MINISTRY OF EDUCATION
FEDERAL RURAL UNIVERSITY OF AMAZONIA
POSTGRADUATE PROGRAM IN FOREST SCIENCES

MARCELO HENRIQUE SILVA DE OLIVEIRA

NATURAL REGENERATION OF TREE SPECIES FOLLOWING REDUCED-IMPACT LOGGING IN EASTERN AMAZONIA

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Dissertation presented to the Federal Rural University of Amazonia, as part of the requirements of the Master Course in Forest Sciences, area of concentration in Ecophysiology of trees, to obtain the title of Master. Supervisor: Dr. Gustavo Schwartz Co-Supervisor: Dr. Arystides Resende Silva

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Approved in October 2017

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“Everything is theoretically impossible,
until it is done.”
(Robert A. Heinlein)

The improvement of understanding is for two ends:
first, our own increase of knowledge; secondly,
to enable us to deliver that knowledge to others.
(John Locke)

RESUMO

As atividades de exploração madeireira podem reduzir o potencial de estabelecimento e crescimento da regeneração natural em florestas tropicais através de alterações na disponibilidade de recursos, podendo mudar a dinâmica da comunidade florestal. No entanto, a sustentabilidade do manejo florestal é apoiada pela regeneração natural das espécies, cujos mecanismos foram investigados durante anos com o objetivo de identificar os impactos a longo prazo das explorações nas florestas tropicais, cruciais para a conservação da biodiversidade. Diversos estudos abordaram a dinâmica das florestas tropicais após as formações de clareias, sempre baseados em uma composição florística e vegetação pré-existente. As clareiras são grandes responsáveis por manter a diversidade nas florestas tropicais, proporcionando ambientes que permitem o estabelecimento de novos indivíduos devido à maior disponibilidade de recursos. O objetivo deste trabalho foi avaliar as respostas da regeneração natural de espécies arbóreas presentes nas clareiras de exploração através de uma cronosequência de 14 anos de uma floresta explorada com técnicas de impacto reduzido, avaliando a densidade de indivíduos e riqueza de espécies em cada um dos anos estudados, comparando com uma área controle de floresta não explorada. O estudo foi realizado na Fazenda Rio Capim, uma área de manejo florestal (FMA) pertencente à empresa Cikel Brasil Verde Madeiras Ltda. Os dados foram amostrados em novembro de 2014 e novembro de 2015 dentro das clareiras abertas devido à retirada de árvores nos anos de 2000, 2001, 2002, 2003, 2004, 2006, 2010, 2010. Um total de 243 clareiras, dentro de oito anos de exploração madeireira foram amostrados ao longo da cronosequência e de uma área de floresta controle não explorada. Considerando os valores encontrados em relação à densidade de indivíduos e riqueza de espécies nas áreas exploradas, os resultados não mostram diferenças estatísticas, demonstrando que a intensidade de exploração utilizada nas áreas estudadas não gerou alteração na regeneração. Em relação aos resultados nos ambientes presentes dentro das clareiras (Centro, Intermediário e Borda), novamente foi confirmado que a intensidade de exploração não foi suficiente para gerar alteração na densidade e composição dos indivíduos, não sendo encontradas diferenças estatísticas. Considerando que a exploração madeireira ainda ocorre em florestas tropicais em todo o mundo, os resultados encontrados podem auxiliar no entendimento dos impactos da exploração madeireira e a capacidade de recuperação da floresta.

Palavras-chave: Regeneração Natural, clareiras exploradas, Exploração de Impacto Reduzido, Cronosequência, Grupos Ecológicos

ABSTRACT

Logging activities may reduce the potential for establishment and growth of natural regeneration in tropical forests through changes in soil properties such nutrient concentration and community dynamics. However, the sustainability of forest management is supported by the natural regeneration of species, whose mechanisms have been investigated by foresters and ecologists with the objective of identifying the long-term impacts of logging disturbances on tropical forests, crucial to biodiversity conservation. Numerous studies have addressed the dynamics of tropical forests after gaps formations, always based on a previously existing vegetation and floristic composition. Canopy gaps are fundamental importance to maintain diversity in tropical forests, providing environments that allow the establishment of new individuals due to an availability of resources. The objective of this work was to evaluate the responses of the natural regeneration of tree species present in logging gaps through a chronosequence of 14 years of logged forests, evaluating density of individual and species richness in each of the years studied, comparing with a control area of mature unlogged forest. The study was carried out in Fazenda Rio Capim, a forest management area (FMA) belonging to the company Cikel Brasil Verde Madeiras Ltda. The data were sampled in November 2014 and November 2015 within canopy gaps opened due to tree felling in the years of 2000, 2001, 2002, 2003, 2004, 2006, 2008, 2010, 2012. A total of 243 gaps from eight years of logging were sampled over a 14-year chronosequence and a control area. Considering the values found in this thesis in relation to the diversity of individuals and species in the logged areas, the results did not show statistical differences, demonstrate that the intensity of logging used in the areas studied did not generate an increase in regeneration. About the environments inside gaps (Center, Intermediate and border), confirming again the intensity of logging was not enough to generate changes in the environments, no statistical differences were found. Considering logging still occurs in rainforests around the world, our results may provide valuable knowledge to understand long-term intensive logging impacts and forest recovery ability.

Keywords: Natural Regeneration, Logging gaps, Reduced-Impact Logging, Chronosequence, Ecological groups

Summary

ILLUSTRATION LIST

TABLE LIST

1 CONTEXTUALIZATION

1.1 Tropical Forests, Forest Degradation and Selective Logging

Tropical forests are a living heritage for humans, they are rich in biodiversity been fundamental to the balance of nature and the maintenance of life on Earth. These forests can contain from a half to two-thirds of terrestrial global biodiversity (Gardner et al., 2010), and approximately 37% of the global terrestrial carbon pool (Dixon et al., 1994). Tropical forests are renewable natural resources in which, under correct management, it is possible to obtain numerous goods and services, like their influence on climate balance, carbon sinking, soil protection, water regimes regulation, as well as other important ecosystem services such as food, wood products, erosion control and biodiversity protection (Alamgira et al., 2016; Costanza et al., 1997).

Primary tropical forests are irreplaceable ecosystems in terms of protecting biodiversity and providing ecosystem services for both wildlife and humans (Gibson et al., 2011; Putz et al., 2012). A main goal of conserving tropical forests has been to halt or, at least, to slow down deforestation, which began to speed up from the 19th century (Asner et al., 2009; Malhi et al., 2014). Recent efforts at tropical forest conservation have had several outcomes: a) peak deforestation in late 20th century; b) deforestation rates have decreased in some countries. Brazil, for example, managed to decrease its deforestation rate by 46% between 2000 and 2010 (Malhi et al., 2014).

As tropical deforestation continues at different rates worldwide, conservation biologists are turning their attention to the state of the remaining forests, most of which are in different degrees of degradation (Putz and Romero, 2014). In this way, the emphasis in biodiversity conservation might shift from avoiding deforestation towards preventing further forest degradation (Putz and Romero, 2014).

