Natural Resources

Dez 2022 a Fev 2023 - v.13 - n.1

ISSN: **2237-9290**

This article is also available online at:
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Residue removal of logging gaps maintains the natural regeneration and soil quality

Harvesting in native forests generates residues, which can bring extra incomes by the charcoal production and small wooden objects manufacturing. In this study, the effects of residue removal over the natural regeneration and physical and chemical soil attributes in canopy gaps created by reduced impact logging were assessed. An experiment including 123 logging gaps (369 plots) randomly chosen in different logging areas, with and without residue removal was set. The treatments were: 6-year-old logging gaps without residue removal (GAP6); 4-year-old logging gaps with two years of residue removal (GAP4-R2); 2-year-old logging gaps without residue removal (GAP2); and 2-year-old logging gaps with residue removed < one month (GAP2-R0). The control treatment included 32 repetitions (96 plots), randomly chosen under the canopy of an unlogged primary forest (FOR). Density of individuals and tree species and environment inside logging gap were compared in relation to the residue removal. Soil samples were done in 0-20 cm and 20-40 cm within the same sampling units of vegetation. FOR presented highest density of saplings, individuals ≥ 3 m in height (0.12 ± 0.03 ind. m-2) and species (0.09 ± 0.03 spp. m-2). Density of seedlings, individuals < 3 m in height in GAP6 (2.11±1.16 ind. m-2) and GAP4-R2 (2.28 ± 1.29 ind. m-2) and species in GAP2 (1.57 ± 0.59 spp. m-2) were higher than FOR. The residue removal from logging gaps increased seedlings' density and decreased the saplings' density of tree species. Logging gaps with and without residue removal showed better soil quality than FOR.

Keywords: Reduced impact logging; Native Forest; Forest management; Density of individuals; Species density.

A remoção de resíduos de clareiras mantém a regeneração natural e a qualidade do solo

A colheita em florestas nativas gera resíduos, que podem trazer renda extra com a produção de carvão vegetal e fabricação de pequenos objetos de madeira. Neste estudo, foram avaliados os efeitos da remoção de resíduos sobre a regeneração natural e os atributos físicos e químicos do solo em clareiras criadas pela exploração madeireira de impacto reduzido. Foi montado um experimento com 123 clareiras (369 parcelas) escolhidas aleatoriamente em diferentes áreas de colheita, com e sem remoção de resíduos. Os tratamentos foram: clareiras de exploração de seis anos sem remoção de resíduos (GAP6); clareiras de exploração de quatro anos com dois anos de remoção de resíduos (GAP4-R2); clareiras de exploração de dois anos sem remoção de resíduos (GAP2); e clareiras de exploração de dois anos com resíduo removido < um mês (GAP2-R0). O tratamento controle incluiu 32 repetições (96 parcelas), escolhidas aleatoriamente sob o dossel de uma floresta primária não explorada (FOR). A densidade de indivíduos e espécies arbóreas e o ambiente dentro da clareira foram comparados em relação à remoção de resíduos. As amostras de solo foram feitas em 0-20 cm e 20-40 cm dentro das mesmas unidades amostrais de vegetação. FOR apresentou maior densidade de mudas, indivíduos ≥ 3 m de altura (0,12 ± 0,03 ind. m-2) e espécies (0,09 ± 0,03 spp. m-2). Densidade de mudas, indivíduos < 3 m de altura em GAP6 (2,11±1,16 ind. m-2) e GAP4-R2 (2,28 ± 1,29 ind. m-2) e espécies em GAP2 (1,57 ± 0,59 spp. m-2) foram maiores do que FOR. A remoção de resíduos das clareiras aumentou a densidade de mudas e diminuiu a densidade de mudas de espécies arbóreas. As clareiras com e sem remoção de resíduos apresentaram melhor qualidade do solo do que FOR.

Palavras-chave: Exploração madeireira de impacto reduzido; Floresta nativa; Manejo florestal; Densidade de indivíduos; Densidade de espécies.

Topic: **Ciências Florestais**

Reviewed anonymously in the process of blind peer.

Received: **10/12/2022**
Approved: **12/03/2023**

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DOI: 10.6008/CBPC2237-9290.2023.001.0002

Referencing this:

SCHWARTZ, G.; DIONISIO, L. F. S.; OLIVEIRA, J.; SILVA, A. R.; BARDALES-LOZANO, R. M.; LOPES, J. C... Residue removal of logging gaps maintains the natural regeneration and soil quality. **Natural Resources**, v.13, n.1, p.13-27, 2023. DOI: http://doi.org/10.6008/CBPC2237-9290.2023.001.0002

INTRODUCTION

Harvesting with reduced impact logging (RIL) techniques is based on planned operations and personnel training, which includes the following procedures: a) to minimize environmental damage, conserving ecosystem services and future harvestings; b) to reduce harvesting operational costs, increasing work efficiency; and c) to reduce waste material (DIONISIO et al., 2018). After the end of RIL operations, some residuals resulting from logging remain in the harvested areas. Logging residues such as pieces of trunks and branches of logged trees are abandoned in canopy gaps. Once a felled tree opens a canopy gap, the residuals after its log removal are left in such open space.

According to Ribeiro et al. (2019), the extraction and processing of post-harvesting residuals is a profitable activity that adds value to managed native forests. Post-harvesting residues can be used to manufacture wooden pieces, such as rustic furniture, toys, and small wooden objects for decoration (AMARAL et al., 2018). They can also be used in the production of firewood and charcoal for energy generation.

Nearly eight million cubic meters of post-harvesting residuals are produced after logging activities per year in the Brazilian Amazon, where almost 100% of this volume is not economically used (BATISTA et al., 2015). The residue removal from managed forests for economic applications, although to be permitted in the Brazilian Amazon, is still not a common activity. Most of the forestry companies do not remove residuals of their managed forests, partially due to doubts on possible legal restrictions regarding the activity. These doubts come mainly with concerns to promote extra disturbances with negative effects over the natural regeneration and soil attributes in canopy gaps after the log removal.

