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Abstract: In this study, we quantify the impacts of reduced-impact selective logging operations on forest health (assessed using 13 litter and 16 soil biogeochemical parameters) in the Brazilian Amazon. We selected one unlogged and four logged primary forests under a sustainable forest management plan at Precious Woods Amazon (PWA), central Amazonia. The logged forests were selected to establish a chronosequence spanning 9 years since logging and to evaluate the responses to logging in a total of 15 permanent plots, three per logged and unlogged forest. In each plot, composite standing litter samples were collected in subplots and soil samples taken at three depths: 0-10, 10-30 and 30-50 cm. A multivariate Principal Component Analysis was used to partition the variance of soil and litter data based on time since logging. The first two components (i.e. multivariate axes) of the analysis each explained 73% and 68% of soil and litter data variability, respectively. Soil texture and organic carbon (C) content were the most important soil variables while nitrogen (N), phosphorus (P), C:N ratios and C stock were the most important in the litter layer. A hierarchical classification dendrogram shows clear separation of two distinct groups on the basis of time since logging. As expected, soil and litter variables where most different amongst forests at the two end members of the chronosequence (i.e., 3 and 9 years). Our findings suggest that the current methodology for reduced-impact selective logging employed at PWA in central Amazonia has a small but significant effect on soil and litter biogeochemistry. Part of that effect, however, diminishes over time and becomes statistically insignificant nine years after logging. Time since selective logging should be considered in future models and management efforts aimed at assessing nutrient cycling recuperation after logging operations in tropical forests.

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*Cover Letter

Dear editors,

Please find attached a manuscript titled: ***Using soil and litter biogeochemistry to assess the effects of reduced-impact logging on central Amazonian forests***. This work is a product of interdisciplinary research including forest science, forest management, soil science and ecosystem biogeochemistry. To the best of our knowledge, this type of interdisciplinary research fits the Aims and Scope of the journal. Our study quantifies the impacts of reduced-impact selective logging operations (removal of 12 to 19 m^3 ha^{-1} yr^{-1}) on 13 litter and 16 soil biogeochemical parameters measured in forests under sustainable forest management plan. We sampled soil and litter in unlogged and logged forests to establish a chronosequence spanning 9 years since logging and to evaluate the responses to logging in a total of 15 permanent plots. Principal component analysis indicated soil texture and organic carbon (C) content (g kg^{-1}) and stock (Mg C ha^{-1}) as the most important soil variables, and nitrogen (N, g kg^{-1}), phosphorus (P, g kg^{-1}), C:N ratio and C stock as the most important litter variables. Overall, our findings suggest that reduced-impact selective logging employed at PWA in central Amazonia has minimal effect on soil and litter biogeochemistry, at least in a single harvesting cycle.

We suggest Ben Hur Marimon Junior, State University of Mato Grosso (bhmjunior@gmail.com), Gabriela Nardoto, University of Brasilia (gbnardoto@unb.br), Rodrigo Correa, University of Brasilia (rodmanga@yahoo.com.br), Fabiano Petter, Federal University of Mato Grosso (petter@ufpi.edu.br), and Ted Feldpausch, University of Exeter (t.r.feldpausch@exeter.ac.uk) as potential reviewers.

Thank you for your time. We look forward to hearing from you.

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*Title Page

Using soil and litter biogeochemistry to assess the effects of reduced-impact logging on central Amazonian forests

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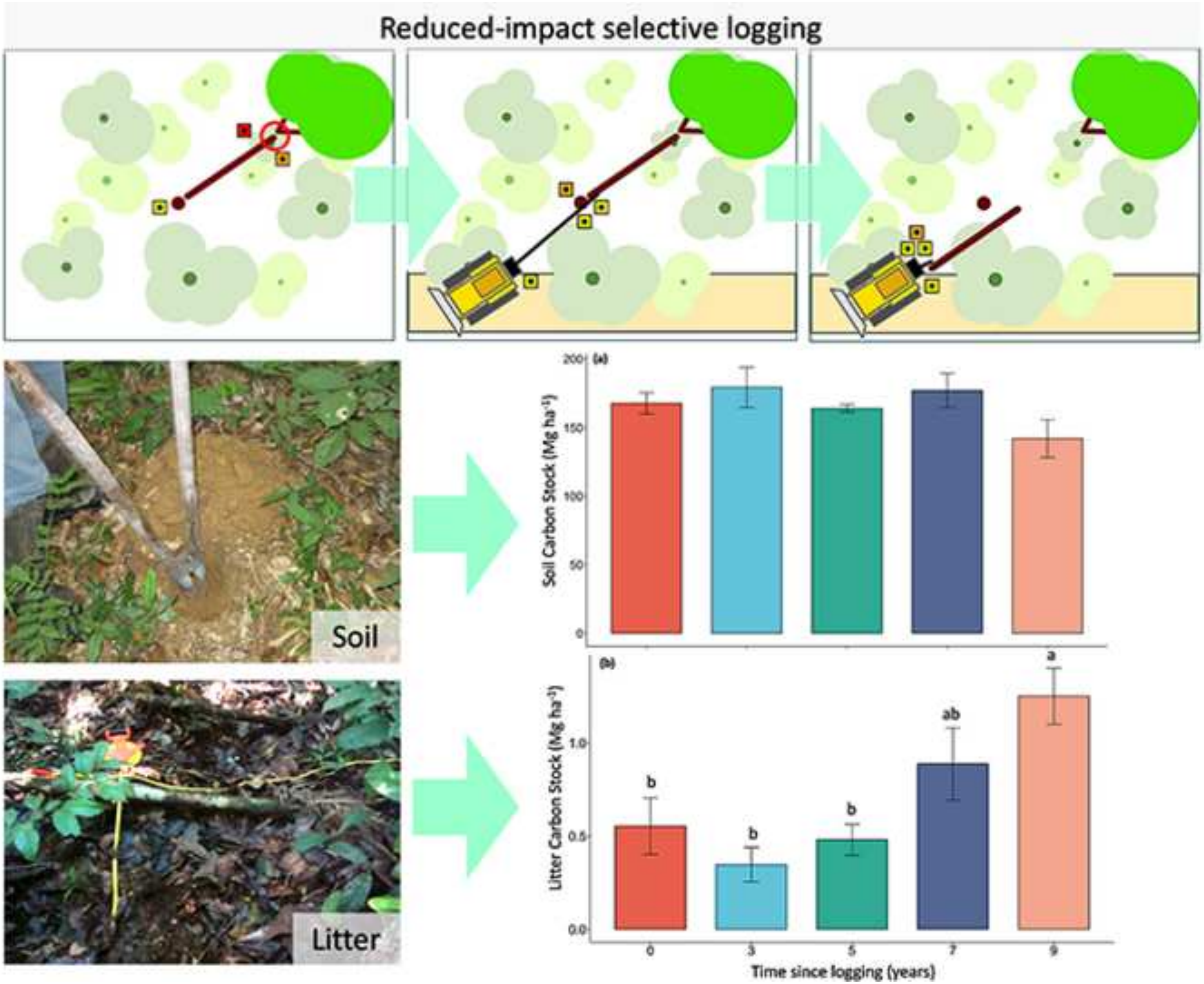
*Graphical Abstract