In comparison with deforestation, the process of forest degradation has received less attention from researchers and conservationists, for several reasons. First, finding a globally applicable and operational definition of forest degradation has proven challenging, not least because of the problematic definition of forest itself (Thompson et al., 2013). Typically, forest degradation is loosely defined as a certain loss of forest values. For example, the Food and Agriculture Organization of the United Nations (FAO) defines forest degradation as ‘the reduction of the capacity of a forest to provide goods and services'. These goods and services include biomass storage and carbon sequestration, water regulating services, soil protection, and harboring biodiversity (FAO, 2011). Degraded forests are considered as fulfilling these services to a lesser extent than those forests that have not been degraded.

With these difficulties in view, some researchers have proposed to use Sustainably Forest Management (SFM) as a reference state (Thompson et al., 2013). This would bring along the possibility of direct, rather than historical, comparison of forests. It would have a further advantage of avoiding a situation whereby any type of forest management falls under a given category of forest degradation, as all way of management necessarily alter some forest property (Putz and Romero, 2014).

Nevertheless, using a Sustainably Forest Management as a reference state draws attention to another issue in defining forest degradation. There are multiple forest properties and values that may change because of human land use, and these do not necessarily respond to disturbances in the same way. Whereas a conversion of a forest to a timber monoculture would not necessarily constitute a loss of biomass when compared to a mature tropical forest, it would certainly lead to a substantial decline in plant and animal biodiversity (Carnus et al., 2006).

Consequently, even if all information on forest properties become available, it may still be impossible to have an internationally harmonized definition of forest degradation (Simula, 2009).

Forest degradation can be caused by fuel wood collection, understory fires and grazing, small scale slash-and-burn agriculture, non-timber forest products collection, hunting, artisanal mining, and, according to the used definition, also by strong natural disturbances (Thompson et al., 2013; Simula, 2009). However, arguably the single most important cause of tropical forest degradation worldwide is unsustainable selective logging (Koltunov et al., 2009; Putz and Romero, 2014).

In silvicultural terms, selective logging is the most common intervention in tropical forests that are managed for timber production. It is also one of the most common uses of forests not assigned for formal management. In both contexts, selective logging can be defined as the extraction of individual trees from a forest. As opposed to clearcutting, selective logging leaves a variable proportion of trees and vegetation stand (Asner et al., 2005; Putz et al., 2000).

Selective logging encompasses a broad range of extraction techniques. These vary according to the forest type, land ownership, forestry tradition, as well as national forest policies, law enforcement, and also the perceived value of each forest by a variety of stakeholders (Putz et al., 2000).

The process of logging, from the planning stage to transport, can result into a variable degree of damage to the forest structure (Putz et al., 2000). The direct impact of logging is determined by the logging intensity, in other words, how many trees are extracted per unit area. The maximum theoretical logging intensity in a previously unlogged forest is dictated by the natural density of commercially valuable trees. In contrast to temperate forests, extracted species of tropical forests typically comprise only a small part of the standing vegetation in tropical forests (Putz et al., 2000)

Many highly priced tropical timber species have high wood densities, which are correlated with very slow growth rates (King et al., 2006). With this in mind, countries regulate timber extraction rates, typically by specifying one or more of the following rules: *i)* minimum cutting diameter, which should ensure that not all individuals from a species are harvested, so that the species can be able to regenerate; *ii)* maximum harvested volume per forest management unit, or per hectare, which should limit the degree to which the forest structure is altered, and *iii)* the time elapsed until a forest to be logged again, also referred to as logging cycle length. This time lasts 30 to 35 years in most tropical countries and should ensure that forests are able to regenerate even when more timber would be available for harvest (Huth and Tietjen, 2007).

Concerning the impacts of logging activities, it is still poorly understood the biodiversity responses caused by these impacts. Even though researchers frequently suggest that selective logging causes changes in the community composition, it is unclear, for most taxonomic groups, which species are sensitive to selective logging (Nichols et al., 2013).

Selective logging alters the forest microclimate. Canopy openings increase solar irradiance over the forest floor, which results in a higher temperature, lower humidity, and higher microclimate variability between day and night (Meijaard et al., 2005). Under the effects of these environmental changes, the regeneration of many plant species can be slowed down, or halted completely. Such potential shifts in species can induce further changes by increase stress and competition strategies with increase pressure or release of new areas for the establishment of individuals (Meijaard et al., 2005).

1.2 The Amazon Forest

The Amazon forest is the largest continuous tropical forest in the world, accounting for 60% of all remaining tropical forests of the world, it encompasses the largest hydrographic basin known as the Amazon basin. This basin covers an area of 6,684 million square kilometers in nine countries (Bolivia, Brazil, Colombia, Ecuador, Guyana, French Guiana, Peru, Suriname and Venezuela) and plays a key role in global climate regulation. The Amazon forest contributes to the storage of terrestrial carbon and biogeochemical cycles (Laurence et al, 2002; Mittermeier et al, 2003). In addition, it presents a high biodiversity, comprising 20% of all known fauna and flora in the world, and it is estimated that more than 12,000 tree species (Azevedo-Ramos, 2008; Garda et al., 2010; ter Steege et al., 2013).

Most of the Amazon forest was relatively inaccessible until new road infrastructure provided in the 1950-1970, which allowed a rapid economic development and exploitation of forest resources. As a result of this it is estimated that from 2000-2013, the Brazilian Amazon lost about 53% of tree cover area and remains the single largest contributor to natural forest loss among tropical countries (Tyukavina et al., 2015)

1.3 Disturbances and forest Dynamics

When a tree falls, either naturally or through logging, a canopy gap of varying size is immediately created. The resultant gap alters the microclimate like light, moisture, and temperature of the forest floor, stimulating the growth of any seedling already present (climax species) or triggering seed germination of pioneer species present in the seed bank (Yamamoto, 2000). These natural disturbances caused by forest gaps play an important role in tropical rainforest dynamics. Canopy gaps created by one or more fallen trees (Whitmore, 1989) are the dominant form of forest regeneration. The creation of canopy gaps continuously reshapes forest structure as gaps are filled again. When canopy gaps are created, large amounts of dead leaves and wood will be decomposed and mineralized so that the availability of soil nutrients for neighboring trees increases (Brokaw, 1985). These nutrient patches are also linked to small-scale spatial variations in forest carbon balance, as shown by Feeley et al. (2007). Another effect of canopy gaps is the local modification of the forest nutrient balance (Rüger et al., 2009).

In this context, the study of the dynamics of the tropical forest species becomes essential to support the decision making to select the best silvicultural system in order to improve long-term forest productiveness. The processes of regeneration are fundamental for the maintenance of forest dynamics. In the case of tree species, the formation of canopy gaps is the most important mechanism to ensure regeneration in forest environments. Regeneration is part of the forest growth cycle and refers to the early stages of its establishment and development. It is a group of young individuals who will be recruited to perpetuate species populations and forest ecosystems.

