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Litter and soil biogeochemical parameters as indicators of sustainable logging in Central Amazonia

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ABSTRACT

One-fourth of Brazilian Amazonia is managed for timber production, but only a few logging sites follow sustainable forest management plans (SFMPs). Amazon forests without SFMPs are susceptible to deforestation because such plans integrate the use of forest products and conservation goals by allowing selective wood extraction following regulations. It remains uncertain whether reduced-impact selective logging (17–20 m^3 ha^{-1} yr^{-1} of 38–70 species), typical of SFMPs, changes forest regeneration, carbon (C) stocks, and nutrient cycling. Here, we tested the hypothesis that litter and soil biogeochemical parameters serve as indicators of sustainable logging as forest regeneration, C stocks, and C-to-nutrient ratios in soil and litter become similar to those in primary forests as time elapses after logging. We used a chronosequence spanning nine years since logging to relate litter and soil (0–10, 10–30, 30–50 cm) C stocks and 12 and 15 biogeochemical parameters, respectively, canopy cover and tree seedling density (10–150 cm tall) in sustainably managed upland evergreen Amazon forests. In one unlogged and four logged stands sampled three, five, seven, and nine years after logging, we compared 15 permanent plots (three replicated 0.5 ha plots per time-since-logging category). Five biogeochemical parameters explained >80% of the variation in soil and litter among logged and unlogged stands. Litter parameters were more sensitive to logging than soil parameters, where litter C stocks and C-to-nutrient ratios increased systematically after logging. Canopy cover decreased over time and was ~14% lower nine years after logging. Total seedling density did not change consistently over time but was ~54% higher seven years after logging. Our data suggest that the SFMP guidelines have served the purpose of maintaining soil quality and forest regeneration. Litter and soil parameters can be useful indicators of sustainable forest management in upland evergreen forests in Central Amazonia.

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1. Introduction

Tropical forests play a crucial role in regulating Earth's climate (Le Quéré et al., 2015), but only a few forests in the tropics follow certified sustainable forest management plans-SFMPs (FAO, 2010; Kraxner et al., 2017). Typical SFMP guidelines integrate the use of timber—and non-timber—forest products while maintaining healthy forests (Burivalova et al., 2017; Canova and Hickey, 2012; Putz et al., 2012; Sasaki et al., 2012), conservation goals, and social justice (de Toledo et al., 2017) by allowing wood extraction following existing regulations. Tropical forests without SFMPs are more susceptible to illegal logging and conversion to monocropping systems than their SFMP-managed counterparts (MacDicken et al., 2015). For this reason, expanding and improving SFMPs (Piponiot et al., 2019) is necessary to achieving local sustainability while simultaneously contributing to regional and global conservation and climate change mitigation goals (e.g., REDD+; Laurance et al., 2014; Sist and Ferreira, 2007).

Brazil encompasses approximately 60% of the Amazon forest and is third in global tropical timber production (ITTO, 2019), but does not sustainably manage its Amazon forests. Minimal SFMPs are underway across 25% of the Amazon forest area managed for timber production (Blaser, 2011; Humberto et al., 2016; INPE, 2019). Typical SFMPs include reduced-impact selective logging operations to harvest a selective number of marketable tree species possessing high wood value from primary forests (17–20 m^3 ha^{-1} yr^{-1} of 38–70 species; Dykstra et al., 2001). Also, only marketable trees whose stem diameter at breast height (i.e., the diameter at 1.3 m above the ground surface) ≥ 50 cm are harvested within a 35-year cycle in this type of SFMP. Given future harvest cycles rely on the natural regrowth of Amazon forests (Pinho et al., 2009) that support 190 to 300 tree species ha^{-1} (ter Steege

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et al., 2013), reduced-impact selective logging provides a concrete path for decreasing impacts on carbon (C) and nutrient cycles.

After the first harvest, logging cycles in SFMPs rely on projections of natural forest regrowth decades in advance. It remains uncertain, however, whether selective logging leads to changes in C and nutrient cycling, which could limit the natural regeneration of logged stands. For instance, periodic harvests of 20 m^3 ha^{-1} in Amazon forests have been projected as not recovering with 30-year harvest cycles (Piponiot et al., 2019). However, variation in site-specific recovery rates exists coincident with variations in geology and, consequently, soil fertility along the east-west gradient (Quesada et al., 2012). Shorter harvest cycles (11–17 years) were indicated for two marketable species in Southern Amazon (de Miranda et al., 2018). Therefore, site fertility and disturbance history (Both et al., 2019; Longo et al., 2016; Quesada et al., 2012) can modulate natural forest regrowth as a function of C and nutrient cycling (Baribault et al., 2012; Breugel et al., 2011; Figueira et al., 2008; Miller et al., 2011). For example, stable soil parameters (e.g., texture) can modulate shifts in nutrient availability (Brady and Weil, 2017), which tends to increase immediately following tree harvesting and gap opening.