Highlights (for review : 3 to 5 bullet points (maximum 85 characters including spaces per bullet point)

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Highlights

- Soil carbon stocks were not affected by reduced-impact logging in central Amazonia
- Litter carbon stocks increased with time since logging
- Not litter nutrient contents but nutrient ratios varied with time since logging
- Single harvesting cycle of reduced-impact selective logging caused minimal effect on soil and litter biogeochemistry

Using soil and litter biogeochemistry to assess the effects of reduced-impact logging on central Amazonian forests

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Abstract

In this study, we quantify the impacts of reduced-impact selective logging operations on forest health (assessed using 13 litter and 16 soil biogeochemical parameters) in the Brazilian Amazon. We selected one unlogged and four logged primary forests under a sustainable forest management plan at Precious Woods Amazon (PWA), central Amazonia. The logged forests were selected to establish a chronosequence spanning 9 years since logging and to evaluate the responses to logging in a total of 15 permanent plots, three per logged and unlogged forest. In each plot, composite standing litter samples were collected in subplots and soil samples taken at three depths: 0-10, 10-30 and 30-50 cm. A multivariate Principal Component Analysis was used to partition the variance of soil and litter data based on time since logging. The first two components (i.e. multivariate axes) of the analysis each explained 73% and 68% of soil and litter data variability, respectively. Soil texture and organic carbon (C) content were the most important soil variables while nitrogen (N), phosphorus (P), C:N ratios and C stock were the most important in the litter layer. A hierarchical classification dendrogram shows clear separation of two distinct groups on the basis of time since logging. As expected, soil and litter variables where most different amongst forests at the two end members of the chronosequence (i.e., 3 and 9 years). Our findings suggest that the current methodology for reduced-impact selective logging employed at PWA in central Amazonia has a small but significant effect on soil and litter biogeochemistry. Part of that effect, however, diminishes over time and becomes statistically insignificant nine years after logging. Time since selective logging should be considered in future models and management efforts aimed at assessing nutrient cycling recuperation after logging operations in tropical forests.

Keywords: Amazon forest; disturbance; forestry; harvesting; sustainability; tropical soils.

Introduction

Tropical forests store over half of the C (470 ± 93 Pg C) of Earth's forests (Lewis et al., 2015) and provide ecosystem services worldwide, which include the regulation of nutrient cycles (Vitousek et al., 2008). Most tropical forests are managed in a way that is not considered sustainable, but some are managed on the basis of a sustainable forest management plan-SFMP approved by international standards (FAO, 2010). The main purpose of SFMPs is to provide sustainable management guidelines that will ensure the maintenance of healthy forests while also allowing for the use of wood and non-wood products for future generations (Canova and Hickey, 2012; Sasaki et al., 2012). In tropical countries, SFMPs could provide a path for balancing conservation goals with increasing demand for wood and other forest products while, at the same time, preserving the livelihood of rural communities and indigenous population in compliance with national forest regulations. Notably, tropical forests lacking SFMPs are subject to more illegal deforestation and conversion to agriculture and cattle ranching than their SFMP-managed counterparts (MacDicken et al., 2015). For this reason, the expansion of SFMP programs is regarded as an important step towards achieving local sustainability while also contributing to regional and global conservation and climate change mitigation goals (e.g., Reducing Emissions from Deforestation and Forest Degradation) (Sist and Ferreira, 2007).

Encompassing most of the Amazon forest and holding the third position in tropical wood production (ITTO, 2019), Brazil does not yet sustainably manage its tropical forests. Nearly 20% of Brazilian Amazonia has been cleared for pastures and agriculture and, among the 25% of the remaining forest that is dedicated to wood production (Blaser, 2011; Instituto Nacional de Pesquisas Espaciais, 2019), only few forests currently have SFMPs (Humberto et al., 2016). Generally, SFMPs in the Brazilian Amazon use reduced-impact selective logging operations (i.e., harvest intensity between 17 and 20 m^3 ha^{-1} yr^{-1}) to harvest marketable trees from primary forests. Due to marketability of wood from only a few tree species, logging typically selects from a range between 38 and 70 tree species that have high wood value to internal and external (i.e., Europe and U.S.A) markets (Dykstra et al., 2002). Given that only marketable trees with diameter at breast height (DBH) ≥ 50 cm are harvested within a 35-year cycle in this type of SFMPs in Amazonia and that future harvest cycles are expected to rely on forest natural regeneration (Pinho et al., 2009) of Amazonian forests that support 190 to 300 tree species ha^{-1} (ter Steege et al., 2013), reduced-impact selective logging provide a concrete path for decreasing perturbations of C and nutrient cycles.

Amazon forest structure and dynamics are strongly related to physical and chemical edaphic conditions (Quesada et al., 2009) which should be resilient to the generally low impact of preharvest tree selection and vine cutting, directional felling, and planned extraction skid trails and log decks (Mello-Ivo and Ross, 2006; Miller et al., 2011). Therefore, the regeneration of marketable tree species can be sustained by ensuring that pre-harvest C levels and nutrient cycles are maintained (Fredericksen and Mostacedo, 2000; Silva et al., 2015). Because of heavy machinery transiting on managed forests, even logging operations that aim to sustainably harvest four trees per hectare can disturb biogeochemical cycles of important elements (e.g, C, nitrogen—N and phosphorus—P). This can happen through soil compaction and changes in available pools and stocks, besides less well-known changes in microbial composition and functional diversity. Previous studies have investigated the ecological consequences of logging on soil and litter properties (da Silva Lopes et al., 2011; Ferreira et al., 2004, 2002; Hirai et al., 2012; Mello-Ivo and Ross, 2006). However, assessments of the biogeochemical consequences of reduced-impact selective logging operations are scarce. As a result, large uncertainty exist regarding the effects of logging operations on soil and litter biogeochemistry and, in turn, on forest regeneration and health (Neves et al., 2001; Reichert et al., 2007).