Canopy gaps created by tree felling due to wood harvesting are defined as logging gaps (SCHWARTZ et al., 2013) (COSTA et al., 2020). The logging gaps cleaning (removal of tree felling residues as log smaller pieces and branches) and its natural regeneration are silvicultural procedures that can contribute for higher timber production in future cutting cycles (KEEFE et al., 2009) (NEVES et al., 2019) (PINTO et al., 2021). In most of the managed tropical forests with harvesting via RIL, it is assumed that abandoned logging gaps are able to recover natural regeneration (BRASIL, 2006) (SCHWARTZ et al., 2012) (SCHWARTZ et al., 2015). Despite this, there is still no scientifically based knowledge on the specific impacts of the residue removal over the regeneration of commercial species and soil attributes in logging gaps.

Scientific knowledge about the effects of residue removal on the natural regeneration as well as soil conditions of logging gaps will contribute for decision making in forest management. Hence, the objective of this work was to assess responses in density of seedlings and saplings and density of tree species to the residue removal from logging gaps in relation to different logging gap's environments and soil quality. To accomplish the work's objective the following questions were considered: 1) Does the density of individuals and tree species vary in relation to (a) residue removal from logging gaps and (b) environment inside logging gap? 2) Does soil quality vary in relation to the residue removal from logging gaps?

METHODOLOGY

Study area

This study was conducted in the forest management area of Rio Capim, located in Paragominas municipality, Pará state, Brazil (3°39’28” S and 48°49’60” W; Figure 1), which belongs to the forestry company CKBV Florestal Ltda. Rio Capim has an area of 140,000 ha, where 121,000 ha is under forest management certified by the Forest Stewardship Council (FSC) since 2001 (DIONISIO et al., 2018).

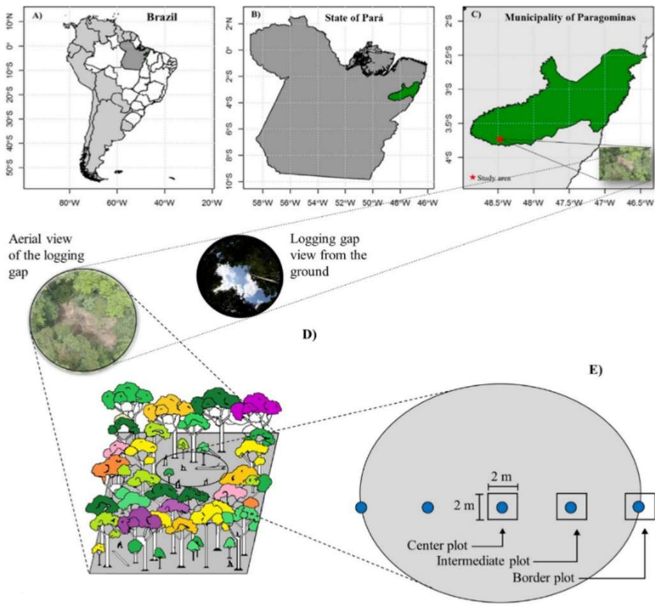

Figure 1: Study area in Rio Capim, municipality of Paragominas, state of Pará, Brazil (A-C). [1]

Dense Ombrophilous Forest is the region’s dominant vegetation (IBGE, 2012). Climate is tropical rainy Awi by the Köppen classification. Average annual rain fall is 1,800 mm with average annual temperature of 26.3 °C, and a relative humidity of 81% (Alvares et al., 2013). Altitude is 20 m a.s.l. and relief is flat to slightly undulated (SIST; FERREIRA, 2007). Most of the soils in the study site are classified as Yellow Latosols, Yellow Argisols, Plinthosols, Gleysols, and Neosols (RODRIGUES et al., 2003).

Experimental design

Data were collected in logging plots located in annual production units of the forest management area of Rio Capim, harvested between 2008 and 2012 and in an unlogged primary forest, 100% inventoried that served as a control. In 2010 the company started removing tree felling residues such as smaller trunk pieces and branches that normally remain abandoned in logging gaps. In the residual removal process, residues are cut in smaller pieces with a chain saw and dragged out the gap by a skidder through cables. Skidders do few movements inside the logging gaps to avoid soil compaction. Residues are dragged through the same skid trails used for logging and piled in log decks for further transport. Currently the forestry company has removed residues one year after logging, however, by the time of this study, the residue

[1] View of a canopy gap from aerial, ground, and schematic perspective (D), 4-m² plots (2 m x 2 m) location for sampling soil and natural regeneration in logging gaps with and without removal of crown residue from felled trees, distributed inside the gap in the border, intermediate, and center position (E).

removal occurred two years after logging. Natural regeneration sampling was carried out in 123 logging gaps randomly chosen in different logging areas (Table 1) in November 2014. Logging gaps had their major and minor axes measured, and their area calculated by the ellipse formula. The control treatment included plots under the canopy cover of an unlogged primary forest (FOR) 100% inventoried in May 2015, with no interference of logging, logging gaps, and residue removal over the natural regeneration and soil. There were 32 groups of three 4-m² plots (2 m x 2 m), summing up a total of 96 control plots. Plots were separated 4 m each other within the group and 40 m from another group (Table 1).

Table 1: Treatments to assess natural regeneration inside logging gaps where tree felling residue was removed, Rio Capim, eastern Amazon, Brazil. Time in years is showed for tree felling followed by log removal and residue removal. Sampling year and number of sampling units are also presented.