The primary goal of this study was to assess the impact of selective logging under SFMP on forest regeneration and litter and soil biogeochemistry in evergreen forests in Central Amazonia. Specifically, we quantified C stocks and other 12 and 15 biogeochemical parameters in litter and soil, respectively, as well as canopy cover and tree seedling density using a chronosequence spanning nine years since logging. We tested the hypothesis that litter and soil biogeochemical parameters serve as indicators of sustainable logging. Our assessment is based on canopy cover and tree seedling density, C stocks, and C-to-nutrient ratios in the soil and litter layer, which we expected to become more similar to those of unlogged stands as time elapsed following logging. We focused on the following questions: (i) Do seedling density and canopy cover vary with time since logging? (ii) Do litter and soil C stocks change with time since logging? (iii) Which litter and soil biogeochemical parameters (e.g., C, nitrogen-N, phosphorus, calcium, magnesium) best explain differences in litter and soil between forest stands over time? We hypothesized that: (H_1) seedling density will be higher in recently logged forests and will negatively correlate with canopy cover; (H_2) soil and litter C stock, and (H_3) litter C-to-nutrient ratios (e.g., C:N) will be higher in recently logged forests, decreasing with time since logging.

2. Methods

2.1. Site description

We conducted this study in logged and unlogged (control) primary evergreen upland (*terra firme*) forest stands owned by Precious Woods Amazon, a sustainable forest management and wood processing company operating in the Brazilian State of Amazonas since 1996 (Fig. 1; Tables 1, A1). Precious Woods Amazon's forest management area comprises ~150 thousand hectares, where approximately 67% are currently managed (Fig. 1; Precious Woods Amazon, 2011). Each studied stand comprised an area ranging from 4 to 5.6 thousand hectares. The climate at Precious Woods Amazon is characterized as Tropical Monsoon (Kottek et al., 2006), with 2200 mm mean annual rainfall, 26 °C mean annual temperature, and 80% mean relative air humidity. Soils in Precious Woods Amazon's forest management area are predominantly *Latossolos Amarelos* (acidic, yellow Oxisols) and *Argissolos Vermelho-Amarelos* (Ultisols) (Santos, 2013).

2.2. Forest management and logging operations in Precious Woods Amazon

Precious Woods Amazon's 35-year polycyclic timber harvesting includes reduced-impact selective logging (~17 m^3 ha^{-1} yr^{-1} or four trees ha^{-1} of ~45 tree species) followed by natural forest regeneration (FAO, 2011), in compliance with the Forest Stewardship Council and the Programme for the Endorsement of Forest Certification guidelines (Precious Woods Amazon, 2017). Selected trees are directionally felled, slashed (i.e., cut into lengths), and dragged by a D6 bulldozer cable to the skid trail—the pre-winching stage. Logs are subsequently dragged by a wheeled skidder—which only circulates on the skid trails—to decks where they are labeled and have their volume measured before transported to the company's sawmill (Precious Woods Amazon, 2011). There, logs are processed into sawn and planed timber, construction piles, and finished products which are locally marketed or exported to Europe, United States, and Asia (Precious Woods Amazon, 2011).

2.3. Sample collection

In February 2012, we estimated canopy cover, recorded tree seedling density (10–150 cm tall), and collected standing litter (i.e., leaf, miscellaneous, and fine wood litter layer covering the forest floor at the moment of sampling) and soil samples from one control and four once-logged forest stands with three (F3), five (F5), seven (F7), and nine (F9) years since logging took place (Fig. 1; Table 1). In each control and logged stand, we simultaneously recorded measurements and collected samples within 15 (3 plots × 5 forests) permanent plots (100 m × 50 m; 0.5 ha) previously established by Precious Woods Amazon. Plots were systematically chosen to minimize travel distance from the main road due to access constraints. One plot in F9 was located on a different soil type, and, thus, was removed from all our analyses. All selected plots in the logged stands were exposed to logging operations following Precious Woods Amazon's standards and are periodically surveyed to monitor forest regrowth (Table A1; Fig. A1). Approximately 10% of each plot area was affected by logging activities such as gaps and skid trails (Precious Woods Amazon, 2011).

