological groups; (b) different logging intensities, and (c) among diameter classes.

Table 1
Units of Annual Production (UAP)/Working Units (WU) inventoried between 2002 and 2015 on Rio Capim Farm, municipality of Paragominas – PA – Brazil.

Harvest year/Remeasurement	Years after harvesting	UAP/WU	Average volume harvested ($m^3\ ha^{-1}$)	Initial number of trees	[b]Number of dead trees
2002–2015	13	4/4	31.12	1604	266
2003–2015	12	6/81	15.30	661	117
2004–2015	11	7/14	16.77	1351	256
[a]2006–2015	10	8/8	0.00	1086	225
2008–2015	7	10/18	12.47	1108	226
2010–2015	5	13/40	22.43	2959	225

[a] Control.
[b] Inventory of 2015.