Treatment	Tree felling and log removal	Residue removal	Sampling	# of sampling units (plots)
FOR	-	-	2015	96 (32 control areas)
GAP6	2008 (6 years)	-	2014	90 (30 logging gaps)
GAP4-R2	2010 (4 years)	2012 (2 years)	2014	90 (30 logging gaps)
GAP2	2012 (2 years)	-	2014	93 (31 logging gaps)
GAP2-R0	2012 (2 years)	2014 (< 1 month)	2014	96 (32 logging gaps)

To evaluate soil and natural regeneration in different environments inside a logging gap, three 4-m² (2 m x 2 m) squares (plots) were placed in the logging gap border, center, and in an intermediate point between border and center. The border's plot was placed 1 m inside and 1 m outside the logging gap in order to better sample individuals in the border (Figure 1). This sampling design was done for treatments with and without residue removal, resulting in 369 plots in logging gaps (123 gaps x 3 plots). Logging gaps without residue removal were six- and two-year-old, with tree felling and log removal in the same year, 2008 and 2012 (treatments GAP6 and GAP2). The logging gaps with residue removal were four- and two-year-old, with tree felling and log removal in the same year (2010 and 2012) and with residue removal two years later, 2012 and 2014 (treatments GAP4-R2 and GAP2-R0). In the treatment GAP2-R0, residues had been removed in less than a month before sampling. Such experimental design permitted to compare same age gaps (GAP2 and GAP2-R0), gaps with the same regeneration age (GAP2 and GAP4-R2), and gaps with older regeneration (GAP6) against the regeneration under the canopy of an unlogged forest (FOR).

Soil sampling was done in both logging gaps and control areas in May 2015 (Table 1). Soil sampling was done in all 32 control areas of FOR, in eight logging gaps randomly chosen in GAP6, and other eight randomly chosen logging gaps of GAP2-R0 (Table 1). In every control area and logging gap soil sampling was done in the depths of 0-20 cm and 20-40 cm. One soil sample was composed by five simple samples for each depth. The five simple samples for each depth were collected in points along the logging gap major axis, being one point in the center, two intermediate, and other two in the border. In the control areas, simple soil samples were distributed along 26 m of each sampling repetition.

Data collection and analysis

In each 4-m² square (plot), both in logging gaps and in control areas, every individual of tree species ≥ 30 cm was identified at the species level by tree spotters and measured. Sampled plants of tree species were divided in two height classes: a) seedlings, individuals with 0.30 m ≤ height < 3.00 m, that had only height measured and b) saplings, individuals ≥ 3.00 m in height that had only diameter (DBH at 1.3 m from the soil) measured.

Physical and chemical analyses included pH in H_2O, Ca, Mg, K, Al, H+Al, organic matter (OM), Carbon, available P, CEC, saturation by bases and by Aluminum, Total Carbon and Nitrogen, and grain size, according to the method of Embrapa (2011) and Teixeira et al. (2017). OM was measured according to the Walkley and Black method, described in Black (1965).

Data analysis

Density of individuals belonging to tree species and species density (species richness represented by the number of species per square meter) were calculated. Data on density were compared through the analysis of variance (ANOVA). In the statistical analyses for density, each plot worked as a sampling unit. To verify ANOVA assumptions, the data were firstly tested for: a) normality with the Shapiro-Wilk test ($p > 0.05$) and b) homoscedasticity through the de Bartlett test ($p > 0.05$). Once complied these assumptions, data were analyzed by ANOVA using the software R version 3.5.2 and, in case of significant differences, means were compared by the post-hoc Tukey test ($p < 0.05$).

The relationship between physical and chemical soil properties in two depths with density of individuals and species density were investigated through the Principal Component Analysis (PCA). To run PCA, highly correlated variables were withdrawn to avoid multicollinearity issues in the correlation matrix. Through the Principal Component scores, it was possible to group the treatments with higher density of individuals, and species density (species richness), and the physical and chemical soil attributes with higher contribution in each treatment.

RESULTS

Density of individuals of tree species and species density

The total abundance of individuals of tree species was 4,059 and the total tree species richness was 121. Density of individuals ≥ 3 m in height (saplings) of control forest (FOR) was significantly higher than in logging gap areas (0.12 ± 0.03 ind. m^{-2}, $F_{4,\,137} = 85.32$, $p = 0.001$) (Figure 2A). Six-year-old logging gaps with no residue removal (GAP6) presented higher density of individuals, differing from 2-year-old logging gaps with residue removed in less than a month (GAP2-R0). Four-year-old logging gaps with two years of residue removal (GAP4-R2) and GAP2-R0 did not differ from 2-year-old logging gaps without residue removal (GAP2) (Figure 2A). Equal result was observed in the species density of individuals ≥ 3 m in height, with higher value of FOR (0.09 ± 0.03 ind. m^{-2}, $F_{4,\,137} = 64.82$, $p = 0.001$) in relation to logging gaps (Figure 2B). The density of individuals < 3 m (seedlings) in the treatments GAP6 (2.11±1.16 ind. m^{-2}), GAP4-R2 (2.28 ± 1.29 ind. m^{-2}), and GAP2 (1.85±1.02 ind. m^{-2}) were significantly higher ($F_{4,\,412} = 11.3$, $p = 0.001$) than FOR (1.39±0.68 ind. m^{-2}) and GAP2-R0 (1.21 ± 0.27 ind. m^{-2}) (Figure 2C). Species density of individuals < 3 m was higher than in GAP6 (1.39

± 0.68 ind. m^{-2}), GAP4-R2 (1.37 ± 0.63 ind. m^{-2}), and GAP2 (1.57 ± 0.59 ind. m^{-2}) differing ($F_{4, 412}$ = 11.73, *p* = 0.001) from the treatments FOR (1.10 ± 0.49 ind. m^{-2}) and GAP2-R0 (1.06 ± 0.24 ind. m^{-2}) (Figure 2D).