The main objective of this study is to assess forest health using several litter and soil biogeochemical parameters measured in unlogged forests and in forests subjected to reduced-impact selective logging, representing a chronosequence of time since logging from three to nine years. Given reduced-impact selective logging has been considered by some to produce little effect on forest structure, composition and dynamics (Dekker and de Graaf, 2003), we hypothesize that selective logging does not significantly affect litter and soil C and nutrient pools relative to unlogged (control) stands. To test this hypothesis, we focus on the following questions: (i) how does litter and soil biogeochemical parameters (i.e., carbon and nutrient concentrations and stoichiometry) change in response to selective logging?; and (ii) how does litter and soil carbon stocks change as a function of time since selective logging?

Methods

Site description

The study was conducted in logged and unlogged upland (*terra firme*) forests owned by Precious Woods Amazon (PWA), a sustainable forest management and wood processing company operating in the Brazilian State of Amazonas since 1996. PWA's forest management area comprises ~ 150 thousand ha, and about 67% of the total area (2° 43' and 3° 07' S, 58° 31' and 58° 57' W, Fig. 1) are currently managed (Precious Woods Amazon, 2011). According to Köppen's Climate Classification System (Kottek et al., 2006), PWA falls within Amw (Tropical Monsoon Climate), with o2,200 mm mean annual rainfall, 26°C mean annual temperature and 80% mean relative air humidity. Soils at the study site are classified as *Latossolos Amarelos* (Oxisols) and *Argissolos Vermelho-Amarelos* (Ultisols) (Santos, 2013). Dense Ombrophilous Forest is the main type of vegetation at PWA (Instituto Brasileiro de Geografia e Estatística, 2012).

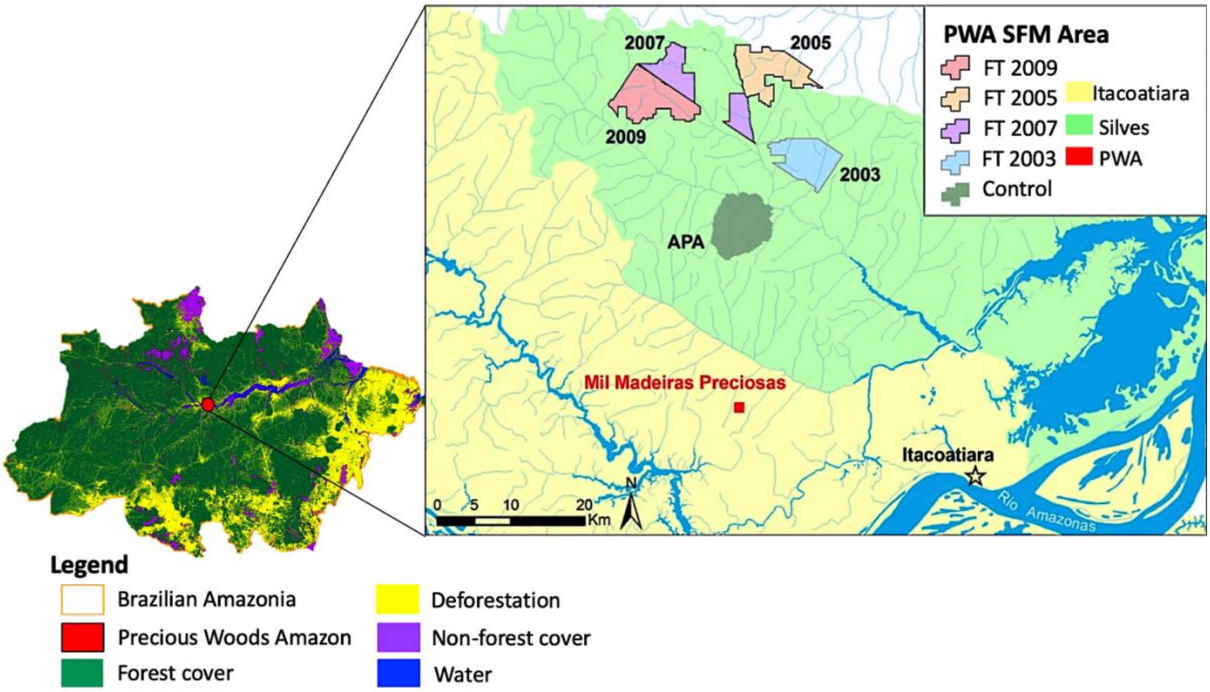


Fig. 1 Map showing the location of Precious Woods Amazon in central Brazilian Amazonia (left of figure) and its Sustainable Forest Management (SFM) area (right of figure). The colored patches on PWA's SFM area map followed by numbers denote forest tracts (FTs) logged in 2003, 2005, 2007 and 2009. APA is an Environmentally Protected Area, which is an unlogged forest stand used as control in this study. Composite soil and standing litter samples were collected from the five forest stands shown in the map.

Forest management and logging operations

PWA is certified by the Forest Stewardship Council (FSC) since 1997 and by the Programme for the Endorsement of Forest Certification (PEFC) since December 2017 (Precious Woods Amazon, 2017). Certification covers forestry processes as well as operational timber production, trading, and the handling of social and environmental demands in the context of tropical forest management. PWA's sustainable forest management is polycyclic, characterized by low-intensity selective logging operations and natural regeneration of the logged forest (FAO, 2011).

Reduced impact selecting logging activities at PWA consider 35-year harvesting cycles and mean allowable cut of 17 m^3 ha^{-1} yr^{-1} (nearly four trees ha^{-1}). Within each forest tract (FT), following directional felling, trees are slashed (i.e. cut into lengths) and dragged by a D6 bulldozer cable to the skid trail (i.e., pre-winching stage). Then, logs are dragged by the wheel skidder, which circulates only on skid trails, to the log decks where labeling and volume determination happen before loaded into trucks and transported to the company's sawmill (Precious Woods Amazon, 2011). The harvested logs are processed into sawn timber, planed timber, construction piles, and finished products at the company's own factory. The final products are exported to Europe, United States, and Asia as well as sold on local markets (Precious Woods Amazon, 2011).

Sample Collection

Soil and standing litter samples were collected in four upland (*terra firme*) logged FTs and in one unlogged upland forest in February 2012, rainy season in central Amazonia (Fig. 1). To represent a chronosequence of time since logging, the FTs selected for this study were logged in 2003, 2005, 2007 and 2009. In each FT and unlogged forest, soil and standing litter were sampled within three permanent plots (100 m x 50 m) previously established by PWA, in a total of 15 plots (3 plots x 5 forests). All plots were systematically chosen according to the shortest distance to the main road due to access constraints. The selected permanent plots in all FTs were logged following PWA standards and are periodically surveyed to monitor forest regeneration and tree growth and to compare to those parameters in the unlogged forest. Approximately 10% of the plot area was affected with logging activities such as gaps and skid trails, among others (Precious Woods Amazon, 2011).