We systematically positioned three sampling points along a diagonal line across each plot (Fig. 1). At each point, we used a 2 m × 2 m subplot to record tree seedling density (number of seedlings/4 m^2) using the following categories: class 1 included seedlings that were 10–50 cm tall, class 2 50.1–100 cm, and class 3100.1–150 cm. We used an inner 0.5 m × 0.5 m quadrat to collect the total amount of litter (i.e., leaf, miscellaneous, and fine wood with diameter < 1 cm) covering the forest floor, totaling 45 samples (3 samples × 3 plots × 5 forests). Litter samples were placed into paper bags, labeled, and carefully processed as detailed below. Soil samples were collected at three depths (0–10 cm, 10–30 cm and 30–50 cm) to calculate carbon stocks in the top 50 cm as influenced by logging history, and because soil properties and their relationships among each other are depth-specific (Goebes et al., 2019). Samples were homogenized by the depth of collection within each plot to account for plot-level differences between stands, in a total of 45 composite samples (3 depths × 3 plots × 5 forests). Soil cores were also taken at the same depths for bulk density (BD) and gravimetric water content determination. Soil samples were placed into sterile plastic bags, labeled, and transported to the headquarters, where BD samples were weighed to obtain total wet weight, and later allowed to air dry along with all other soil samples. After completing the field sampling, all air-dried samples were transported to *Soloquimica* Laboratory (soloquimica.com.br, Brasília, Brazil) for the analyses listed below. BD samples were oven-dried at 105 °C and weighed to obtain total dry weight and gravimetric water content (Table A2). BD (g cm^{-3}) was calculated as the total dry weight of the sample divided by the volume of the core sampler (77.72 cm^3).

Fig. 1

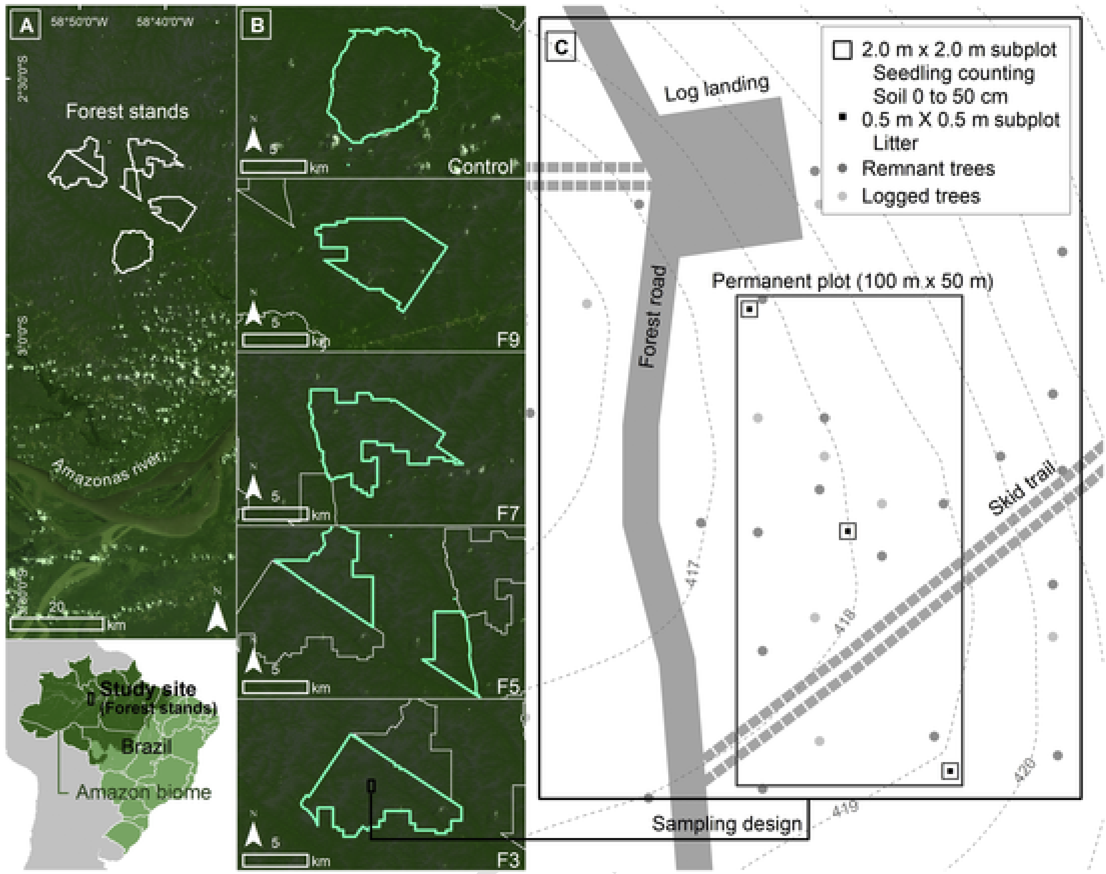

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Table 1
Plot (0.5 ha) structure data including trees ≥30 cm in diameter at breast height (DBH, the stem diameter at 1.3 m above the ground surface) collected by Precious Woods Amazon's forest census team between 2007 and 2009.