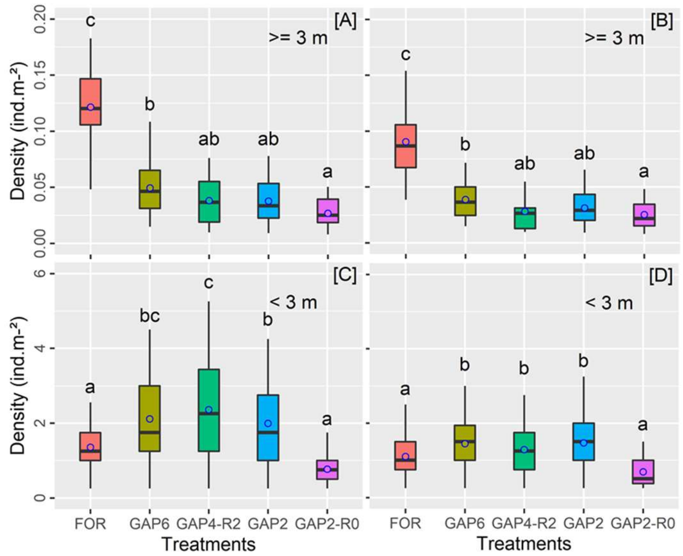

Figure 2: Density of individuals belonging to tree species (A) and species density of individuals ≥ 3 m in height (B) and density of individuals (C) and species density of individuals < 3 m in height (D) in gaps created by reduced impact logging in Rio Capim, eastern Amazon, Brazil.[2]

Density of individuals in relation to the environment

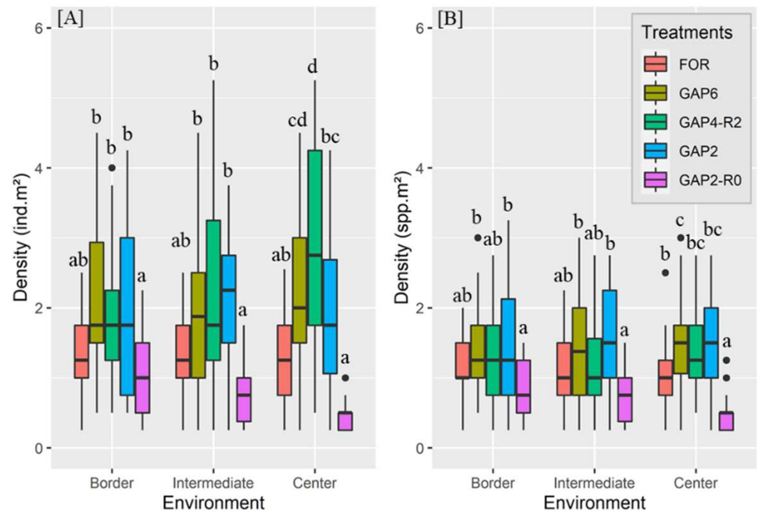

Figure 3: Density of individuals belonging to tree species (A) and species density (B) of individuals < 3 m in height in the environments border, intermediate, and center inside canopy gaps created by reduced impact logging, Rio Capim, eastern Amazon, Brazil. [3]

Treatments within each environment presented differences in density of individuals in the logging

[2] FOR = control forest (unlogged); GAP6 = 6-year-old logging gaps (2008-2014) without residue removal; GAP4-R2 = 4-year-old logging gaps (2010-2014), with four years of log removal (2010-2014) and two years of residue removal (2012-2014); GAP2 = 2-year-old logging gaps (2012-2014) without residue removal; and GAP2-R0 = 2-year-old logging gaps (2012-2014) with two years of log removal (2012-2014) and residue removed in less than a month (2014). Boxplots: where horizontal thick lines, dots, boxes, and dashed lines represent median, mean, interquartile intervals, and extreme values, respectively. Letters above boxplots indicate statistical differences, by the post-hoc Tukey test at 5% of probability.

[3] FOR = control forest (unlogged); GAP6 = 6-year-old logging gaps (2008-2014) without residue removal; GAP4-R2 = 4-year-old logging gaps (2010-2014), with four years of log removal (2010-2014) and two years of residue removal (2012-2014); GAP2 = 2-year-old logging gaps (2012-2014) without residue removal; and GAP2-R0 = 2-year-old logging gaps (2012-2014) with two years of log removal (2012-2014) and residue removed in less than a month (2014). Boxplots: where horizontal thick lines, boxes, and dashed lines represent median, interquartile intervals, and extreme values, respectively. Letters above boxplots indicate statistical differences, by the post-hoc Tukey test at 5% of probability.

gap border ($F_{4, 133}$ = 5.516, p = 0.001), center ($F_{4, 134}$ = 17.17, p = 0.001), and in the intermediate side ($F_{4, 135}$ = 7.27, p = 0.001) (Figure 3A). Despite of the environment, the treatments presented a same tendency. The three logging gaps environments (border, intermediate, and center) in GAP6, GAP4-R2, and GAP2 presented highest means, differing from GAP2-R0. In the logging gaps borders, GAP6 (2.18 ± 1.10 ind. m^{-2}), GAP4-R2 (1.89 ± 0.87 ind. m^{-2}), and GAP2 (2.11 ± 0.87 ind. m^{-2}) showed highest means, differing from GAP2-R0 (1.06 ± 0.50 ind. m^{-2}) (Figure 3A). Similar results were found in species density among environments. In the logging gap border, intermediary, and center GAP6, GAP4-R2, and GAP2 presented larger species density than GAP2-R0 (Figure 3B).

Residual removal, natural regeneration, and soil properties

Regarding individuals < 3 m in height, the Principal Component Analysis (PCA) unveiled 91.9% of the data variance of physical and chemical soil attributes in the two first Principal Components (70.5% = PC1 and 21.4% = PC2) for depths 0-20 cm (Figure 4A) and 87.9% (64.4% = PC1 and 23.5% = PC2) for depth 20-40 cm (Figure 4B) of individuals < 3 m in height. In the depth 0-20 cm, three groups were formed: FOR, GAP2, and GAP2-R0. In the first Principal Component (PC1), the main physical and chemical attributes of N, organic matter (OM), C, K+, Ca^{2}+, Mg^{2}+, Silt, Clay, H+Al, CEC, and soil pH were associated with GAP2-R0 and P in the second Principal Component (PC2). The density of individuals and species density were positively associated to PC1 with the values of Fine Sand and Al^{3}+ in a cluster with GAP2. The physical and chemical attributes as Na, Coarse Sand, and Total Sand were correlated to FOR (Figure 4A). A similar result was observed in the 20-40 cm depth, with three groups (FOR, GAP2, and GAP2-R0), where density of individuals and species density were positively associated to GAP2 (Figure 4B).