Within each plot, soil and standing litter samples were collected at three sampling points diagonally positioned across the plot. At each sampling point, a 0.5 m x 0.5 m subplot was established for standing litter collection, which included senesced leaves and small branches, but avoided large branches. Standing litter samples collected at each sampling point were combined into a composite sample per plot, in a total of 45 composite samples (3 samples x 3 plots x 5 forests). Following litter sampling, soil samples were collected at three depths: 0-10 cm, 10-30 cm and 30-50 cm, and samples per depth were combined in a total of 45 composite samples (3 depths x 3 plots x 5 forests). Soil cores (77.72 cm^3) were also taken at the same soil depths for bulk density (BD) and gravimetric water content determination. All fresh soil samples were weighted immediately after sampling and later dried at 105 °C for oven-dry weight (g) gravimetric water content (%) determination. Soil BD was calculated as the ratio between soil dry weight at 105 °C (g) and core volume (cm^3).

Soil analyses and calculations

The following soil measurements were conducted: pH in H_2O (2:1), phosphorous (P) availability (Mehlich-1), exchangeable calcium (Ca^{2+}), exchangeable magnesium (Mg^{2+}), available potassium (K^+), exchangeable aluminum (Al^{3+}), sulfur (S), potential acidity ($H^+ + Al^{3+}$), sum of bases, cation exchange capacity (CEC) at pH 7, soil organic matter (SOM) and total organic carbon (SOC), calculated as: SOM = SOC * 1.724 (Walkley and Black, 1934). Soil samples were analyzed by *Soloquimica* Laboratory (Brasília, Brazil) following (Teixeira et al., 2017). Soil organic C stock (OCS, Mg ha^{-1}) was calculated as: OCS = (SOC * BD * d)/10, where SOC is organic carbon at a given content soil depth (g kg^{-1}), BD is bulk density (g cm^{-3}), and d is thickness of the soil layer (cm) (Usuga et al., 2010). All soil variables are listed in Tables A1 and A2.

Litter analyses and calculations

Fresh standing litter samples were weighed immediately after sampling for wet weight determination. After the field work was completed, samples were oven-dried at 50°C for 48 hours for oven-dry weight determination. Dry samples were mechanically ground using a 60 mm mesh and chemically analyzed for total nitrogen-N, C, P, Ca, Mg, K, and S contents at

Soloquimica Laboratory (Brasília, Brazil) following (Teixeira et al., 2017). Standing litter biomass was scaled up to Mg dry weight ha^{-1} using the oven-dry weight values (g) per 0.25 m^2 subplot. Litter C stocks (Mg C ha^{-1}) were calculated as litter C content (g kg^{-1}) * litter biomass (Mg dry weight ha^{-1}) / 1000.

Statistical analysis

The Shapiro-Wilk test was used to verify data normality and log transformations were performed when $p \geq 0.05$ or $W \geq 0.95$ was not met. Linear regressions and ANOVAs were used to evaluate the effect of time since logging (0, 3, 5, 7 and 9 years) on litter parameters, and both time since logging and depth (0-10, 10-30 and 30-50 cm) on soil parameters. Mean values were compared by least squares means adjusted for Tukey's HSD test at 95% significance level. Since the composite soil sample from one plot in FT 2003 showed significantly higher sand and available P contents, it was removed from all statistical analysis to better detect differences in soil carbon and nutrient contents among forests with similar clay contents.

Principal Component Analysis (PCA) – Separate PCA analyses were run (function *prcomp*, package *stats*) for both soil and litter parameters to ordinate the logged and unlogged forests with respect to the main drivers of variations in soil and litter. First, preliminary soil and litter PCAs were run separately, using matrices of standardized variables so that the most important variables could be selected for a final PCA. In the preliminary soil PCA low eigenvalues (< 1.0) (Peña-Claros et al., 2012) were found for all variables except for clay, sand, P, Ca, CEC, TOC, OCS and moisture content, which were used in the final PCA and further post-hoc Cluster Analysis. The same procedure was conducted for the litter data whose final matrix included C stock, Ca:Mg, N:P, C:N and C:P ratios, P, N, K and litter biomass.

Hierarchical Cluster Analysis (HCA) – Hierarchical cluster methods produce a hierarchy of clusters, ranging from small clusters of very similar items to larger clusters of increasingly dissimilar items. A dendrogram was generated to classify logged and unlogged forests in groups sharing similarities with the measured soil and litter parameters (function *hclust*, package *stats*). Euclidean distance and Ward grouping methods were used to combine both final soil and litter matrices (Mérigot et al., 2010). Function *eclust* (package *factoextra*) was used for HCA visualization. Package *NbClust* and Euclidean distance were used to select the ideal number of clusters. Cophenetic correlation coefficient (function *cophenetic*) was used as grouping significance and 0.7 was the threshold value indicating a reasonable correspondence between the dendrogram and the data matrix (Sokal and Rohlf, 1962). All statistical analyses were performed in R 3.3.2 software (R Core team, 2015).