The term natural regeneration presents more than one definition, and there is no well-structured and widely accepted definition. However, for this study, natural regeneration is defined as dynamic concept of renewability of the individuals of a community in a given area (Jardim, 2015).

Gap size varies over a continuum in which environmental conditions follow the same continuous pattern of variation. In terms of light, for example, gaps can be said to vary from a small area on the forest floor reached by direct solar radiation that gets through the canopy to high levels of radiation from large gaps. Within this range of variation, the interactions between environmental factors and between plants and these factors are so numerous and so complex that any simplification will result in many exceptions and difficulties of ecological classification of species (Jardim, 2015). Inside gaps, there is a continuum in environmental conditions, resulting in a great variation due to the heterogeneous environment. The 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 (Schwartz et al., 2017).

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2 CHAPTER 1

Natural regeneration of tree species following Reduced-Impact Logging in Eastern Amazonia

2.1 Introduction

Forests are viewed, defined, assessed, and valued through different lenses. From different points of view, forests can be a source of timber products, an ecosystem composed of trees along a myriad of biological diversity, a home for indigenous people, a repository for carbon storage, a source of multiple ecosystem services, and as social-ecological systems, or as all the above (Chazdon et al., 2016).

Among the economic activities developed in tropical forests, selective logging has an important position. More than 20 % of the world's tropical forests have already been selectively logged (Blaser et al., 2011; Mayaux et al., 2013). Because of this, it becomes even more important to study long-term effects of logging in the forest regeneration to increase efforts and knowledge to ensure the sustainability of forest resources.

Historically, logging activities in tropical forests were intensive and destructive to several forest functions, which rapidly decreased the density of some species of great commercial interest. Generally known as 'Conventional Logging', this activity was applied throughout the tropics with little or no concern for potential negative effects over the forests (Putz et al., 2001). Less destructive approaches for extracting timber products were developed over the last decades (Dykstra, 2002; Putz et al., 2012). One of these approaches is called Reduced-Impact Logging (RIL), which encompasses several techniques to prevent over-exploitation of target species and minimize damage to the surrounding vegetation (Putz et al., 2012; West et al., 2014).

RIL was introduced in the management of tropical forests to avoid unnecessary damage on the remaining trees and improve the efficiency in harvesting operations through careful and detailed operations (Putz et al., 2008). It consists in a set of techniques applied to provide a more sustainable alternative to conventional selective logging, where destructive logging effects are minimized (Pinard and Putz, 1996; Putz et al., 2008). Although the logging techniques under RIL vary from country to country, the Brazilian forest laws prescribe the same silvicultural system for all Brazilian Amazonian forests. This system sets the minimum harvest cycle length at 10 years for low intensity logging

(<10 m^3 ha^{-1}) and 25–35 years for higher intensity logging: (10–30 m^3 ha^{-1}; CONAMA, 2009).

RIL is more environment-friendly than conventional logging, since studies show that RIL does not cause negative effects on several groups of animal species (Avila et al., 2017; Azevedo-Ramos et al., 2006; Bicknell and Peres, 2010; Burivalova et al., 2014; Imai et al., 2009; Wunderle et al., 2006). In terms of tree species, RIL techniques can improve post-harvesting survival rates of standing trees (Pereira et al. 2002), increasing chances of these individuals to become available in future cutting cycles (Macpherson et al., 2012).

To understand the impacts of selective logging, it is important to know the extent and degree of canopy opening and soil damage, how these disturbances affect tree regeneration, and for how long their impacts persist (Carvalho et al., 2017).

In tropical forests, natural disturbances have a crucial role on maintenance the regeneration processes. Disturbance dynamics of forests refer to the combined action of factors that cause tree mortality at multiple spatial scales, such as tree, stand and landscape (Keane et al. 2009). The consequence of these factors is a diverse set of habitat types and the release of space and resources for tree growth (Attiwill, 1994).

Seedling growth and survival are driven mainly by small-scale disturbances resulting in canopy gaps (Hartshorn, 1978; Brokaw, 1982; Zagt, 1997). Studies on the formation of canopy gaps are relevant because the intensity of light penetrating through the forest to the ground can determine which species will constitute the forest, as well as the abundance and distribution of the species in the area. The opening of gaps will influence the germination of solar radiation species present in the soil seed bank, which may lead to the increase of pioneer and light-demanding species in the area. Good tree growth is expected after logging, where there are new logging gaps (Francez et al., 2013). However, Martini (2010) states that the opening of a gaps begins a process of competition that has great potential to modify relations between individuals previously established in the place, with consequences for the following phases. Follow this studies on natural regeneration in forests are of great relevance for the understanding of the ecological functioning of these ecosystems, since they allow inference about the dynamics of communities and populations of tree species, which represents a fundamental information for forest management (Santos et al. 2015).

Logging creates different habitats that vary in light availability and soil disturbance. Because of the differences in environmental conditions, these habitats are supposed to promote the regeneration of different plant species with different regeneration requirements. High light availability and soil disturbance caused by logging, generally favor only the regeneration of pioneer species (Mostacedo and Fredericksen 1999; Park et al. 2005)

2.2 Objectives, research questions and hypotheses

2.2.1 General Objective

The general objective of this study is to analyze the effects of Reduced Impact Logging on the regeneration of tree species in Eastern Amazonia.

2.2.2 Specific Objectives

To evaluate the responses in density of individuals and species richness in logging gaps through time.

To evaluate the responses in density of individuals and species richness in different environments inside logging gaps.

To evaluate the responses in density of individuals and species richness of each ecological group through time in logging gaps.

2.2.3 Research Questions and Hypotheses

1. What is the logging effect over the density of individuals and species richness in logging gaps through time?
   Hypothesis 1: In the early years after logging there will be an increase in the density of individuals and species richness inside a logging gap regenerated which will decrease towards time.
2. Does the regeneration of tree species differ in density of individuals and species richness at different environments inside a logging gap?
   Hypothesis 2: The highest density of individuals and species richness will be found in the border position of the logging gap.
3. Are there differences in the density of individuals and species richness regarding the species ecological group?

Hypothesis 3: In the first years, after logging, pioneer species will increase and will be further replaced by light demanding species, while shade-tolerant species will not change their density of individuals and species richness.

2.3 Material and methods

2.3.1 Study Site

This study was carried out in Fazenda Rio Capim, a forest management area belonging to the company Cikel Brasil Verde Madeiras Ltda, which has been operating in Brazil since 1991. The company is certified since 2001 under the Forest Stewardship Council (FSC) scheme (Cikel, 2009). The area is in the municipality of Paragominas, Pará state, Brazil; between the coordinates 3º 30' to 3º 45' S and 48º 30' to 48º 45' W (Maciel et al., 2009) (Fig.1).

According to the Köppen classification, the predominant climate in the region is "Aw", (tropical rainy) with clearly-defined dry season from July to October, with an annual average temperature of 26 ºC, relative air humidity of 81% and average rainfall of 1,800 mm year^{-1}, with occurrence of lower water availability (Bastos et al., 2005).