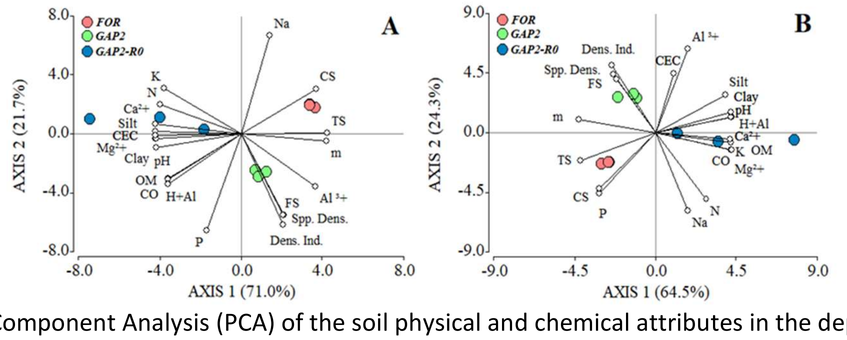

Figure 4: Principal Component Analysis (PCA) of the soil physical and chemical attributes in the depth 0-20 cm (A) and 20-40 cm (B) of density of individuals and species density, considering individuals < 3 m in height under different treatments in canopy gaps created by reduced impact logging, Rio Capim, eastern Amazon, Brazil. [4]

For individuals ≥ 3 m in height, the two first Principal Components explained 100% (80.1% = PC1 and 19.9% = PC2) of the variability of the soil physical and chemical attributes both in depth 0-20 cm (Figure 5A) and in depth 20-40 cm (74.3% = PC1 and 25.7% = PC2) (Figure 5B). In the depth 0-20 cm, three groups were formed: FOR, GAP2, and GAP2-R0. The density of individuals and species density were positively associated to FOR, also in depths 0-20 cm and 20-40 cm (Fig. 5A and 5B).

[4] FOR = control forest (unlogged); GAP2 = 2-year-old logging gaps (2012-2014) without residue removal; and GAP2-R0 = 2-year-old logging gaps (2012-2014) with two years of log removal (2012-2014) and residue removed in less than a month (2014).

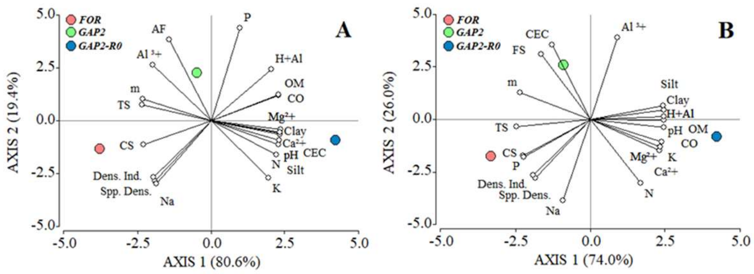

Figure 5: Principal Component Analysis (PCA) of the soil physical and chemical attributes in the depth 0-20 cm (A) and 20-40 cm (B), density of individuals, and species density, considering individuals ≥ 3 m in height under different treatments in canopy gaps created by reduced impact logging, Rio Capim, eastern Amazon, Brazil. [5]

There was no interaction among treatments and the two soil depths sampled in the 12 variables presented in Table 2. FOR, GAP2, and GAP2-R0 had low amounts of nutrients. On the other hand, the highest values of organic matter (OM), Carbon, Clay, CEC, and $H+Al^{3+}$ were found in the logging gaps (GAP 2 e GAP2-R0), being significantly higher than FOR ($F_{2, 187}$ = 8.921, p = 0.001). In relation to depths, the highest values of N, OM, C, K, TS, Clay, m, and $H+Al^{3+}$ were found in depth 0-20 cm (Table 2).

Table 2: Values of soil attributes measured in each treatment of the experiment, Rio Capim, eastern Amazon, Brazil.

Factor		**N**	**OM**	**C**	**K**
		%	**g Kg^{-1}**	**g Kg^{-1}**	**mg dm^{-3}**
Treatments	FOR	0.08±0.02 a	19.03±5.84 a	1.10±0.34 a	18.93±7.43 a
	GAP2	0.08±0.02 a	21.62±9.36 b	1.25±0.54 b	17.26±7.20 a
	GAP2-R0	0.09±0.03 b	23.33±10.16 b	1.31±0.52 b	24.85±11.62 b
Depths (cm)	0-20	0.09±0.02 b	26.70±6.74 b	1.53±0.35 b	25.14±6.54 b
	20-40	0.07±0.02 a	14.10±4.79 a	0.82±0.28 a	13.35±7.78 a
CV (%)		24.58	26.96	25.39	32.12
		TS	**Silt**	**Clay**	**CEC**
		g kg^{-1}	**g kg^{-1}**	**g kg^{-1}**	**Cmol$_c$ dm^{-3}**
Treatments	FOR	639.20±57.91 c	194.80±52.14 a	159.24±39.52 a	1.70±0.16 a
	GAP2	567.97±155.78 b	227.74±54.77 b	204.14±64.03 b	2.04±0.35 b
	GAP2-R0	450.36±220.73 a	286.25±78.07 a	263.40±58.51 c	2.58±0.85 c
Depths (cm)	0-20	592.76±168.37 b	237.46±78.72 a	222.47±66.75 b	2.13±0.64 a
	20-40	521.80±163.55 a	224.79±57.78 a	189.63±66.22 a	1.99±0.56 a
CV (%)		26.61	27.66	25.64	23.79
		CS	**FS**	**m**	**H+Al^{3+}**
		g kg^{-1}	**g kg^{-1}**	**%**	**Cmol$_c$ dm^{-3}**
Treatments	FOR	304.57±42.66 c	334.63±49.90 ab	60.10±6.70 b	3.97±0.82 a
	GAP2	185.50±57.83 b	383.47±105.36 b	57.55±10.66 b	4.33±1.30 b
	GAP2-R0	128.51±52.00 a	321.85±159.25 a	43.08±17.80 a	4.56±1.05 b
Depths (cm)	0-20	231.82±87.04 b	360.94±111.02 a	61.58±11.78 b	4.93±0.91 b
	20-40	188.34±85.80 a	333.46±110.50 a	48.94±13.25 a	3.41±0.62 a
CV (%)		33.12	35.72	18.89	17.99

N = Nitrogen, OM = Organic Matter, C = Organic Carbon, K = Potassium, CS = Coarse Sand, FS = Fine Sand, TS = Total Sand, CEC = Cation Exchange Capacity, m = Aluminum saturation. FOR = control forest (unlogged); GAP2 = 2-year-old logging gaps (2012-2014) without residue removal; and GAP2-R0 = 2-year-old logging gaps (2012-2014) with two years of log removal (2012-2014) and residue removed in less than a month (2014). Means followed by the same letters in the column indicate no statistical difference by the Tukey test (p<0.05).