Results

Soil biogeochemistry in logged and unlogged forests

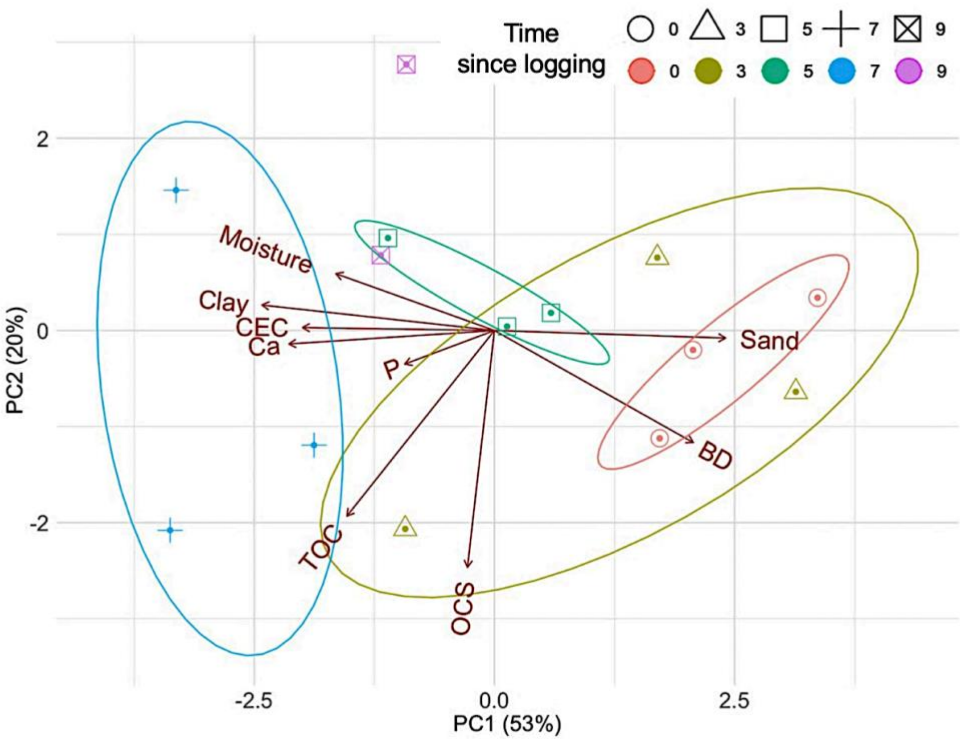


Fig. 2 PCA biplot of the most important soil biogeochemical properties (0-50 cm) of the studied unlogged and logged forest tracts—FTs (three plots per forest), grouped according to time since logging: 0 = unlogged, 3 = FT logged in 2009, 5 = FT logged in 2007, 7 = FT logged in 2005, 9 = FT logged in 2003 (which presented only two points due to outlier removal).

Soil texture, moisture, fertility parameters and organic C stock were the most important soil properties in the ordination of the studied forests (Fig. 2; Table A3). Soil PCA (components 1 and 2) captured 73% of the total variability across all soil biogeochemical parameters (0-50 cm). In general, soil samples from the same forest tract clustered among themselves except for those from FT 2009 and FT 2005—3 and 7 years post-logging, respectively. Principal component 1 (53% of the variation) ordinated the studied soils with respect to physical properties—texture (clay and sand contents), moisture and bulk density (BD) —and fertility (CEC and Ca availability). Also in principal component 1, FT 2005 (7 years post-logging) soils appeared strongly correlated with moisture while the unlogged forest soils were strongly correlated with sand and BD on the opposite side. Principal component 2, which explained 20% of the variation, was negatively correlated with C content (TOC, -0.56) and stock (OCS, -0.72), closely correlated with FT 2009 and FT 2005 soils.

Although soil physical and chemical properties varied differently across logged and unlogged forests, all soils were highly acidic (pH < 4) and had low fertility low because of low availability of P, Ca+Mg, and CEC (Tables A1, A2). Soil texture (clay and sand contents) and moisture content had little variation across logged and unlogged forests. FT 2009 soils presented the highest clay and moisture contents, and bulk density values. High bulk density values were also found in the control forest and (on average) were not statistically different from those found in FT 2009.

Litter biogeochemistry in logged and unlogged forests

Principal components 1 and 2 of litter PCA explained 68% of the data variability (Fig. 4; Table A4). Litter C-to-nutrient ratios (C:N and C:P) and C stock were the most important variables in component 1 while N, P and N:P ratio were the most important in component 2. Component 1 explained 43% of the total litter data variability and was negatively correlated with C stock and C-to-nutrient stoichiometry. Ca:Mg ratio was positively correlated with component 1 and negatively with C stock, and C:N and C:P ratios. Component 2 explained 25% of the total variability and correlated negatively with N, P, N:P ratio, and positively correlated with litter biomass (Fig. A1).

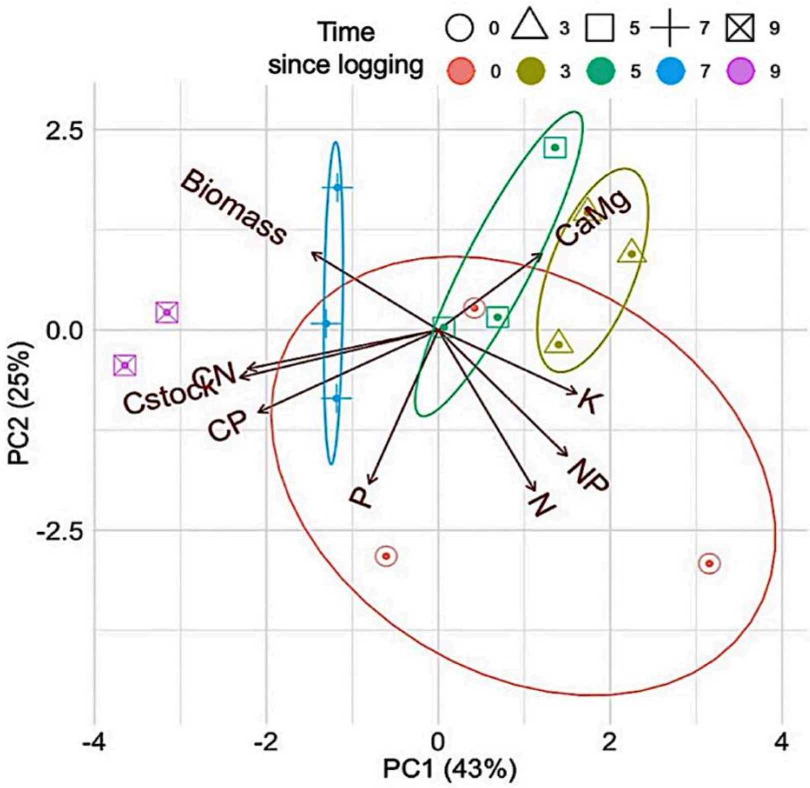
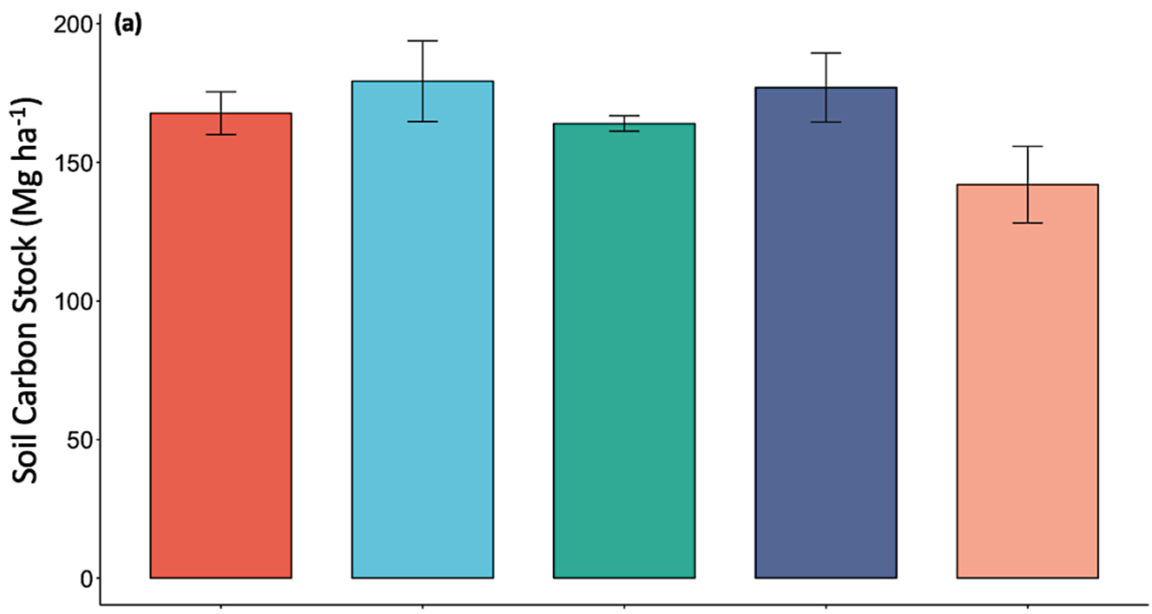