Stand ID [a]	Plot ID	Logging year	Logging intensity (m^3 ha^{-1})	Shannon's diversity	Species density	Stem density	Tree basal area (m^2/ha) [d]
F9	P7	2003	12.1	3.0	24	38	111.6
	P6			2.5	19	50	108.0
F7	P2	2005		3.0	23	33	13.2
	P1		17.4	3.3	38	76	15.4
	P3			3.0	23	38	16.6
F5	P8	2007		3.0	23	35	20.2
	P17		13.5	3.3	29	34	13.2
	P19			3.2	28	40	14.6
F3 [b]	P20	2009		3.2	36	74	208.2
	P21		19.1	2.8	23	66	147.2
	P22			3.2	34	77	195.2
Control [c]	PCO1	–		3.4	33	51	19.4
	PCO2		–	3.0	25	40	15.6
	PCO6			3.3	30	52	17.4

[a] Stand F9 is the forest sampled nine years after logging, F7 seven, F5 five, and F3 three, given sample collection happened in 2012. Survey years were 2007, 2008, 2009, 2009, and 2009 for F9, F7, F5, F3, and the control, respectively.
[b] Pre-logging data collected in 2009.
[c] Control is the unlogged primary evergreen upland forest.
[d] Basal area in m^2 = DBH^2 in m/4.

2.4. Canopy cover estimation

We estimated total canopy cover at each sampling point using a spherical crown densiometer following Paletto and Tosi (2009). Four measures were taken with the densiometer held at 1.30 above the ground and oriented in the direction of a different cardinal point, in a total of 45 canopy cover estimates (3 points × 3 plots × 5 forests), each including four cardinal point measures. The spherical densiometer used consists of a concave mirror with 24 (6.35 mm) squares engraved on the surface within each of which we scored canopy closure at four equally spaced points (3.18 mm × 3.18 mm), in a total of 96 dots representing smaller square areas counted within the grid. The number of dots, representing the smaller square areas of canopy openings, was counted up to a total of 96, and the number determined was then multiplied by 1.04 to obtain the percent of the overhead area not occupied by the canopy. We estimated canopy cover percentage as the difference between this percentage and 100%.

2.5. Soil analyses and calculations

The following soil parameters were measured (listed in Table A3): soil particle-size analysis by modified pipette method (Staff, 1993); soil pH determined in H_2O (2:1); available phosphorus (P) by Mehlich-1 extractant; exchangeable calcium (Ca^{2+}) and magnesium (Mg^{2+}) by 1 M KCl extractant and complexometric titration (Pereira et al., 2011); exchangeable potassium (K^+) by 0.05 M HCl extractant and atomic absorption spectroscopy determination; exchangeable aluminum (Al^{3+}) by 1 M KCl extractant and volumetric determination with 0.025 M NaOH and bromothymol blue; sulfur (S) by gravimetric analysis using HCl 1:1, aqueous solution of 1 M $BaCl_2$, and $BaSO_4$ insoluble precipitate measurement; exchangeable acidity ($H^+ + Al^{3+}$) by 1 M KCl extractant; sum of bases = $K^+ + Ca^{2+} + Mg^{2+} + Na^+$; and effective cation exchange capacity (CECe), calculated as CECe = $H^+ + Al^{3+} + K^+ + Ca^{2+} + Mg^{2+} + Na^+$. Total soil organic carbon (SOC, in g C kg^{-1}) was determined by the Walkley-Black chromic acid wet oxidation method and calculated as SOC = soil organic matter content in g kg^{-1}/1.724 (Walkley and Black, 1934). Soil organic C stock, in Mg C ha^{-1}, was calculated as C stock = (SOC × BD × d)/10, where SOC is organic carbon content at a given soil depth in g C kg^{-1}, BD is bulk density in g cm^{-3}, and d is soil layer depth in cm (Usuga et al., 2010).

2.6. Litter analyses and calculations

The fresh litter samples were weighed immediately after sampling to record their wet weight. Then, dry litter weight was determined by oven drying at 50 °C for 48 h. Oven-dry samples were mechanically ground using a 60 mm mesh and sent to *Soloquimica* Laboratory for the following measurements (listed in Table A4). Total nitrogen-N by Kjeldahl digestion (Muñoz-Huerta et al., 2013); organic C by potassium dichromate-sulfuric acid digestion (Shaw, 1959); P by sulfuric acid digestion (Claessen et al., 1997) followed by colorimetric determination (Murphy and Riley, 1962); Ca and Mg by atomic absorption spectroscopy; K by flame photometry, and; S by gravimetric analysis using HCl 1:1, aqueous solution of 1 M $BaCl_2$, and $BaSO_4$ insoluble precipitate measurement. Litter mass was scaled to Mg dry weight ha^{-1} using the oven-dry weight values, in g, per 0.25 m^2 (quadrat area). Litter C stocks, in Mg C ha^{-1}, were calculated as C content in g C kg^{-1} × litter mass in Mg dry weight ha^{-1}/1000.