A significant interaction was detected among treatments and the two soil depths for the six variables presented in Table 3. GAP2-R0 had highest average values of pH, Ca^{2+}, Mg^{2+}, and K and lowest average values

[5] FOR = control forest (unlogged); GAP2 = 2-year-old logging gaps (2012-2014) without residue removal; and GAP2-R0 = 2-year-old logging gaps (2012-2014) with two years of log removal (2012-2014) and residue removed in less than a month (2014).

of Al^{3+} in the depth 0-20 cm, differing from FOR and GAP2 (Table 2 and Table 3). FOR presented lowest values of pH and consequently lowest Ca^{2+} and Mg^{2+} values (Table 2 and Table 3). The logging gaps (GAP2 and GAP2-R0) presented higher mean values in Phosphorous, differing significantly for depth 0-20 m in FOR (Table 3).

Table 3: Characteristics of soil properties in each treatment of the experiment, Rio Capim, eastern Amazon, Brazil.

Depths (cm)	**pH (H_2O)**			**P (mg dm^{-3})**		
	Treatment			Treatment		
	FOR	GAP2	GAP2-R0	FOR	GAP2	GAP2-R0
0-20	3.99±0.17 aA	4.10±0.16 aB	4.28±0.27 aC	3.49± 0.72 aA	4.51±0.88 bB	4.13±1.14 bB
20-40	4.26±0.10 bA	4.29±0.11 bA	4.33±0.14 aA	3.29±1.10 aA	2.87±0.34 aA	2.78±0.42 bA
CV (%)	3.99			23.35		
Depths (cm)	**Na (mg dm^{-3})**			**Ca^{2+} ($cmol_c$ dm^{-3})**		
	Treatment			Treatment		
	FOR	GAP2	GAP2-R0	FOR	GAP2	GAP2-R0
0-20	13.18±3.73 bB	6.93±3.12 bA	8.20±4.56 aA	0.28±0.08 aA	0.49±0.16 bB	1.14±0.31 bC
20-40	8.19±3.57 aB	5.19±2.12 aA	7.30±4.29 aAB	0.26±0.05 aA	0.33±0.13 aA	0.72±0.06 aB
CV (%)	43.1			30.32		
Depths (cm)	**Mg^2+ ($cmol_c$ dm^{-3})**			**Al^3+ ($cmol_c$ dm^{-3})**		
	Treatment			Treatment		
	FOR	GAP2	GAP2-R0	FOR	GAP2	GAP2-R0
0-20	0.33±0.04 aA	0.44±0.07 bB	0.57±0.25 bC	1.15±0.07 bB	1.22±0.41 bB	0.84±0.31 aA
20-40	0.27±0.04 aA	0.27±0.16 aA	0.45±0.11 aB	0.93±0.11 aA	1.04±0.06 aA	0.99±0.07 bA
CV (%)	30.69			22.43		

Na = Sodium, Mg =Magnesium, P = Phosphorous, Ca = Calcium, Al = Aluminum. FOR = control forest (unlogged); GAP2 = 2-year-old logging gaps (2012-2014) without residue removal; and GAP2-R0 = 2-year-old logging gaps (2012-2014) with two years of log removal (2012-2014) and residue removed in less than a month (2014). Means followed by the same letters in the column indicate no statistical difference by the Tukey test ($p<0.05$).

A significant interaction was detected among treatments and the two soil depths for the six variables presented in Table 3. GAP2-R0 had highest average values of pH, Ca^{2+}, Mg^{2+}, and K and lowest average values of Al^{3+} in the depth 0-20 cm, differing from FOR and GAP2 (Table 2 and Table 3). FOR presented lowest values of pH and consequently lowest Ca^{2+} and Mg^{2+} values (Table 2 and Table 3). The logging gaps (GAP2 and GAP2-R0) presented higher mean values in Phosphorous, differing significantly for depth 0-20 m in FOR (Table 3).

Table 4: Characteristics of soil properties in each treatment of the experiment, Rio Capim, eastern Amazon, Brazil.

Depths (cm)	**pH (H_2O)**			**P (mg dm^{-3})**		
	Treatment			Treatment		
	FOR	GAP2	GAP2-R0	FOR	GAP2	GAP2-R0
0-20	3.99±0.17 aA	4.10±0.16 aB	4.28±0.27 aC	3.49± 0.72 aA	4.51±0.88 bB	4.13±1.14 bB
20-40	4.26±0.10 bA	4.29±0.11 bA	4.33±0.14 aA	3.29±1.10 aA	2.87±0.34 aA	2.78±0.42 bA
CV (%)	3.99			23.35		
Depths (cm)	**Na (mg dm^{-3})**			**Ca^{2+} ($cmol_c$ dm^{-3})**		
	Treatment			Treatment		
	FOR	GAP2	GAP2-R0	FOR	GAP2	GAP2-R0
0-20	13.18±3.73 bB	6.93±3.12 bA	8.20±4.56 aA	0.28±0.08 aA	0.49±0.16 bB	1.14±0.31 bC
20-40	8.19±3.57 aB	5.19±2.12 aA	7.30±4.29 aAB	0.26±0.05 aA	0.33±0.13 aA	0.72±0.06 aB
CV (%)	43.1			30.32		
Depths (cm)	**Mg^2+ ($cmol_c$ dm^{-3})**			**Al^3+ ($cmol_c$ dm^{-3})**		
	Treatment			Treatment		
	FOR	GAP2	GAP2-R0	FOR	GAP2	GAP2-R0
0-20	0.33±0.04 aA	0.44±0.07 bB	0.57±0.25 bC	1.15±0.07 bB	1.22±0.41 bB	0.84±0.31 aA
20-40	0.27±0.04 aA	0.27±0.16 aA	0.45±0.11 aB	0.93±0.11 aA	1.04±0.06 aA	0.99±0.07 bA
CV (%)	30.69			22.43		