Fig. 3 Principal Component Analysis (PCA) biplot showing the most important litter parameters of the unlogged and logged forest tracts-FTs. Each point represents one plot, in a total of three plots per forest. Data was grouped according to time since logging: 0 = control plots, 3 = FT logged in 2009, 5 = FT logged in 2007, 7 = FT logged in 2005 and 9 = FT logged in 2003. FT 2003 presented only two data points due to removal of one outlier plot.

Small variation was detected in the most important litter parameters across logged and unlogged forests (Table A5). The C:P and C:N ratios were significantly higher in FT 2003 and significantly lower in FT 2009, but none of those forests differed significantly from the control. Total C was significantly higher in FT 2003 (162.4 ± 61.5 g C kg^{-1}) and lower in FT 2009 (67.1 ± 22.8 g C kg^{-1}). Total K was significantly higher in the control (4.21 ± 0.8 g K kg^{-1}) and lower in FT 2003 (2.60 ± 1.2 g K kg^{-1}) and 2005 (2.33 ± 0.3 g K kg^{-1}). The litter variables biomass, total N and P contents, and N:P and Ca:Mg ratios did not vary significantly across forests.

Organic carbon stocks in soil and litter across forests

The calculated soil organic carbon stocks (OCS, 0-50 cm) did not vary significantly across logged and unlogged forests (Fig. 4a). The OCS values ranged from 142 to 179.3 Mg C ha^{-1} in FT 2003 and 2009, respectively. In general, soil OCS values decreased with time since logging, though not significantly. Litter OCS varied significantly across logged and unlogged forests (Fig. 4b). Litter OCS (1.10 ± 0.7 Mg C ha^{-1}) in FT 2003 was the highest among logged forests, also significantly higher than the control (p < 0.05). The OCS in FT 2009 litter layer (3 years since logging) was 0.35 ± 0.2 Mg C ha^{-1}, the lowest among logged and unlogged forests. Overall, litter OCS values increased along with time since logging while no clear trend was verified in soil OCS values across forests.



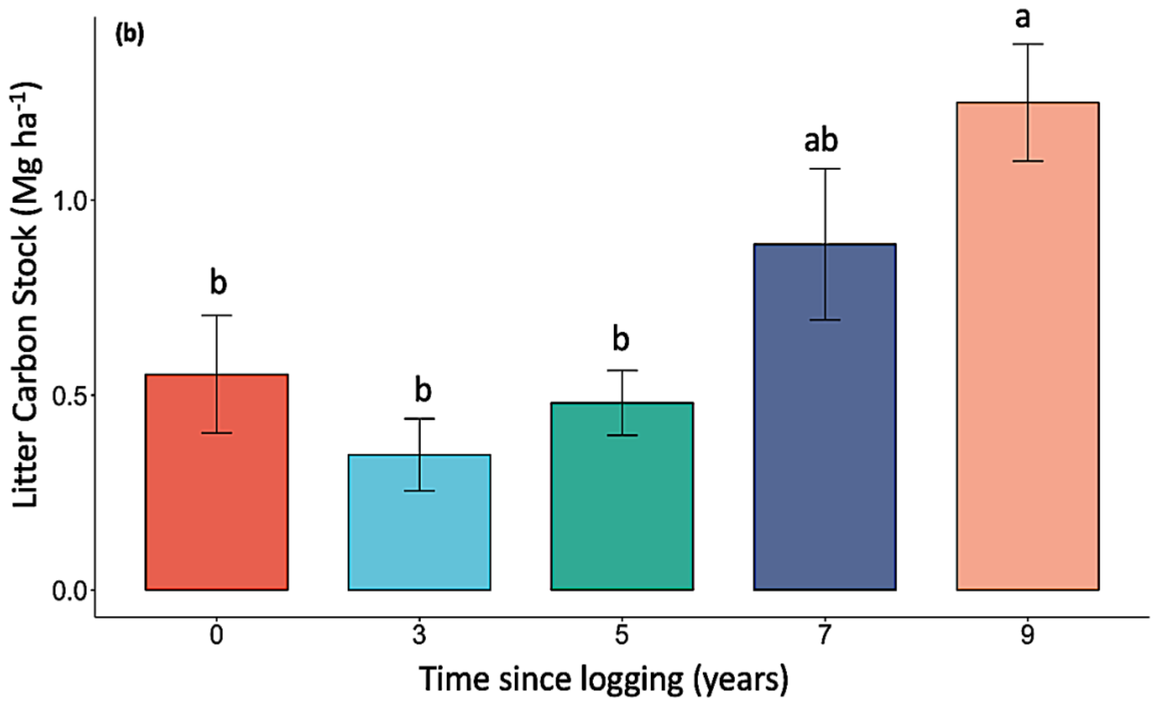


Fig. 4 Organic carbon stocks calculated for **(a)** soil (0-50 cm) and (**b)** litter, Mg C ha^{-1}, in logged and unlogged forest stands at Precious Woods Amazon, Amazonas State, Brazil. All error bars report standard errors and bars report mean values (n = 9) per forest, except for FT 2003 (9 years since logging) which has two plots (n = 6). No significant differences were found between soil carbon stock means. Different letters in litter carbon stock means indicate significant differences by least squares means adjusted for Tukey's test ($p < 0.05$). 0 = unlogged forest, 3 = FT logged in 2009, 5 = FT logged in 2007, 7 = FT logged in 2005, and 9 = FT logged in 2003.