2.7. 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 mixed models were used to evaluate the (fixed) effect of time since logging—considered a factor—and replicate nested within the plot (random effect) on canopy cover, seedling density, and litter biogeochemical parameters. To evaluate the (fixed) effect of time since logging and depth (0–10, 10–30, and 30–50 cm) on soil parameters, linear mixed models were used considering plot as a random effect. We calculated the conditional (entire model) and marginal (fixed effect) coefficients of determination for the mixed-effect models. Mean values were compared by least-squares means adjusted for Tukey's HSD test at a 95% significance level. Relationships between canopy cover, seedling density, litter, and soil parameters were assessed using Spearman's correlations (r) and multivariate linear models. Given soil sand content and P availability in the samples collected in one plot in F9 was higher ($p < 0.05$), that plot was removed from all statistical analyses.

We conducted separate principal component analysis (PCA) of litter and soil parameters to ordinate the stands regarding the main drivers of variations in soil and litter. Preliminary soil and litter PCAs were run using standardized data matrices to select the critical parameters for each final PCA. In the preliminary litter PCA, low eigenvalues (< 1.0) (Peña-Claros et al., 2012) were found for all parameters except P, K, C, N:P, Ca:Mg, C:N, and C:P, which were included in the final PCA (Table A5) and further post-hoc Cluster Analysis. The same procedure was conducted for soil whose final matrix included clay, sand, CECe, SOC, C stock, S, pH, and BD (Table A6). We produced a hierarchical cluster dendrogram using Euclidean distance and Ward grouping methods to classify the stands in groups sharing similarities based on the PCA-selected soil and litter parameters (Mérigot et al., 2010). The cophenetic correlation coefficient 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).

We used permutational multivariate analysis of variance (PERMANOVA) to partition the soil-litter Euclidean distance matrix among sources of variation and identify which parameters best explain differences among stands. We used Bray-Curtis similarity to classify the stands based on the pre-logging tree species abundance data collected by Precious Woods Amazon (DBH ≥ 30 cm; Table A1; Fig. A4). PERMANOVA was used to test whether the measured litter and soil parameters explain pre-logging species abundance (Mcardle and Anderson, 2001). We used R version 3.6.1 (R Core Team, 2019) for all statistical analyses.

3. Results

3.1. Canopy cover and seedling density

Canopy cover decreased as time since logging increased (F-value = 3.9, R^2_m = 0.3, p = 0.04). Plot-level canopy cover estimates ranged from 97.1 ± 3.0% in the control to 79.7 ± 7.8% in F9 (Table 2; Fig. A2). Approximately 28% of the variation was explained by post-logging age, and 99% was explained by the whole model whose random effect had a non-zero variance, indicating variation among sampling points. Canopy cover correlated positively ($p < 0.05$) with class 3 seedling density (r = 0.24;), litter N content (r = 0.38), litter N:P ratio (r = 0.34), soil BD (r = 0.81), sand content (r = 0.66), and clay content (r = −0.69; Figs. A3 and A4).

Approximately 12% of the variation (R^2_m) in total seedling density was explained by time since logging (fixed effect), and ~92% of the variation was explained by the entire mixed-effect model—which included the random effect of replicate (nested within the plot). Our ran-

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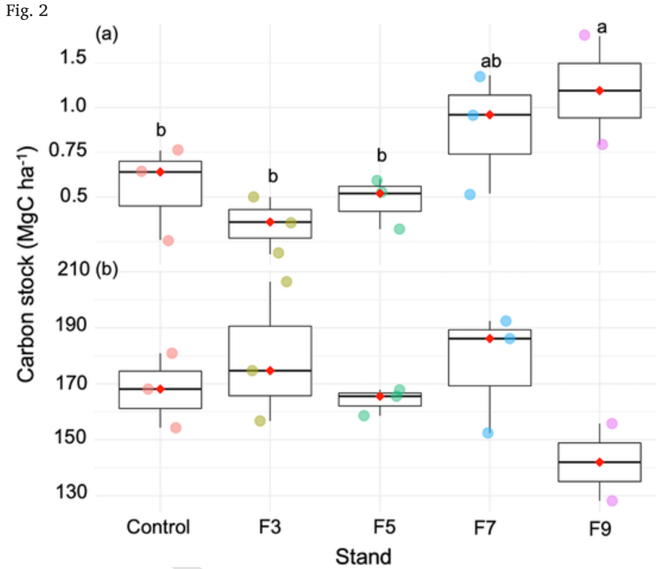
Table 2
Plot-level (average of three sub-plots ± standard deviation) woody seedling density for each height class, where class 1 includes 10–50 cm tall individuals, class 2 = 50.1–100 cm, class 3 = 100.1–150 cm, and total is the total number of seedlings in all height classes recorded within the subplots. Canopy cover represents the in situ estimated percent area covered by leaves using the densiometer method.