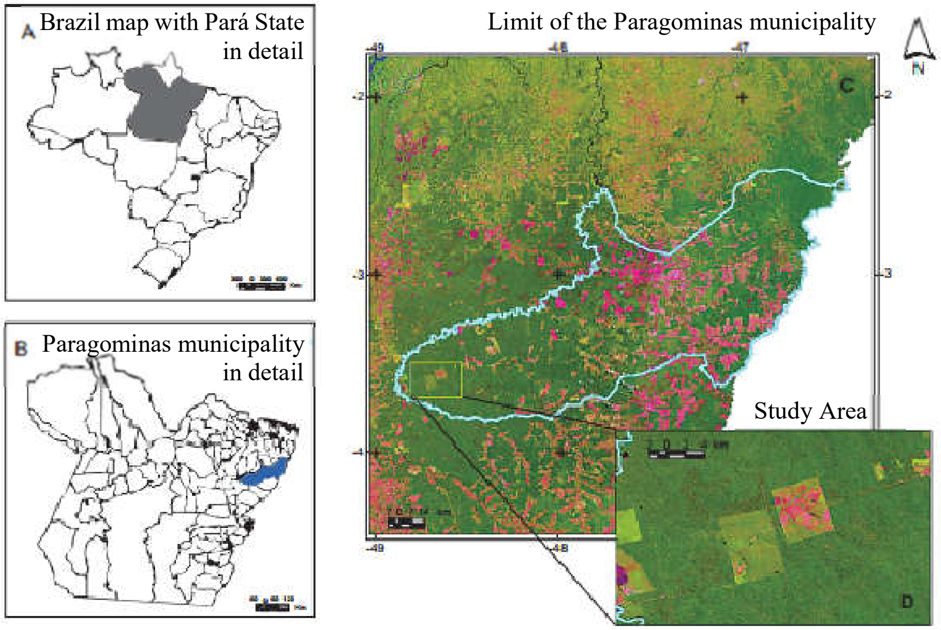


Fig 1, The Brazilian territory (A), with Pará State and Paragominas municipality in detail (B and C), and Fazenda Rio Capim (D). Source: Hirai et al., (2007).

2.3.2 Data Sampling

A total of 243 logging gaps (2,916 m²) in eight Units of Annual Production (UAP) logged in eight different years were sampled over a 14-year chronosequence a control forest with data sampled in eight areas (Table. 1). Each gap and the control areas were installed 3 squares 2x2 m² at determined points, and were classified as the environments center, border and intermediate (Fig. 2). As the areas of the unlogged forest were not anthropogenic or natural gaps, the classification of environments like center, border and intermediate in this area was not used for the analysis. The Sampling effort in the control area consisted in twenty-four repetitions of 2 x 2 m² squares (total = 24 squares = 96 m²) (Fig. 2).

The vertical projection of each canopy gap was estimated by measuring the diameter of the longest axis and the perpendicular diameter to that (Fig. 2). The gap area was estimated according to the ellipse's formula = πLW, where L is the radium of the major axis and W is the radium of the perpendicular axis that crosses the major axis (Barton et al., 1989). For the 8 areas in the control forest, the values of the axis for the ellipse's formula were defined as 24 m for the major axis and 12 m for the minor axis

All individuals ≥ 30 cm in height and < 5 cm in DBH were sampled. They were identified at the lowest taxonomic level and had their height or DBH and light incidence measured. Height was measured in individuals up to 299.9cm height while DBH was measured in individuals ≥ 300 cm in height.

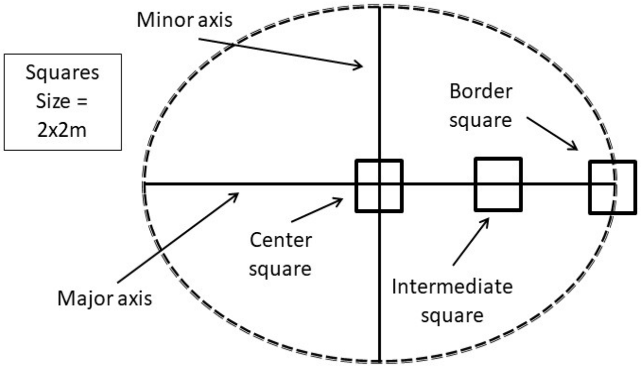


Fig 2. Schematic figure with a measurement of the logged gaps areas, through the major and minor axis, and positions of the squares representing three different environments: Center, Border and Intermediate.

The classification of ecological groups used in this study was based on the works of Amaral et al. (2009); Condé and Tonini (2013) and Pinheiro, et al. (2007).

Two variables were tested as response variables in this work: density of individuals (# ind. m^{-2}) and species richness (# ssp. m^{-2}). Species richness was used as a proxy to estimated richness and it use was demanded in order to be possible compare different size plots (Schwartz et al., 2017).

Table 1. Number of sampled logging gaps and environment squares in the years after logging and a control area in Fazenda Rio Capim, Pará, Brazil.

Years After Logging	**# of logged gaps**	**# of Center squares**	**# of Border squares**	**# of Intermediate squares**
2 yrs	30	30 = 120m^2	30 = 120m^2	30 = 120m^2
6 yrs	30	30	30	30
8 yrs	30	30	30	30
10 yrs	30	30	30	30
11 yrs	30	30	30	30
12 yrs	30	30	30	30
13 yrs	30	30	30	30
14 yrs	30	30	30	30
Control	8 areas 20 m x 12 m	3 rep of 2 x 2 m^2 squares in each area = 96 m^2		
Total	243	247	242	245

2.3.3 Data Analysis

To evaluate the effect of the treatment (time after logging), the environments inside logging gaps (center, border and intermediate plots) and the gap area (the size area of the gaps in m^2), and their possible interactions on the density of individuals and species richness, one ANCOVA was performed to compare the effects of logging to the density of individuals and species richness through: a) time after logging; b) different environments inside a logging gap; and c) species separated in three different ecological groups (pioneers, light-demanding and shade tolerant), as the factors; and the individuals density and species richness as the response variables, considering $p < 0.05$. Data were transformed in Ln(x+1) to increase variance homogeneity.

To evaluate the effect of the time after logging and the environments inside the gaps, on the species richness for each ecological group, one ANCOVA was used for each ecological group, with year after logging, environments and gap size as factors and the species richness as the response variables, considering $p < 0.05$.

Analyses were carried out using R software version 2.2-0 (R Core Team, 2015). Differences were considered significant at p values < 0.05.

2.4 Results

A total of 5558 individuals (seedlings and samplings) belonging to 172 species and 46 families were sampled in 243 logging gaps spread over eight UAPs and eight areas in a control forest were sampled (Table 2).

In the table 2 is possible to observe a trend of higher individual density and species richness in the initial years after logging while the lower density was observed in the control.

