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ECOSYSTEMS

Does selective logging affect litter deposition rates in central Brazilian Amazonia?

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Abstract: Selective logging is one of the main human activities that are drastically modifying tropical forests around the world. Reduced-impact logging emerged as a rational model of timber harvesting that reduces the impacts on the ecosystems and contributes to the conservation of natural resources. Nevertheless, this type of activity may still alter the forest structure, nutrient cycling, soil drainage, and other important ecosystem processes. Here, we aimed at testing the effects of selective logging on litter deposition in central Brazilian Amazonia. We estimated litter production during one dry and one rainy season in 11 sites logged between 2003 and 2017 and one unlogged site. Mean litter deposition was greater during the dry season. Although litter deposition rates varied between a few study sites, this variation was independent of the time after logging. The results suggest that the low logging intensity in the study site (16.8 m^3/ha) had no intense impacts on litter deposition. Reduced-impact logging may be an alternative for the use of forest resources in Amazonian forests without compromising nutrient cycles.

Key words: ecosystem function, nutrient cycle, seasonality, sustainable development, tropical forest.

INTRODUCTION

Tropical forests extend over approximately 6% of the Earth's surface and contain the greatest biodiversity on the planet (Hofsvang 2014). These forests offer essential ecosystem services (Miura et al. 2015) and contribute to the stabilization of global climate (Malhi & Grace 2000, Lewis et al. 2006), functioning as carbon stocks (Bello et al. 2015) and influencing rainfall by evapotranspiration (Makarieva et al. 2014). Therefore, tropical forests affect regional and global dynamics and contribute to the maintenance of hydrological resources and climate regulation (Lele 2009).

Human activities may drastically affect tropical forest ecosystem services (Corlett & Primack 2008, Laurance 2015). Deforestation, expansion of agricultural lands, forest fires, and selective logging are among the major threats to these ecosystems (Peres et al. 2006, Langner et al. 2007, Asner et al. 2009). Selective logging reduces vegetation cover and alters forest structure by changing biotic and abiotic conditions (Gatti et al. 2015, França et al. 2017). Examples include the release of stocked carbon back into the atmosphere, which contributes to climate change (Watson et al. 2018), biodiversity loss (Burivalova et al. 2014, Martin et al. 2015), and forest fragmentation (Nepstad et al. 1999).

Reduced-impact logging (RIL) is a rational model of forest exploitation that aims at reducing environmental impacts by allying natural resource conservation with forestry (Pinto et al. 2002, Sabogal et al. 2006). RIL is proposed as a sustainable activity in tropical forests, but it still negatively affects ecosystem functioning (Gatti et al. 2015). The intensity of the impacts is related to the number and volume of trees removed from the natural ecosystems (Henriques et al. 2008). The effects include changes in essential ecosystems processes, such as carbon cycling, hydrological cycling, and nutrient cycling (Asner et al. 2009, Morris 2010).

Nutrient cycling is essential for the maintenance of tropical forests (Luizão 2007). Litter deposition and decomposition (i.e., organic remains that are deposited on the soil surface, mainly of plants; Luizão 2007, Camargo et al. 2015, Da Silva et al. 2018) are directly connected to the capacity of the forest to recycle nutrients (Bray & Gorham 1964, Luizão 2007, Sanches et al. 2008). Litter accumulation is what allows tropical forests to grow on poor soils, a condition found in most areas of the Amazon Forest (Quesada et al. 2011). Thus, litter dynamics are responsible for the availability of nutrients that allow the maintenance and growth of plants in these forests, including litter deposition, accumulation and decomposition (Vitousek & Sanford 1986, Selle 2007, Sanches et al. 2008).

The impacts of RIL activities on tropical-forest ecosystem services, such as nutrient cycling are still understudied. As low-impact selective logging is one of the most important sustainable economic activities in tropical forests, understanding these impacts is essential to evaluate RIL as a sustainable solution. Here we evaluate the effects of RIL on litter deposition in central Brazilian Amazonia. We tested whether litter deposition is dependent on time after logging and if this effect is also dependent on seasonality. Also, we compared vegetation cover between areas with different times of recovery since logging.