Na = Sodium, Mg =Magnesium, P = Phosphorous, Ca = Calcium, Al = Aluminum. FOR = control forest (unlogged); GAP2 = 2-year-old logging gaps (2012-2014) without residue removal; and GAP2-R0 = 2-year-old logging gaps (2012-2014) with two years of log removal (2012-2014) and residue removed in less than a month (2014). Means followed by the same letters in the column indicate no statistical difference by the Tukey test ($p<0.05$).

DISCUSSION

Density of individuals of tree species and species density

Two-year-old logging gaps with residue removed in less than a month (GAP2-R0) lost higher numbers of large individuals (saplings, individuals ≥ 3 m in height, dead by skidding operations) and species when compared to the control forest (FOR) and with 6-year-old logging gaps with no residue removal (GAP6) (Figure 2), resulting in a natural regeneration delay. Some of the small individuals (seedlings, individuals ≥ 3 m) lost, were probably present in the area covered by the logging gap before tree felling. In this study, the time between gap opening followed by log removal and the residue removal was two years. When the process of residue removal is carried out in a long time after harvesting, it can have negative impact over the natural regeneration since the after logging established seedlings and saplings present prior to tree felling are destroyed. To reduce both damage over the advanced regeneration and delay on the new regeneration and still getting advantage from augmented sunlight entrance due to the canopy opening, the residue removal should be taken in a short time after tree felling and log removal. Opportunities of abundant sunlight can be lost by canopy closure in case of long delays in residue removal, especially in small logging gaps. Francez et al. (2007), pointed out that, seven months after logging, species composition did not differ among unlogged, logged, and logged forests with residue removal. The authors suggest that even with the residue removal, the forest recovers its original features in a short time.

In the 2-year-old logging gaps with residue removal in less than a month before sampling (GAP2-R0), the residue removal destroyed the natural regeneration below 3 m in height. Even small size individuals (seedlings < 3 m in height), with more flexible stems, were negatively affected by residue removal. However, in 4-year-old logging gaps with two years of residue removal (GAP4-R2) the density of individuals and species increased significantly after residue removal (Figure 2C and Figure 2D). This indicates that residue removal delays the natural regeneration but has no effect over the abundance of individuals and species richness, which recover fast from such disturbance. The regeneration delay depends on the interval between logging gap opening and residue removal. An important aspect to point out during residue removal is the branches skidding process. It scarifies the gap's soil, activating seed bank and consequently speeding up the natural regeneration.

Various studies both in tropical and in temperate forests have showed that canopy openings by logging as well as soil scarification work as silvicultural treatments to activate seed banks (ZACZEK, 2002) (KARLSSON et al., 2005) (PEÑA-CLAROS et al., 2008) (SCHWARTZ et al., 2017) (NAKHOUL et al., 2020). The present study showed that residue removal with some soil scarification is an efficient tool to stimulate natural regeneration, as can be seen in better results presented by GAP4-R2 in relation to GAP2. The control (FOR) showed lower density of individuals than GAP6 and GAP4-R2, since FOR encompasses species with different ecological requirements than those found in logging gaps. Most of the species sampled in FOR are shade-tolerant species, adapted to survive under canopy conditions. There was a significant increase in the density of individuals and species density in logging gaps with residue removal. According to the environmental regulations about forest management in Brazil, specifically in Pará state (Brazilian Amazon), the IN-05 published in 2015 (SEMAS, 2015) allows residue removal from logging gaps.

Density of individuals in relation to the environment

Treatments in relation to the environment within logging gaps presented significant differences in density of individuals and species density (Figure 3). The treatments GAP6, GAP4-R2, and GAP2 showed higher means of density of individuals than GAP2-R0. Individuals placed in the gap center tended to have higher densities, but no statistical differences were detected (Figure 3). These results reinforce the fact that the logging gap center receives the longest and strongest sunlight intensity along the day, offering the best survival chances for pioneer and light-demanding species.

Residual removal, natural regeneration, and soil properties

Principal Component Analysis (PCA) results indicated three clusters formed by different treatments in relation to the physical and chemical soil attributes. GAP2-R0 presented positive correlations in the physical and chemical soil properties (Ca^{2+}, Mg^{2+}, K, H + Al, N, organic matter (OM), CO, pH, and the silt and clay quantities) in both depths (Figure 4A, Figure 4B, Figure 5A, and Figure 5B). FOR showed more discrimination power both for individuals < 3 m and ≥ 3 m in height for the chemical properties Na, CS, and TS, corroborating results of Yimer et al. (2008), where the exchangeable Na is higher in soils of the unlogged forest than disturbed soils. FOR soils have better drainage conditions because of its texture, with more sand (CAMPOS et al., 2012) (ARYA et al., 2018) and lower values of Ca^{2+}, Mg^{2+} in relation to GAP2-R0 and GAP2, since the greatest Ca^{2+}, Mg^{2+}, and K concentrations are related to higher amounts of clay (GENU et al., 2013) (ARYA et al., 2018).

The non-removal of tree felling residues benefits the abundance of individuals and tree species < 3 m in height (Figure 4). The abundance of individuals and tree species ≥ 3 m was strongly correlated with FOR (Figure 5A and Figure 5B). This presented a discriminatory power in the attributes Al^{3+}, Al saturation, and Fine Sand that presented intermediate values in relation to FOR and GAP2-R0.