Table 2. Number of sampled logging gaps, seedlings, species and families in eight units of Annual Production (UAP) and a control area in Fazenda Rio Capim, Pará, Brazil.

Years after logging	# of Logging gaps	# of Seedlings	# of Species	# of Families
2 yrs	30	724	104	36
6 yrs	30	784	94	39
8 yrs	30	767	94	40
10 yrs	30	669	81	37
11 yrs	33	698	95	34
12 yrs	30	574	85	39
13 yrs	30	584	68	32
14 yrs	30	636	73	30
Control	8	122	33	19
Total	**251**	**5558**	**172**	**46**

Table 3 shows the most abundant families in all sampled logging gaps and in the control areas, representing the total number of individuals by families and percentage of values in relation to the total value of individuals found. It is possible to observe that the families Violaceae, Burseraceae and Hypericaceae were found only in the logging areas, with densities of 14.07%, 2.98% and 2.59% respectively; while Ochnaceae, Apocynaceae and Moraceae families were found only in the control forest with densities of 13.93%, 3.28% and 4.28%, respectively. Table 4 shows the species found in greater quantity in the logged areas and unlogged forest. These results demonstrate that during the studied periods at the same time, the forest can maintain or even increase the forest diversity.

Table 3. Rank of 10 most abundant families in number of individuals in logging gaps and control area in Fazenda Rio Capim, PA, Brazil

Logging gaps		**Control**	
Family	**# of individuals**	**Family**	**# of individuals**
Fabaceae	864 (15.89%)	Annonaceae	28 (22.95%)
Annonaceae	859 (15.80%)	Ochnaceae	17 (13.93%)
Violaceae	765 (14.07%)	Fabaceae	16 (13.11%)
Sapotaceae	502 (9.23%)	Lecythidaceae	12 (9.84%)
Lecythidaceae	352 (6.48%)	Sapotaceae	10 (8.20%)
Euphorbiaceae	254 (4.67%)	Chrysobalanaceae	8 (6.56%)
Myrtaceae	217 (3.99%)	Apocynaceae	4 (3.28%)
Burseraceae	162 (2.98%)	Euphorbiaceae	4 (3.28%)
Hypericaceae	141 (2.59%)	Moraceae	4 (3.28%)
Chrysobalanaceae	139 (2.56%)	Myrtaceae	4 (3.28%)
Total	**5436**	**Total**	**122**

Table 4. Rank of 10 most species in number of individuals in logging gaps and control area in Fazenda Rio Capim, PA, Brazil

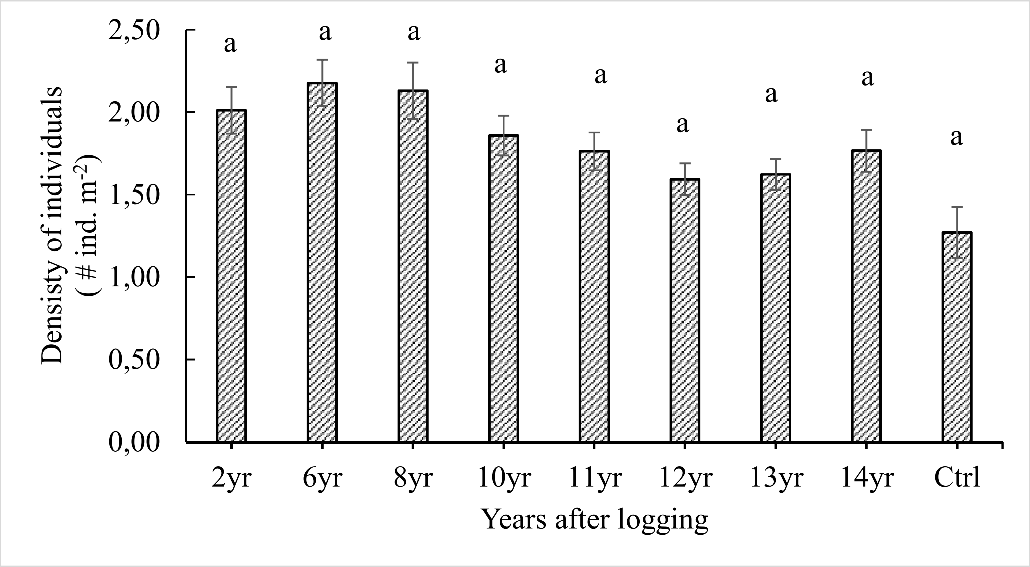
Logging gaps		**Control**	
Species	**# of individuals**	**Species**	**# of individuals**
Rinorea guianensis	568 (10.45%)	*Duguetia surimanensis*	17 (13.93%)
Duguetia surimanensis	264 (4.86%)	*Ouratea ssp.*	15 (12.30%)
Duguetia echinophora	249 (4.58%)	*Inga alba*	10 (8.20%)
Guatteria poeppigiana	236 (4.34%)	*Eschweilera amazonica*	9 (7.38%)
Inga alba	232 (4.27%)	*Pouteria guianensis*	9 (7.38%)
Pouteria guianensis	216 (3.97%)	*Guatteria poeppigiana*	7 (5.74%)
Myrcia ssp.	215 (3.96%)	*Licania canescens*	6 (4.92%)
Amphiodon effusus	194 (3.57%)	*Brosimum ssp.*	4 (3.28%)
Rinorea falcata	180 (3.31%)	*Duguetia echinophora*	4 (3.28%)
Eschweilera amazonica	170 (3.13%)	*Myrcia ssp.*	4 (3.28%)
Total	**5436**	**Total**	**122**

2.4.1 Density of individuals and species richness in different years after logging

When compared the density of individuals in relation to time (years after logging), statistical difference was found (ANCOVA, $F_{8;108} = 2.47$, $p < 0.05$). But when used the Tukey test to find Post-hoc differences, was not found among the years after logging. The highest density of individuals was found in six years after logging (mean 2.18 ind. m^{-2}) and the lowest in Control (mean 1.33 ind. m^{-2}) (Fig.03a).