MATERIALS AND METHODS

Study site

The study was undertaken in an area of 248,059 ha destined to RIL in the municipalities of Itacoatiara, Silves and Itapiranga in Amazonas State, Brazil (Fig. 1). While logging can have variable impacts on the forest ecosystem depending on its intensity, the RIL system adopted in this area follows the CELOS Management System (Werger 2011). RIL techniques include the following: selection of trees to be harvested (a subset of all trees with diameter at breast height ≥ 50 cm); planning the construction of stockyards, roads, and dragging trails; and directing tree fall to minimize impacts (Werger 2011). The company is certified by the Forest Stewardship Council (FSC). As a recent study suggests that certified companies may not show better results than uncertified companies at reducing the impacts from logging (Ellis et al. 2019), we report the logging intensity in the study sites to provide a better estimate of the intensity of the disturbances (see details in the Data collection subsection).

Climate is rainy (mean annual precipitation of 2,200 mm) and warm (mean annual temperature of 26°C) most of the year, with a short dry season of approximately three months (type “AmW”; Kottek et al. 2006). Monthly precipitation bettween 2014 and 2015 in the dry season was between 100 mm to 200 mm, and in the rainy season from 250 mm to more than 400 mm (Zhuang et al. 2017). The evergreen forest is on a low-fertility clayish soil and shows great environmental complexity and biodiversity (IBGE 2017). Emergent trees reach from 30 to 50 m high, most canopy trees are 20 to 30 m, and woody lianas and epiphyte are common (IBGE 2017).

We sampled 11 logged sites, exploited in different years from 2003 to 2018, and one

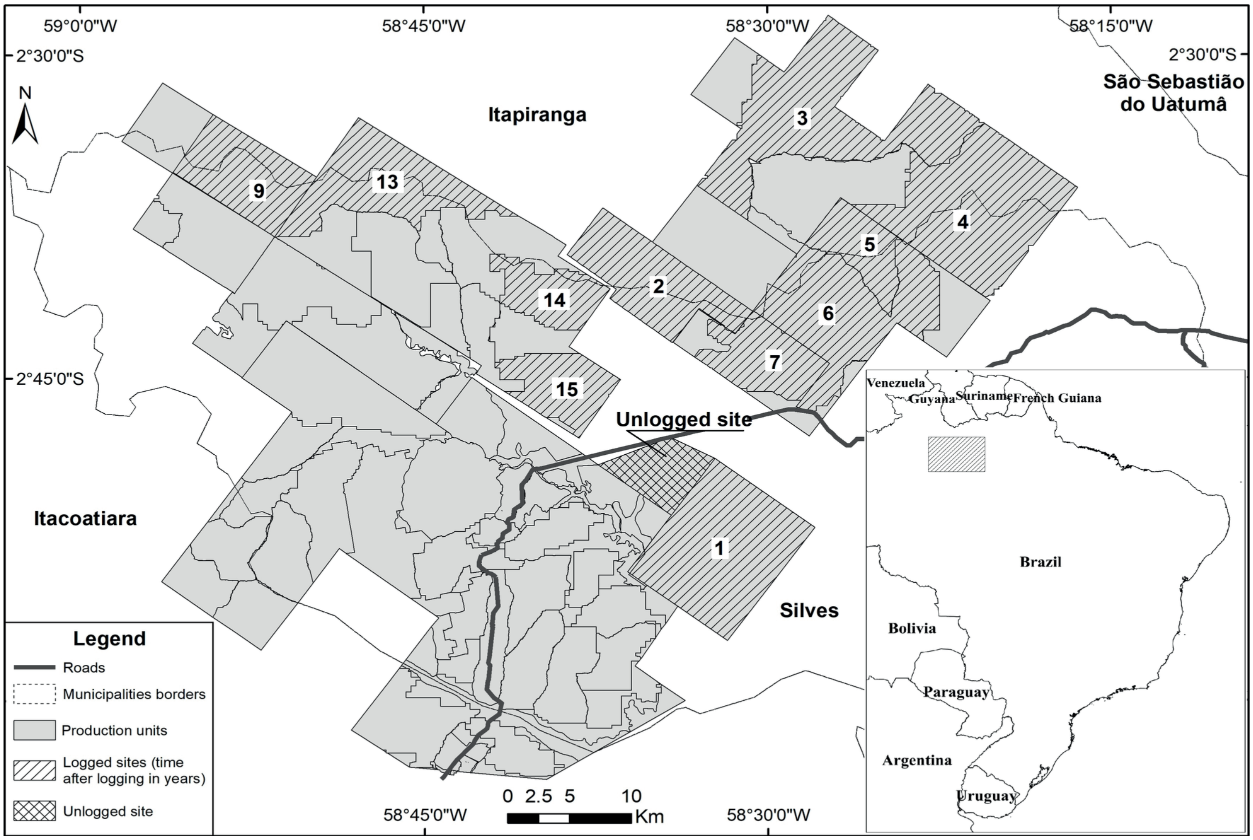

Figure 1. Location of the 11 study sites logged from 15 to one year before sampling and the unlogged site in central Brazilian Amazonia.

unlogged site (Fig. 1). Vegetation in the unlogged site is primary and well-preserved. In each site we sampled five transects separated by > 2 km. Each transect was 30 m long and started more than 100 m from the main roads constructed for the transportation of the logged wood, workers, and equipment used forRIL.