Stand ID	Plot ID	Canopy cover (%)	Seedling density (number of individuals/4 m ^{2})			
			Class 1	Class 2	Class 3	Total
F9 [a]	P6	79.7 ± 7.8	6.7 ± 3.5	1.3 ± 1.5	1 ± 1	9.0 ±
	P7	82.2 ± 8.9	5.3 ± 4.0	0	0	5.3 ±
F7 [b]	P2	82.2 ± 8.9	5.3 ± 4.0	0	0	5.3 ±
	P1	88.4 ± 4.5	7.3 ± 6.1	4.3 ± 2.5	2.7 ± 2.1	14.3 ±
	P3	88.7 ± 5.9	7.7 ± 4.6	1.3 ± 2.3	0.7 ± 1.2	9.7 ±
F5	P8	83.6 ± 2.2	5.7 ± 3.0	0.3 ± 0.6	1.7 ± 0.6	7.7 ±
	P17	85.6 ± 13.8	7.0 ± 3.6	2.0 ± 1.0	0.7 ± 1.2	9.7 ±
	P19	91.5 ± 3.1	5.3 ± 5.9	0.3 ± 0.6	0.3 ± 0.6	6.0 ±
F3	P20	90.8 ± 5.7	3.3 ± 0.6	1.0 ± 0.0	0.7 ± 0.6	5.0 ±
	P21	97.1 ± 1.2	8.0 ± 1.7	3.0 ± 1.7	1.7 ± 1.5	12.7 ±
	P22	84.6 ± 13	5.7 ± 3.1	2.0 ± 2.7	0.7 ± 0.6	8.3 ±
Control	PCO1	95.7 ± 4.5	7.0 ± 4.0	1.0 ± 1.0	1.3 ± 0.6	9.3 ±
	PCO2	97.1 ± 3.0	2.3 ± 0.6	1.0 ± 1.7	0	3.3 ±
	PCO3	92.9 ± 6.9	7.3 ± 0.6	1.7 ± 2.1	1.3 ± 1.5	10.3 ±

[a] Significantly lower canopy cover in F9.
[b] Marginally higher total seedling density in F7 (p = 0.1). The density of seedlings in classes 1 and 3 did not vary significantly along the post-logging chronosequence at a 95% confidence level.

Fig. 2



dom effect had a non-zero variance, indicating a variation among sampling points. Stand-level averages of total seedling density had a little variation with time since logging ($p > 0.1$), ranging from 7.7 ± 4.8 in the control stand to 11.8 ± 5.3 seedlings/4 m^2 ($p = 0.1$) in F7 (Table 2). Class 2 density was marginally higher in F7 ($p = 0.09$) and correlated positively ($p < 0.05$) with canopy cover ($r = 0.31$), class 3 density ($r = 0.51$), and litter Ca:Mg ratio ($r = 0.4$; Fig. A2). The density of seedlings in classes 1 and 3 did not vary significantly ($p > 0.1$) with time since logging.

3.2. Litter and soil carbon stocks

Litter C stocks varied with time since logging ($p = 0.06$), whose fixed-effect explained 50% of the variation in the mixed-effects model (Fig. 2a). On average, litter C stock in F9 was the highest among all forests (1.10 ± 0.7 Mg C ha^{-1}; $p < 0.05$), being 50%, ~56%, and ~68% greater than the control (0.55 ± 0.4 Mg C ha^{-1}), F5 (0.48 ± 0.2 Mg C ha^{-1}), and F3 C stocks (0.35 ± 0.2 Mg C ha^{-1}).Stand-level soil C stocks (0–50 cm) ranged from 142 ± 19.5 to 179.3 ± 25.2 Mg C ha^{-1} ($p > 0.1$) in F9 and F3, respectively (Fig. 2b).

3.3. Litter and soil biogeochemical parameters

A PCA of litter parameters explained 74% of the variance on the first two principal components (Fig. 3a). The most robust gradient was defined by variation in C content, C:N, and C:P, whereas the second axis represented a gradient of P content and N:P ratio (Table A5). Plots within the same stands were grouped tightly together, distant from the other stands, and displayed in an increasing post-logging age from the right to the left of the PCA biplot. F9 plots correlated with litter C:N and C:P, which were higher in that stand and lower in F3 but not different from the control. Two F7 plots correlated negatively with N and N:P, one F5 plot correlated negatively with P while the other two clustered in the center of the ordination, and F3 plots strongly correlated with Ca:Mg and K. Control plots appeared more distant from one another compared to logged plots, where one control plot correlated with P, another with N:P and N, and the third with Ca:Mg ratio.