Classification of logged and control stands based on soil and litter traits

The cophenetic correlation coefficient, a goodness-of-fit statistic calculated for the hierarchical classification dendrogram, was 0.89. Values above 0.75 indicate very high correlation between the original similarity matrix and the dendrogram (Fig. 5). The vertical axis of the dendrogram represents the distance or dissimilarity between clusters and the horizontal axis represents the studied forests. Two main clusters merged at Euclidean distance (dissimilarity) 7.5: one including unlogged forests and forests with less time since logging (right cluster) while the other (left cluster) included forests logged after 2009 (except for one plot logged in 2009). Other two clusters merged between 0 and 2.5 Euclidean distance, wherein plots with higher similarity with each other were aggregated. In general, control forests showed higher similarity in soil and litter properties with one forest plot logged in 2009, and plots from the same forest tract appeared close together in the dendrogram.

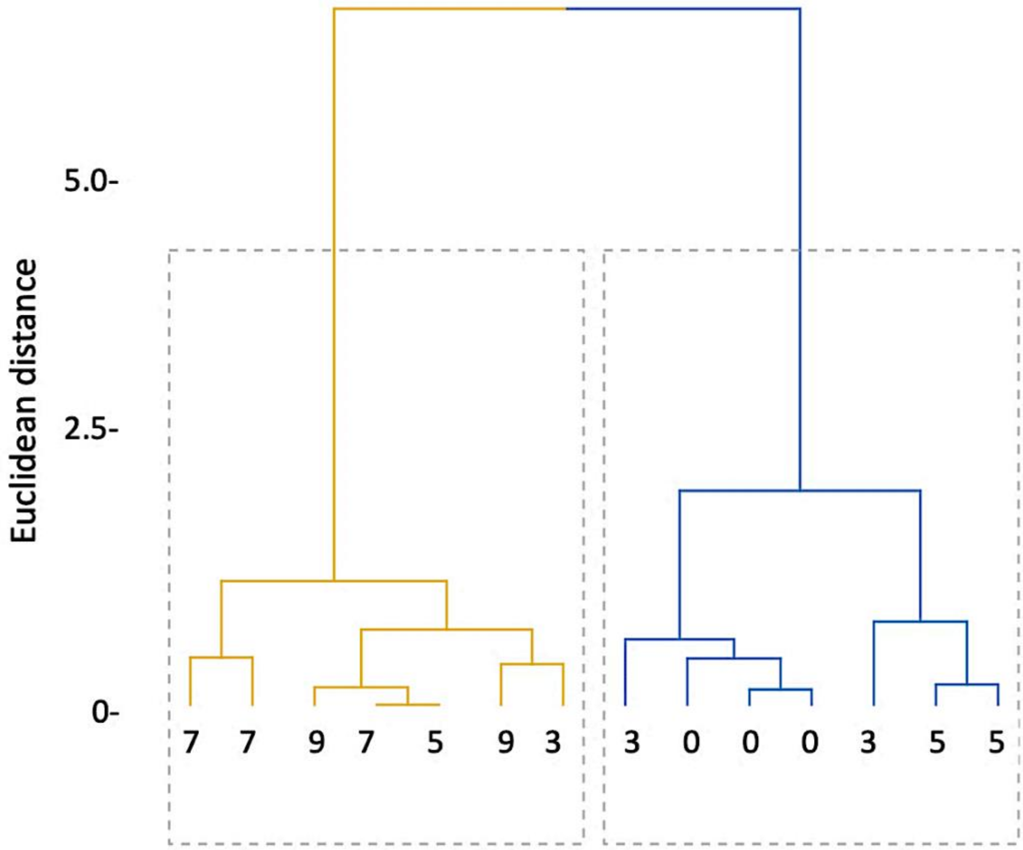


Fig. 5 Hierarchical classification dendrogram using Euclidean distance and Ward grouping method to calculate similarities among forests using a single matrix combining both litter and soil data matrices. The y-axis is the value of the Euclidean distance metric between clusters. Calculated cophenetic correlation of 0.88 and two clusters were indicated by gap statistic method for optimal number of clusters. Numbers on the x axis represent time since logging, where 0 = unlogged forest, 3 = FT logged in 2009, 5 = FT 2007, and 7 = FT 2005, and 9 = FT 2003.

Discussion

Reduced-impact selective logging did not affect soil biogeochemistry

The removal of 12 – 19 m^3 ha^{-1} of selected large (DBH ≥ 50 cm) commercial trees through reduced-impact selective logging in central Amazonian forests did not have a long term (i.e., decadal) effect on soil and litter C and nutrient cycling. Among 16 parameters measured in soil only a few (e.g., clay and sand contents, Ca+Mg, CEC) showed significant differences between logged and unlogged forests (Tables A1, A2), but some of those differences (e.g., CEC, Ca+Mg) diminished over time and became statistically insignificant ~9 years after logging. Overall, forest stands had similar SOM contents in the top 10 cm, ranging from 49.7 ± 2.3 in the unlogged forest to 64.3 ± 15.4 in FT 2005. This range is consistent with values found in other central Amazonian forests (de Oliveira Marques et al., 2017). Soil OCS values did not differ across forests (Fig. 4a), while litter C stock was significantly higher in FT 2003—9 years since logging (Fig. 4b) and, within both groups separated by the hierarchical classification, most logged forests presented high similarity in soil and litter properties with each other. For example, the control forest did not significantly differ from most recently logged forests (3 and 5 years since logging) (Fig. 5). Taken together, these results generally support our hypothesis that selective logging operations do not compromise soil physical and chemical quality.

Significant evidence of the low impact of selective logging comes from high SOM and organic C contents (as well as similar bulk densities) in surface soils of logged and unlogged forests. A key soil quality and forest health indicator, SOM is sensitive to most land use and management practices (Oliveira et al., 2017) and is strongly correlated with inorganic soil attributes, especially in the tropics where soils are typically highly weathered and nutrients tend to be primarily found in organic pools (Brady and Weil, 2017). Besides, the harvest intensity of nearly 4 trees ha^{-1} may have minimized the overall disturbance caused by logging. For instance, conditions in upland mineral soils generally favor fast decomposition, resulting in relatively low soil OCS values. On the other hand, in wetlands and peatlands where anaerobic conditions frequently persist, decomposition occurs at slower pace, and deep layers of organic matter accumulate on top of mineral layers (Davidson and Janssens, 2006).