The result of ANCOVA comparing the species richness after logging showed a statistical difference (ANCOVA, $F_{8;108} = 2.96$, $p < 0.01$). This indicate that the species richness was affected by time after logging, with the highest means in two years after logging (mean 1.43 ssp. m^{-2}), and the lowest mean was observed in Control (mean 1 ssp. m^{-2}) (Fig.03b).

a)



b)

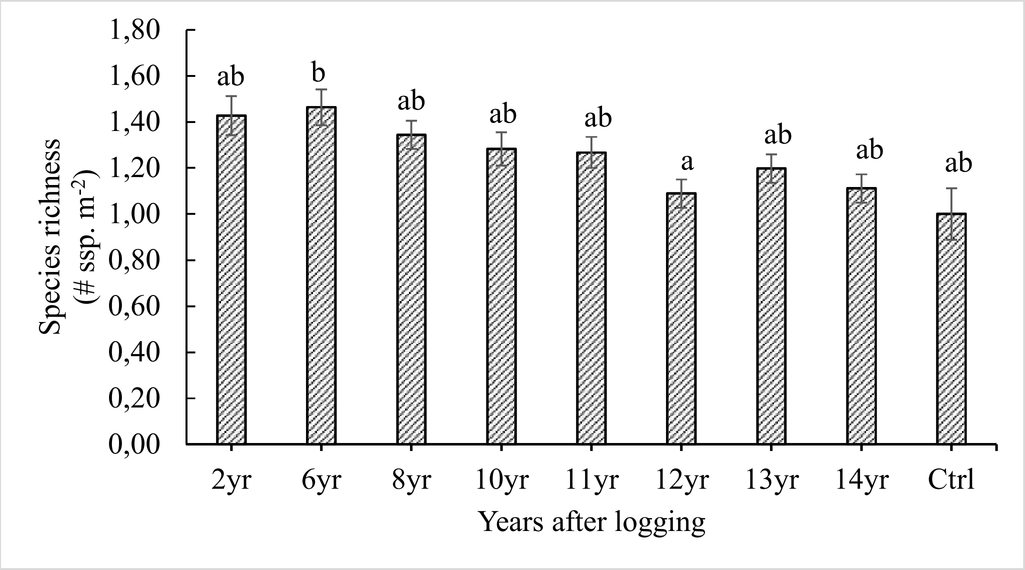


Fig 3. Density of individuals (a) and species richness (b) of seedlings in logging gaps and control area of a managed forest in Fazenda Rio Capim, PA, Brazil. Letters indicate differences on density among areas with different time after logging. the Tukey post-hoc test was used for multiple comparisons.

2.4.2 Density of individuals and species in different environments inside logging gaps

When comparing the environments inside logging gaps with the density of individuals no differences were found among the environments (ANCOVA, $F_{2;108} = 0.24$, $p = 0.79$). Neither variations were found in the gap area (ANCOVA, $F_{117;108} = 1.33$, $p = 0.06$); interactions between the variables time since logging, environments and gap area also was not found.

The same factorial analysis was repeated for species richness, and when compared with the environments, the result was similar with density of individuals (ANCOVA, $F_{2;108} = 0.67$, $P = 0.51$); gap area (ANOVA, $F_{117;708} = 1.16$, $p = 0.21$) and no interactions was found between time since logging, environments and the gap area.

The comparison of the density of individuals and species richness among environments inside a logging gap was done through a simple regression, and was compared only in each year, not between the years. The result found points to a high value of R^2, but the dependent variable not explained the density based on the environments inside gaps (fig 4.).

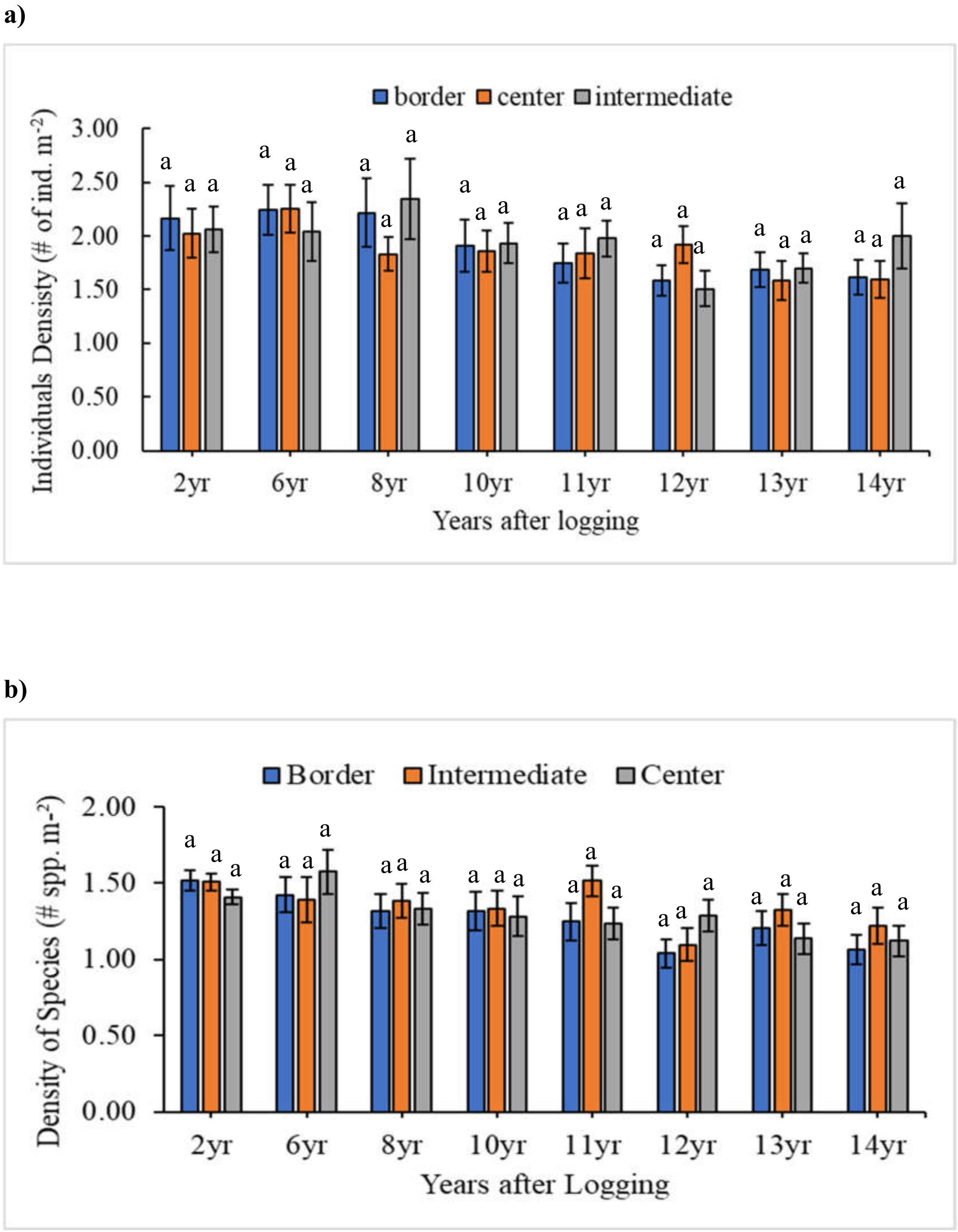


Fig 4. Density of individuals (a) and species richness (b) of seedlings in three environments (border, intermediate and center) of logging gaps in a managed forest in Fazenda Rio Capim, PA, Brazil. Tukey post-hoc test was used for multiple comparisons only per environment in each year after logging and the letters indicate differences on density among areas with the same time after logging.

2.4.3 Density of species richness per ecological group in different years after logging

To identify the species richness per ecological groups within the years of logging, it was necessary to classify species within the groups of Pioneers, Light-demanding and Shade-tolerant. As the highest concentration of individuals was observed in the group of Shade Tolerant (Table 6.).