Increases in organic matter and Carbon in GAP2 and GAP2-R0 augmented the soil CEC. This effect contributed to increase the soil negative charges with higher nutrients storage. This effect was observed in GAP2 and GAP2-R0, which presented the highest quantities of Ca, Mg, and K. Clay soils have higher amounts of H + Al because of the organic matter and vegetal residues decomposition, which takes to the liberation of organic compounds in the soil surface with the formation of water-soluble organic complexes between Ca^{2+} and Mg^{2+}. Such process facilitates the descent of these cations through the soil profile (FRANCHINI et al.,

1999) making it more acidic. The greater relation with pH indicates that a soil becomes acidic when it has many H^+ or Al^+ ions and low Ca^{2+}, Mg^{2+}, and K^+ ions adsorbed in its colloidal exchange complex. This appears in FOR, which showed the lowest pH values and consequently the lowest levels of Ca^{2+}, and Mg^{2+} (Table 3). This result corroborates the fact that the more acidic soil, the higher the content of exchangeable Al in absolute value, the lower the levels of Ca, Mg, and K, the lower the sum of bases, and the higher is percentage of Al saturation (LOPES et al., 2004).

Low phosphorus levels are commonly found in highly weathered soils in the Amazon basin (DELARMELINDA et al., 2017). Higher values of phosphorus in the unlogged forest, GAP2 and GAP2-R0 (Table 3) may be due to large concentration of residues deposited in the canopy gaps as a result of logging, since broadleaf trees are a source of phosphorus and potassium for soils (SALIM et al., 2018). In this sense, we highlight that residue removal from logging gaps, besides bringing economic benefits to managed forests, also contributes to the improvement of physical and chemical soil conditions for further natural regeneration, as observed by the increase in OM, C, K, and P in GAP2-R0 (Table 2 and Table 3).

Organic matter content, C accumulation, and nutrient content have been considered as indicators of soil fertility and quality (YUAN et al., 2012) (AHMAD 2017). In this way, OM and C play important role in forest succession as nutrient sources for plants in tropical and subtropical soils (FEITOSA et al., 2016). Thus, the forest disturbance generally leads to soil CEC reduction (IAREMA et al., 2011). Nonetheless, the opening of a logging gap followed by residue removal two years after logging was not a disturbance strong enough to interfere negatively in the chemical soil properties. On the contrary, OM, CEC, pH, Ca^{2+}, Mg^{2+}, K increased, while Al saturation decreased (Table 2 and Table 3). The levels of OM and C were equal in the treatment with residue removal (GAP2-R0) and without residue removal (GAP2) demonstrating that residue removal does not interfere in soil chemical properties, since leaves and thin branches remain in the area providing OM. The interval between canopy opening and residue removal therefore becomes necessary to decrease the residue volume and consequently damage to the surrounding vegetation as well as to return important nutrients to the soil.

Forests naturally produce woody residues, either through the fall of leaves, twigs, and branches, or even entire trees. So that, the improvement in soil quality inside logging gaps can be attributed to the higher concentration of harvesting residues followed by the removal of only woody parts, leaving a high concentration of leaves, twigs, and fine branches that work as a nutrient input to the system (SALIM et al., 2018; ZHU et al., 2019). The amount of residue can vary depending on the number and size of harvested trees. Cruz Filho and Silva (2009) found that a forest under reduced impact logging in the eastern Amazon can produce three times more woody residues than an unlogged forest.

Implications for forest management and recommendations

In the present study, the residue removal from logging gaps indicates no regeneration losses, although some individuals within gaps were killed due to the residue removal operations. The community, however, recovered from the disturbance, both in number of individuals and species. In addition, the residue removal brings more economic appreciation of managed forests by the financial income increasing through the use of tree felling residues for charcoal production to energy generation. Other possibilities of using tree felling residues are the supply of raw materials for products that do not require sawn wood, such as handicraft, frames for painting canvas, and rustic furniture.

The residue removal from logging gaps should not be done immediately after tree felling and log removal to avoid damage to the surrounding vegetation, but not so long after that, to avoid extra delay in natural regeneration. In this work, it was still not possible to determine the optimal time for the residue removal from large trees in primary tropical forests. Based on information from the forestry company, residue removal is not recommended immediately after tree felling and log removal. In this situation, leaves and branches are still green and very heavy. Their removal would demand more energy spend from the machinery and would cause more damage to the surrounding vegetation. Furthermore, the removal of green leaves would also take out important nutrients that would return to the gap's soil. The residue removal does not seem to cause other damage to the natural regeneration than some delay. In this work, the residue was removed two years after the canopy opening and log removal, which can be a long time for the recovery of natural regeneration. In other management areas of the Brazilian Amazon and currently in the forestry company, residue removal is carried out one year after canopy opening and log removal. Therefore, the one-year interval seems to be a reasonable time to balance the surrounding vegetation protection and the regeneration delay, without losing the window of abundant light availability with the canopy opening. Residue removal can also have the advantage for managers to have a clean logging gap for the application of other silvicultural treatments, such as enrichment planting in gaps (GOMES et al., 2019) (PINTO et al., 2021) and the natural regeneration tending (ARAUJO, 2016) (SCHWARTZ et al., 2017) (NEVES et al., 2019).

The absence of studies on residue removal in logging gaps was a limitation for comparisons and discussion of our results. Nevertheless, the present study stimulates and instigates new research in the field, seeking to analyze and expand results about natural regeneration in logging gaps after residue removal. Further studies should assess the impacts of residue removal over a longer period and assess different intervals between tree felling and residue removal to consolidate the procedure efficiency and its recommendation as a possible post-harvesting silvicultural treatment.

CONCLUSIONS

Residue removal from logging gaps decreased the density of individuals ≥ 3 m in height (saplings) and species in this size class. It also increased density of individuals < 3 m in height (seedlings) as well as species. Logging gaps two years after residue removal showed higher density of individuals regardless the sampling environment (border, intermediate, or center).

Residue removal did not interfere negatively in the soil quality, where the values of OM, C, Ca, Mg, K, and P, indicators of good soil quality, were higher in logging gaps with and without residue removal than in the control plots in the unlogged reference primary forest. Residue removal from logging gaps should be done not so long after tree felling and log removal to reduce damage over the advanced natural regeneration and avoid light loss due to gap closure.

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