Data collection

Litter deposition was sampled during the dry (July to October 2018) and rainy (January to April 2019) seasons. To quantify the rate of litter deposition we used collectors (50 cm x 50 cm x 10cm) made with a soft mesh and fixed with wooden stakes at 15 cm above the ground. Four sampling points with collectors were installed along each transect, at 10 m intervals, for the total of 20 collectors in each study site and 240 collectors in the study.

Plant material collected was removed from the collectors monthly, following Scoriza et al. (2012). The material was collected in plastic bags and screened in lab conditions for classification into leaves, branches or miscellaneous material (i.e., bark, flowers, fruits, seeds). After separation the materials were dried in an oven at 65°C until their mass remained constant over time. The rate of litter deposition (based on Scoriza et al. 2012) was determined as:

$$LD = (\Sigma MD \,.10{,}000) / Ac$$

Where LD = litter deposition ($Mg.ha^{-1}.month^{-1}$), MD = monthly litter deposition ($Mg.month^{-1}$), and Ac = area of the collector (m^2).

To estimate vegetation cover we took photographs at each sampling point, aiming perpendicularly from approximately 1.7 m above the ground. Vegetation-cover percentage was estimated by calculating the amount of leaves in the photos using the software Canopy App (University of New Hampshire). We used georeferenced data of all trees logged in the study sites to calculate logging intensity as the volume of all trees exploited (data provided by the logging company).

Statistical analysis

We used the mean monthly litter deposition rate per transect as the sampling units. We used a linear mixed model to test the effects of time after logging and seasonality on litter deposition. Time after logging (the identity of the study site, a categorical variable) and season (rainy or dry) were the predictor variables, logged-transformed litter deposition rate was the response variable, and the identity of the sampling transects was a random effect variable to account for the data collected in the same transects in different months within a season. The model was tested as a Two-way Mixed ANOVA, including the interaction between the predictors. Variation in vegetation cover in the sampling transects was compared between study sites with one-way ANOVA. We calculated the least-square means and confidence intervals for each study site to compare with the unlogged site while controlling for statistically significant interaction effects.

RESULTS

Mean litter deposition rate during the study was 6.1 $Mg.ha^{-1}$, 8.9 $Mg.ha^{-1}$ during the rainy season and 3.3 $Mg.ha^{-1}$ during the dry season. Leaves were the most common component of litter (84.7%), followed by miscellaneous (8.3%) and branches (7.1%), in both rainy and dry seasons (Table I). Mean logging intensity in the study sites was 16.8 $m^3.ha^{-1}$, with a minimum of 12.1 $m^3.ha^{-1}$ and maximum of 23.3 $m^3.ha^{-1}$.

Mixed-effects model analysis indicated that the effects of time after logging on litter deposition were dependent of season ($F = 2.26$, $df = 11$, $p = 0.011$; Supplemental Material - Table SI). Litter deposition (least-squares means) was lower during the rainy season (3.1 $Mg.ha^{-1}$) than the dry season (8.5 $Mg.ha^{-1}$) and time after logging had no clear effects on litter deposition (Figure 2a). Vegetation cover varied among sites ($F = 4.50$, $df = 11$, $p = 0.0001$) and study sites logged more than six years before had higher vegetation cover, while more recently logged sites were similar to the unlogged site (Figure 2b).