A PCA of soil parameters explained 61% of the variance on the first two principal axes, where soil texture, fertility parameters, C stock, and bulk density were the most important (Fig. 3b; Table A6). In axis 1, fertility parameters—SOC, CECe, and S—defined the most robust gradient, where logged forests overlapped each other except for a few data points (F7 and F9). In axis 2, sand content, bulk density, and C stock, closely correlated with the control and most F3 plots, defined the strongest gradient. Soils in the same stand were generally closely clustered; control soils clustered more closely, while F7 soils showed high variability. Sand content in the top 50 cm of the soil was lower in F7 ($p = 0.01$) and marginally lower in F9 ($p = 0.09$) compared to the control. Surface (0–10 cm) and subsurface (10–30 cm) sand contents did not vary across stands (Table A2). Sand content correlated positively with BD ($r = 0.70$), and negatively with SOC ($r = -0.62$) and CECe ($r = -0.59$; Fig. A4).

3.4. Classification of control and logged stands based on biogeochemical parameters

Two dominant clusters emerged from the classification of control and logged stands based on eight litter and eight soil parameters (Fig. 4). The lower cluster (horizontal axis) included all the control and most recently logged forests, while the upper cluster included F9 and F7 plots. The lower cluster further divided into two clusters: One including the control and two F3 plots—which had higher sand contents, and the other including one F7 plot and F3 and F5. The upper cluster was also further separated into two clusters, including F9 in one and two F7 plots in the other.

Two dominant clusters emerged, dividing the sixteen litter and soil parameters (vertical axis). The rightmost cluster included litter C, P, and C-to-nutrient ratios, as well as soil clay content and CECe. The leftmost cluster included the remaining ten parameters. While soil C content and stock and litter Ca:Mg clustered closely, sand, bulk density, litter K, litter N:P, and soil pH grouped themselves in another cluster. Variation partitioning indicated that five variables explained 82% of the variation in the Euclidean distance matrix, where sand content and litter C:N explained 30% and ~22%, respectively, followed by BD (11%), CECe (10%), and litter Ca:Mg (9%).

Fig. 3

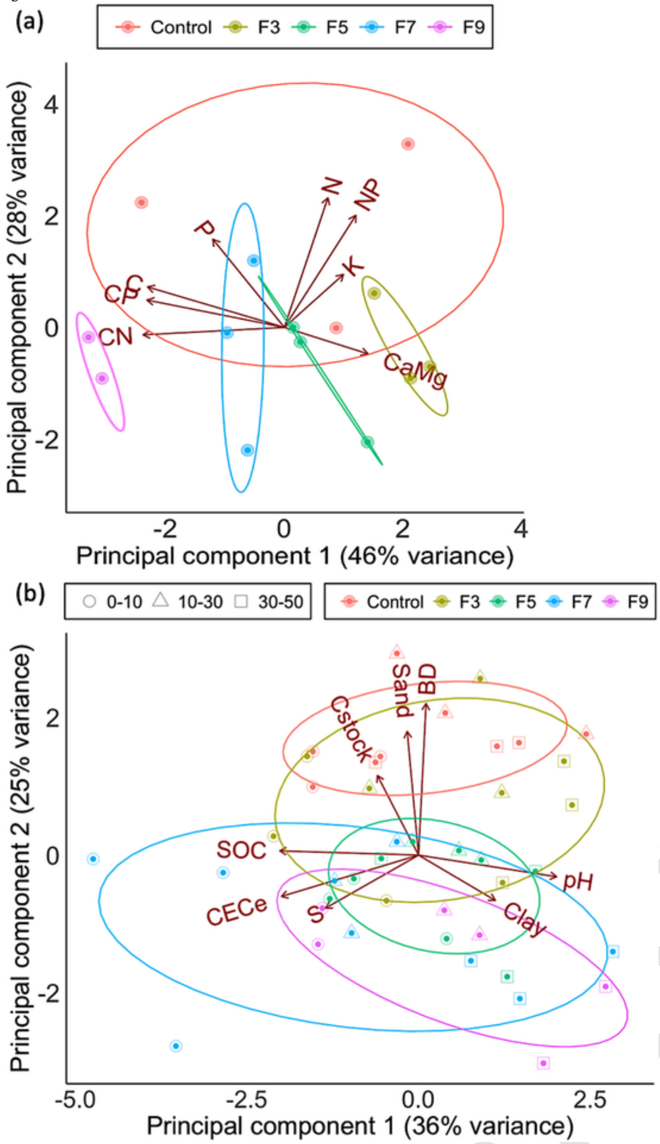
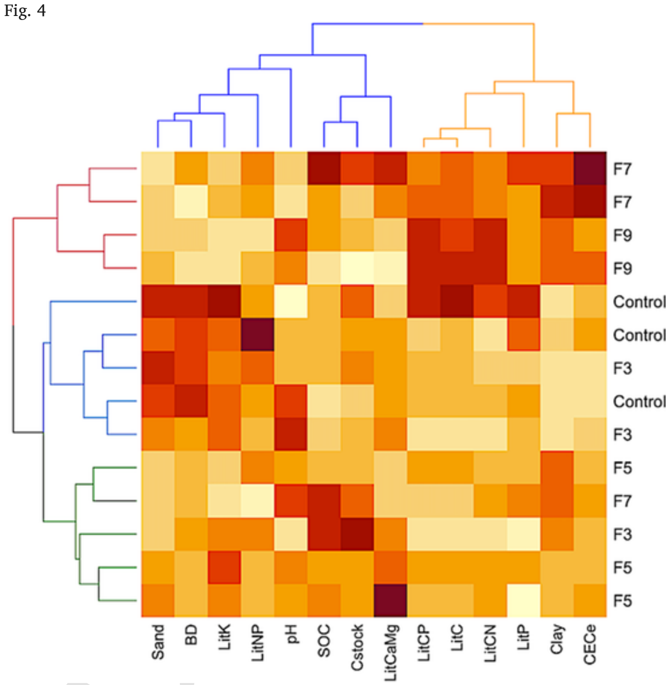