Changes in litter C stock and nutrient content

Litter C content, C stock K, C:N and C:P were the only litter variables which varied significantly among forests (Table A5). The litter layer of unlogged forests and of forest tracts most recently logged generally showed stronger correlation with nutrients such as N and K and nutrient ratios such as N:P and Ca:Mg, while one unlogged forest plot was highly correlated with P (Fig. 3). On the other hand, FT 2003 (9 years since logging) was highly correlated with litter C stock and C:N and C:P ratios. In fact, an increase in litter C stock was observed with time since logging (Fig. 4b), while no significant change occurred in soil C stock (Fig. 4a). This makes sense since the litter layer is generally more dynamic than the soil, varying both within and between forest ecosystems due to differences in species composition across spatial scales. Thus, litter production is expected to change indirectly with logging operations via changes in forest structure (e.g., stand basal area and stem density) (Almeida et al., 2015). This is expected since forest tree species have distinct leaf chemical contents due to varying requirements for leaf construction and nutrient resorption before senescence, among others (Asner et al., 2011).

Despite substantial differences in litter quality, the main driver of litter decomposition is land-use type (Both et al., 2017). This is consistent with recent findings of land-use-specific C and nutrient cycling in forest ecosystem in the tropics (Bomfim et al., 2019) and elsewhere where litter quality affects litter decomposition, which is the principle pathway for nutrient cycling and transfers of above-ground C to soil, by providing the primary resources for the micro-organisms and detritivores involved in the process (Parton et al., 2007; Paudel et al., 2015). However, unlike those authors we did not find any significant difference in litter N content across forests, although litter C:N ratio varied significantly (Table A5). The low C:N ratio found in the litter layer of FT 2009 can affect litter decomposition (not measured here but see litter biomass in Fig. A1), whose rates are highly variable and linked to the quality of organic material—high when the C:N ratio is low and decomposers are not N limited and low when C:N is high (Sylvia et al., 2005). This change in litter quality can affect decomposition and trigger or suppress asymbiotic N fixation in the litter layer (Reed et al., 2011). The internal recycling of N from litter decomposition provides a key resource for ecosystem productivity, especially since estimates of biological N fixation in lowland tropical forests across the Amazon basin are low (Nardoto et al., 2014). Those authors suggest that a tighter cycling of N in those forests, through litter deposition, decomposition, and mineralization through soil organic matter may suffice plant N demand.

Total annual litterfall production for *terra firme* forests averages 4.4 Mg C ha^{-1} $year^{-1}$ and there is no or little difference in total fine litter production with soil type (Buscardo et al., 2016). In this study, standing litter C in the unlogged forest was 137.0 ± 78.8 g kg^{-1} and litter C stock was 0.55 ± 0.4 Mg C ha^{-1} (Table A5), nearly 13% of the estimated total annual litterfall production in the same vegetation type in the Amazon basin (Buscardo et al., 2016). Also, nutrient concentration and stock in the litter layer vary as a function of vegetation type, population density, individual species ability to absorb, use and redistribute nutrients, natural habitat and tree age (Buscardo et al., 2016). Notably, the successional status of each forest may affect litter nutrient content as well as the species composition, which affect nutrient cycling within each forest (Vitousek and Sanford, 1986).

Sustainability of reduced-impact selective logging may depend on the dynamics of the forest litter layer. It has a crucial role on the sustainability of forest productivity (Sanches et al., 2008) because it shapes the structure and biogeochemical function of forest communities by regulating the amount and quality of litter inputs (Paiva et al., 2015). Litter deposition and litter-to-soil nutrient transfer help maintain nutrient cycling and surface soil fertility (Gartner and Cardon, 2004; Vitousek, 1984; Vitousek and Sanford, 1986). Forest canopy openness can increase due to road and skid trail construction and tree felling thus affecting microclimate and luminosity within the forest (Broadbent et al., 2008). In turn, this may alter the rate of litter decomposition in logged forests (Gartner and Cardon, 2004), although some studies have found no significant difference between primary and secondary Amazonian forests (Barlow et al., 2007). If litter decomposition, a key ecological process in tropical forest ecosystems, is altered so that the accumulation of litter biomass on the forest floor is significantly diminished, vegetation succession can be jeopardized. This could happen as a result of changes in seed germination and seedling survival, which rely on litter biomass via protection from direct sunlight (Martins and Rodrigues, 1999). Indeed, litter decomposition has been recently found to be slower in a selectively logged forest compared to an old-growth forest in Borneo (Both et al., 2017).

Broader Impact

Amazonia plays an important role in the global C cycle due to its large extent, its relatively high C density and undesirable high deforestation rates (Cerri et al., 2007). The enlargement of the agricultural frontier, which causes deforestation and is associated with illegal wood supply, continues to be a limiting factor to the promotion of forest management plans in the Amazon. Thus, reduced-impact selective logging has been considered an important tool in reducing deforestation rates in many tropical forests including those in the Brazilian Amazon (Schwartz et al., 2012). For instance, PWA's sustainable use of the forest generates a source of income for the local population, which in turn contributes further to the protection of the forest. Besides, after 20 years of sustainable forest management in the broader Amazonia, PWA reports annual growth of 4 m^3 ha^{-1} in sustainably managed forest productivity was four times higher than in unmanaged forests (1 m^3 ha^{-1}) (Precious Woods Amazon, 2017). However, PWA is still economically dependent on the export markets and therefore on long-term partnerships in their traditional European and increasingly also Asian countries (Precious Woods Amazon, 2011).

Conclusion

Our findings suggest that reduced-impact selective logging employed at PWA in central Amazonia has minimal effect on soil and litter biogeochemistry, at least in a single harvesting cycle. Given the same reduced-impact logging scheme was conducted in all forest tracts and that harvesting intensity was also similar throughout, time since disturbance was expected to evince differences in soil and litter biogeochemical parameters among logged forests and between those and the unlogged forest. While only a few soil variables differed significantly between unlogged and logged forests, higher variability was found in the litter layer but mostly amongst logged forests. Therefore, time since selective logging should be considered in future models and management efforts aimed at assessing nutrient cycling recuperation after logging operations in tropical forests. Detailed information on the influence of logging on the distribution and structure of plant populations and in nutrient processes is fundamental for a sustainable logging system to be developed. Importantly, reduced-impact selective logging can alter the distribution of resources (light and soil factors), modifying the performance of seedlings and impacting the natural regeneration of the forest which is vital to provide wood for future harvest cycles.

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