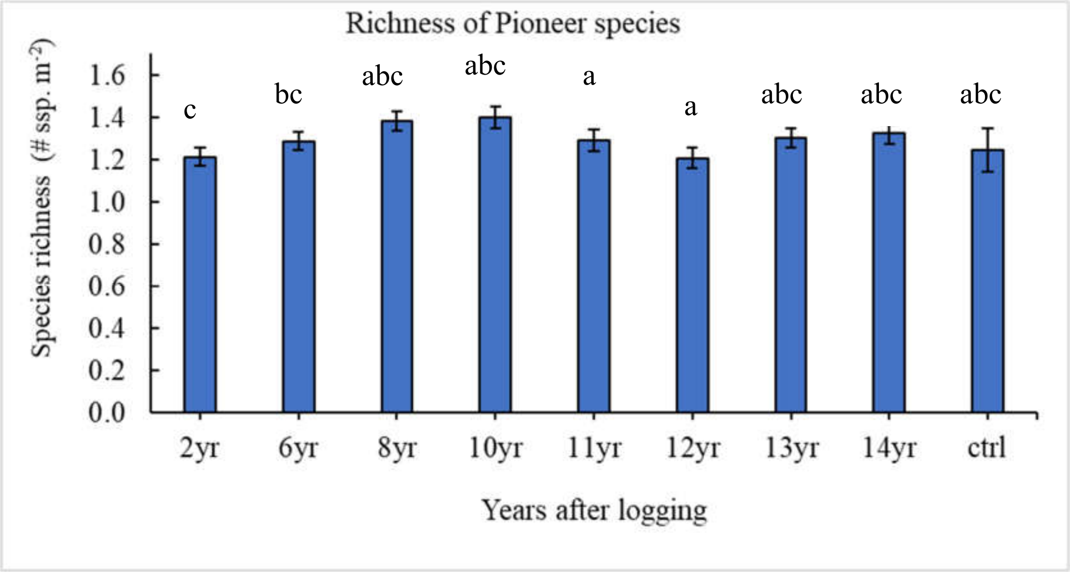
Table 6. Number of individuals, species and families in relation to each ecological group in Fazenda Rio Capim, PA, Brazil.

Ecological groups	Species	Families	Individuals
Not classified (NC)	4	4	85
Pioneer (PI)	14	9	367
Light-demanding (LD)	74	20	1335
Shade tolerant (ST)	80	31	3771
Total	172	64	5558

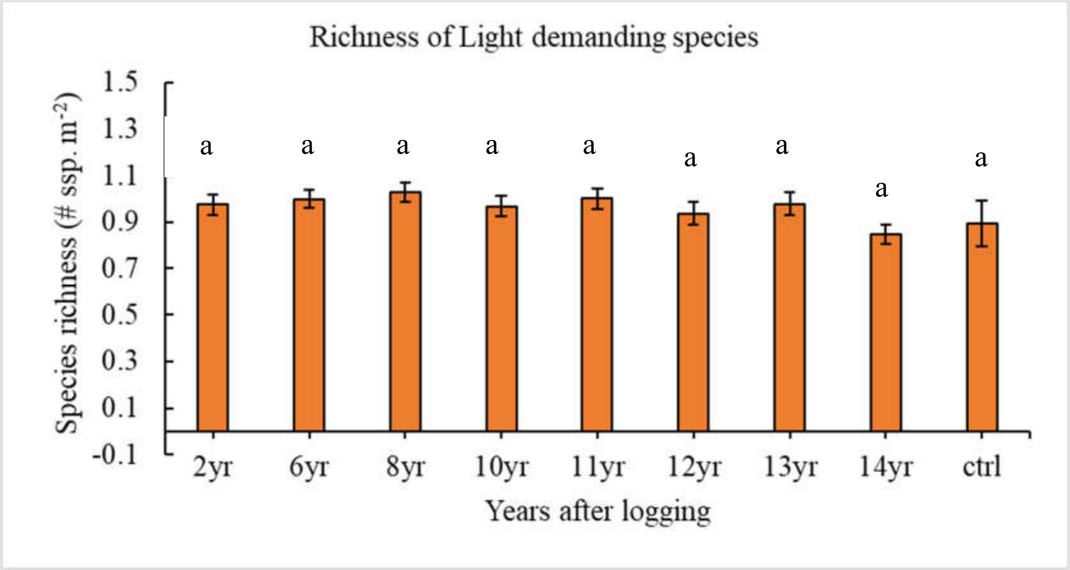
When compared the species richness per ecological groups in relation to time (years after logging), statistical difference was found only for the years after logging at the group of the Pioneer (ANCOVA, $F_{8;11} = 5.58$. $p < 0.01$) and it is possible to observe this result in the fig 5a. For the groups of Light demanding and Shade tolerant species, no statistical difference was observed over the years after logging (see the Fig 5b and 5c).

For the variables environments (Center, border and intermediate) and gap size used for ANCOVA, no statistical differences was found for the ecological groups studied, and no interactions were found between the variables.

a)


Richness of Pioneer species
Species richness (# ssp. m-2)
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
c
bc
abc
abc
a
a
abc
abc
abc
2yr
6yr
8yr
10yr
11yr
12yr
13yr
14yr
ctrl
Years after logging

b)


Richness of Light demanding species
Species richness (# ssp. m-2)
1.5
1.3
1.1
0.9
0.7
0.5
0.3
0.1
-0.1
a
a
a
a
a
a
a
a
a
2yr
6yr
8yr
10yr
11yr
12yr
13yr
14yr
ctrl
Years after logging

c)

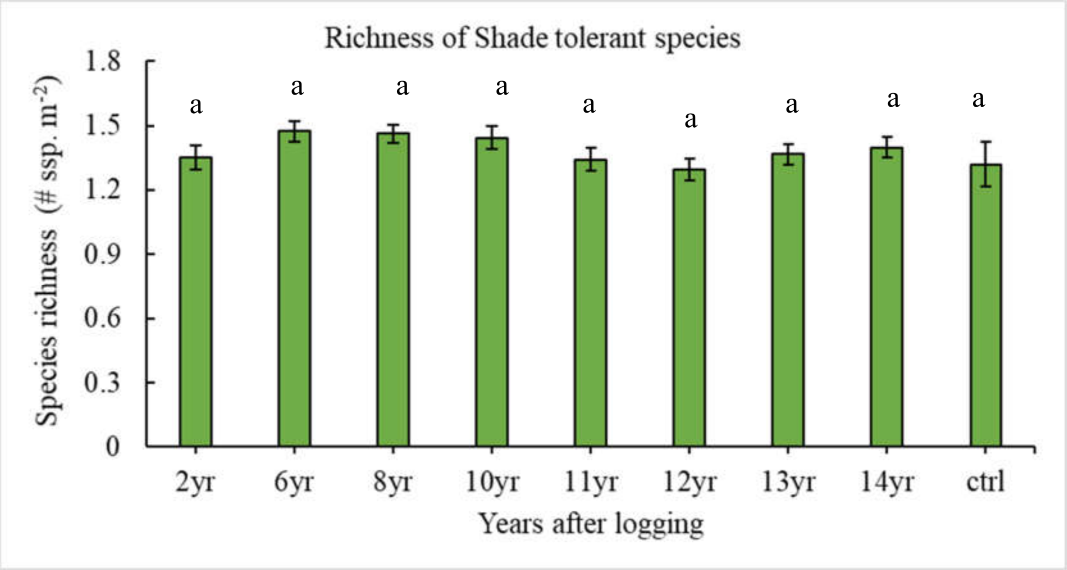


Fig 5. Species richness of seedlings per ecological group in logging gaps and control area of a managed forest in Fazenda Rio Capim, PA, Brazil. Letters indicate differences on density among areas with different time after logging. the Tukey post-hoc test was used for multiple comparisons only per environment in each year after logging.