DISCUSSION

Mean litter deposition rate in the study site (6.1 $Mg.ha^{-1}$) is among the lowest reported in tropical forest (usually between 4 to 25 $Mg.ha^{-1}$; Golley et al. 1978) and is the lowest recorded in the Amazon Forest (between 8 and 10 $Mg.ha^{-1}$; Luizão & Schubart 1987, Luizão 1989, Martius et al. 2004, Almeida et al. 2015). Variation in litter deposition is related to seasonality (Matos & Costa 2012) and extreme climatic phenomena, such as El Niño and La Niña (Martius et al. 2004). Leaves were the most common component in the study sites and this is common in areas within the Amazon Forest (Klinge & Rodrigues 1968, Luizão & Schubart 1987, Martius et al. 2004) and in other tropical forests, such as the Atlantic Forest (Martinelli et al. 2017). The highest rates of litter deposition occurred during the dry season (July to October), a pattern also observed in other Brazilian biomes, such as Caatinga (Moura et al. 2016), Atlantic Forest (Martinelli et al. 2017), ecotonal regions between Cerrado

Table I. Litter deposition ($Mg.ha^{-1}.month^{-1}$) by fraction – leaves (L), branches (B), and miscellaneous (M) – and total (T) in the studied sites sampled from July 2018 to October 2018 (dry season) and from January 2019 and April 2019 (rainy season).

Years after logging	Dry Season				Rainy Season				Mean
	L	B	M	T	L	B	M	T	
15	7.1	0.5	1.0	8.6	2.3	0.5	0.3	3.1	5.8
14	8.3	1.0	0.6	9.9	2.3	0.2	0.4	2.9	6.4
13	7.0	0.7	0.6	8.3	2.8	0.4	0.3	3.5	5.9
9	8.3	0.7	1.0	10.0	2.3	0.2	0.3	2.8	6.4
7	8.1	0.7	0.7	9.4	2.9	0.4	0.4	3.7	6.6
6	7.3	0.7	0.5	8.6	2.4	0.4	0.4	3.2	5.9
5	7.6	0.8	0.5	8.9	2.3	0.5	0.4	3.2	6.0
4	5.6	0.9	0.8	7.3	2.5	0.3	0.6	3.4	5.4
3	6.1	0.7	0.8	7.6	2.2	0.3	0.6	3.2	5.4
2	7.6	0.6	1.0	9.2	2.5	0.3	1.0	3.8	6.5
1	6.3	1.2	1.1	8.5	2.6	0.4	0.5	3.4	6.0
Unlogged	8.2	1.1	0.6	9.9	2.3	0.4	0.3	3.0	6.4
Mean	**7.3**	**0.8**	**0.8**	**8.9**	**2.4**	**0.4**	**0.5**	**3.3**	**6.1**

and the Amazon Forest (Peixoto et al. 2018), and the Pantanal (Haase 1999). The increase in litter deposition during the dry season may be a response to hydrological stress – a physiological mechanism to reduce water loss from evapotranspiration (Valentini et al. 2008, Londe et al. 2016). Also, leaf flushing is common in Amazonian forests during the dry season (Myneni et al. 2007), and it may also increase litter deposition rates.

Vegetation cover is considered a major factor determining ecosystem processes in tropical forests. During the first years after logging vegetation cover was similar to the unlogged site, while sites with more than seven years since logging showed higher values (Figure 2b). However, these effects were small and litter deposition was independent of time after logging (Figure 2a). Vegetation cover may be decreased by 10% after logging and it is usually fully recovered within the first years after logging (Duah-Gyamfi et al. 2014, Darrigo et al. 2016). Logging intensity in the study sites (average 16.8 m^3/ha) is among the lowest in RIL systems applied to tropical forests (from 11 to 61 m^3/ha; Azevedo-Ramos et al. 2006, De Avila et al. 2017, Schwartz et al. 2017). The minor impacts may minimize the effects on vegetation cover and, consequently, on litter deposition.

Impacts of human activities on litter deposition may vary according to the intensity of the disturbance (Silva et al. 1995, De Souza et al. 2017), such as the intensity of exploitation. It is possible that vegetation cover recovered quickly in the study sites logged more recently and that had lower logging intensities (Duah-Gyamfi et al. 2014). Also, the rapid growth of plants after logging (Darrigo et al. 2016) may have increased vegetation density in intermediate strata, resulting in more shade in low forest strata independent of canopy closure.

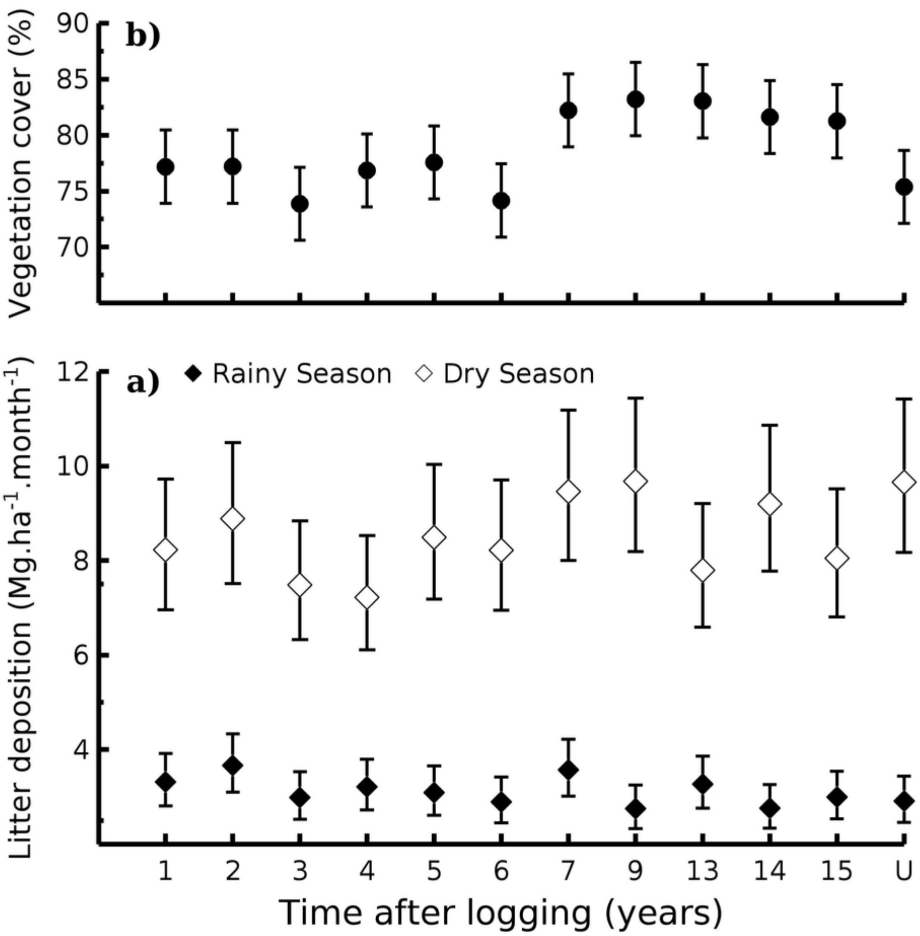

Figure 2. Comparisons of study sites with different years after logging and one unlogged site of the least-squares means and confidence intervals of: a) monthly litter deposition; b) vegetation cover.

Logging can alter tropical forests by reducing tree diameter and height, decreasing the number of emergent trees, and opening clearings (Uhl & Vieira 1989, Veríssimo et al. 1992, Putz et al. 2001). These impacts can reduce plant productivity immediately after logging. However, we did not detect significant variation in litter deposition over time. This result suggests that litter deposition and, consequently, forest productivity were not greatly affected by RIL. Similar results were found by Blate (2005) in a Bolivian forest. However, the vegetation in that study was not as well-conserved as it was in our study site. Furthermore, our results indicate that vegetation cover in older-sites was greater than in the unlogged site. This suggests that RIL possibly promoted plant growth and development after the disturbance, resulting in an increasing vegetation cover from the seventh year after logging (Figure 2b).

In RIL sites, the opening of clearings results in greater luminosity in the forests, which benefits pioneer species (Bazzaz & Pickett 1980) and the growth of remaining trees (Yamamoto 2000, Duah-Gyamfi et al. 2014, De Carvalho et al. 2017). Rapid-growth species tend to produce more leaves than late succession species during the first years of life (Bazzaz & Pickett 1980). Thus, these pioneers may contribute to the maintenance of forest productivity in disturbed environments. It remains to be tested if the increased productivity from pioneer species along with the low logging intensity in the study area explains the absence of differences in litter deposition between logged and unlogged sites.

Sustainable development in the tropics may depend on aligning the exploitation of wood resources with the conservation of forest ecosystems. RIL practices may minimize the impacts on litter deposition rates, contributing to the maintenance of important forest ecosystem services, such as nutrient cycling. These processes are crucial for the conservation of tropical forests as they allow plants to grow in otherwise poor soil conditions. Thus, RIL may allow the economic and social benefits from the use of forest resources without compromising ecosystem functioning.

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SUPPLEMENTARY MATERIAL

Table SI.

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JLB: collected and analyzed data, wrote the article (draft preparation). NSO: collected and interpreted data. RASC: analyzed and interpreted data, wrote, critically revised and edited the article. LKJ: conceptualized the article, analyzed and interpreted data, wrote, critically revised and edited the article.