2.5 Discussion

The view that RIL is a viable alternative to maintain the sustainability of managed forests through the application of their pre- and post-logging techniques is true based on the results found in this work. It must be taken into consideration that different logging intensities can promote different alterations in the dynamics of the natural regeneration of these forests.

Possibly the intensity of logging was not sufficient to promote a positive alteration in natural regeneration, causing an observable increase in the number of seedlings. To prove this theory, further studies would be needed in that area and to analyze the forests exploited over a longer period.

One observation contrary to the hypothesis proposed in this work was the fact that there was no great difference in density of individuals and species richness. Close values were found in each year after logging when compared among them and with the control area. The unlogged forest was expected to be less variable for tree community attributes because it is an old-growth forest, relatively free from human disturbances in the recent past (Chapman et al., 2010).

2.5.1 Density of individuals and species richness in different years after logging

The similarities in the densities of regenerating trees in logging gaps and unlogged forest two years after logging indicates that post-logging recruitment is rapid, as previously reported (e.g., Duah-Gyamfi et al., 2014; Karsten et al., 2014)

Although it is possible to find differences among years after logging and when they are compared with the unlogged forest area, no statistical differences were detected in density of individuals. Despite the decrease tendency in density of individuals over the years after logging (fig. 3a), possibly caused by competition for resources and the overshadow caused by other individuals. Perhaps this is caused because of the death of the pioneer short-lived species that emerge shortly after the exploration. Different from Bertacchi et al. (2016), who find statistical differences were found between the years after logging for species richness and density of individuals regenerated in logging gaps.

As reported for other Amazonian forests, tree regeneration density varied with time since disturbance (d'Oliveira and Ribas, 2011), however the similarities in the densities of regenerating trees in disturbed and undisturbed habitats one year after logging indicates that post-logging recruitment is rapid, as previously reported for Duah-Gyamfi et al. (2014); Karsten et al., (2014) and Rockwell et al. (2014).

Edwards (2014) assessed the environmental impacts of logging and concluded that natural forests assigned for production generally retain most of their biodiversity and associated ecosystem functions, as well as their services as carbon retention and cycle, climate maintenance and hydrology. Based on this, exploited forests have a greater value for the conservation of ecosystems than other forms of land use, such as agriculture and even forest fragments isolated by farms

2.5.2 Density of individuals and species in different environments inside logging gaps

For the density of individuals in environments (center, intermediate, and border), even if no statistical differences between environments was found, the small differences observed may be related to the intrinsic characteristics of the area, or even a greater availability in the bank seeds for example (Fig.4.).

It is possible to observe a pattern of decrease in the density of individuals over the years after harvest. This can be related to the competition for space while individuals require more space, or even species replacement of different ecological groups, as the canopy gap closes, which consequently reduces the availability of light.

The species richness presented a very similar pattern in relation to the density of individuals, not showing statistical differences between the years after logging, but is possibly to observe a decrease in the density of individuals over the years after logging (Fig 4b).

The results did not match the hypothesis proposed that there would be a difference in density individuals and species richness in relation to the environments inside logging gaps due to a greater availability of light in the center than in other environments. Possibly this result is due to the intensity of logging applied over the areas that were not sufficient to open the canopy in such a way to significantly increase the light incidence, and thus to favor the individuals to establish themselves in the logging gaps.

2.5.3 Density of individuals and species per ecological group in different years after logging

With logging, the density of pioneer species increased in the first six years, but after that period it began to decrease. This is possibly due to the life cycle of the species being short and also to time factor, the canopy begins to close again, and this prevents sunlight to reaching the soil in large amounts, negatively influencing the dynamics of this ecological group (fig 5b).

The ecological group of the light-demanding species can benefit from resources availability and conditions offered by the artificially created logging environments. These species can take advantage from soil disturbances and the highly increased light availability in the places opened by logging activities (Fredericksen and Mostacedo, 2000; Peña-Claros et al., 2008). This group showed a similar pattern to the ecological group of pioneer species, but with a decrease in their community much lower, which reinforces the issue of light availability decrease with canopy closing. However, since the species present in this group do not necessarily require high amounts of light to develop, but they benefit from light presence, so their decrease was not so marked in this study. This result is possibly related to the intensity of disturbance provided by the exploration in the studied areas, not being enough to cause large openings in the forest canopy that could provide a benefit for this ecological group

In the group of Shade tolerant species as the species already present small individuals in the seedling bank due to their slow growth in the forest understory, their density of individuals was hardly altered by logging**.**

According to Heraut et al. (2010), limited opening of the canopy and soil disturbance enhances the growth of non-pioneer, shade-tolerant and shade-intolerant tree recruits, such as all most important timber species.

Different from what was proposed in the hypothesis, it was possible to observe that ecological group of pioneer species show differences in their density of species over the analyzed time after logging. Whereas the groups of Light demanding and Shade-tolerant species, leastwise with the logging intensity applied in the studied areas, did not show statistical differences in their density over this time, although small differences possible to be observed in Figure 5. This is possibly related to characteristics of the study areas, and not directly related to the intensity of logging specifically

2.6 Conclusions

Only species richness presented increase after the years of logging, and mostly recovered to undisturbed forest conditions within twelve years after the logging; the density of individuals did not change during the years after logging studied in this work.

The environments within the logging gaps (center, intermediate and border) had no differences in number of individuals and species richness when compared in each year of logging and not even when comparing only the environments, disconcerting the time after logging.

The species richness within the ecological groups did not differ greatly from the years after logging; the group of pioneer species presented differences in relation to the time after logging, showing that the logging effects in the studied areas not cause great alterations at the natural regeneration of the area, but silvicultural interventions affected species composition and stimulated recruitment of pioneer species, supporting our first hypothesis.

The results showed that the logging system evaluated is sustainable at least in regards to the natural regeneration of density of individuals and richness of tree species during the studied period.

I believe that the results of this study will not only be relevant to Amazonia, but to other tropical forests, because it shows that tropical forests can present different patterns of regeneration, according to the logging intensity.

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