Fig. 4



4. Discussion

Our field observations in unlogged and logged stands provide partial support to our overarching hypothesis that biogeochemical parameters serve as indicators of sustainable logging. Partially contradicting H_1, total seedling density was similar across logged and unlogged stands, corroborating previously published evidence that reduced-impact selective logging appears to maintain natural forest regeneration (Rivett et al., 2016). Also, seedling density did not correlate with canopy cover, which decreased with time since logging. Nevertheless, canopy cover had a weak correlation with the density of taller tree seedlings (100–150 cm), but a robust relationship with soil sand and clay contents. C stocks in the soil had a little variation with time since logging, but those in the litter layer increased systematically with time since logging, partially contradicting H_2. In contrast to H_3, litter C:N increased systematically with time since logging as a result of natural succession following disturbance. The main trend that emerged is that five biogeochemical parameters explained >80% of the variation in soil and litter among logged and unlogged stands, but litter parameters appeared more sensitive to the effects of time since logging than soil parameters.

4.1. Biogeochemical parameters as sustainable logging indicators

Minimizing selective logging-driven changes in forest nutrient cycling and productivity is one of the goals of a SFMP such as that underway in Precious Woods Amazon. Tropical forests growing on old, strongly weathered soils such as those included in this study depend mainly on the fast decomposition and dynamics of the litter layer (Cusack et al., 2009; Parton et al., 2007; Vitousek and Sanford, 1986), which guarantee a rapid turnover of litterfall C and nutrient stocks. Considering logging can alter vegetation structure (i.e., canopy cover and tree density), the production and distribution of the litterfall can also be affected (Almeida et al., 2015; Silver et al., 2014). As a result, forest nutrient cycling and productivity can be altered by logging (Wood et al., 2009), whose impacts remain uncertain in primary forests logged for the first time. In assessing which litter and soil biogeochemical parameters are useful indicators of sustainable logging, we found that soil sand content and litter C:N explained most of the variation (30% and ~22% of the total, respectively) in soil and litter among logged and unlogged stands.

The studied logged stands are at the early stages of secondary succession after reduced-impact logging. As time elapses since logging, we expected that stocks and pools of C and nutrients on the forest floor would become analogous to those in unlogged forests. On the contrary, unlogged forest litter and soils were more biogeochemically similar to recently-logged litter and soils. We noted that litter parameters reflected such temporal progression of recovery, as indicated by the pattern in the litter PCA matching our post-logging chronosequence (Fig. 3a). This biogeochemical pattern, even at a decadal scale, can be related to time since logging rather than solely differences in the floristic composition of large trees (Figs. 4 and A1). For example, soil sand content, which does not change with management, was the only variable among the sixteen parameters that significantly explained ~13% of the pre-logging floristic composition across stands.

4.2. Systematic changes in litter C stocks and C-to-nutrient ratios with time since logging

Selective logging impacts on C stocks and C-to-nutrient ratios in the litter layer result from a combination of canopy cover reduction, nutrient-rich green plant material deposition, and tree colonization and regrowth. Higher C:N and C:P ratios were expected in recently logged forests because, in Precious Woods Amazon, felled tree crowns are left in the forest to decompose. Over time, the decomposition of tree crowns contributes to a massive influx of nutrient-rich material and, possibly, nutrient input into the soil (Olander et al., 2005). We found that litter C stocks and C:N ratios systematically changed from low (i.e., higher litter N) to high as time since logging increased (Figs. 2 and 3a; Tables A4 and A5). The C:N ratio of the litter layer is essential because it influences the rate of decomposition and the rate at which N is recycled and made available to plants, thus affecting forest regrowth and productivity (Brady and Weil, 2017; Sanches et al., 2008; Vitousek and Sanford, 1986). We did not observe the same dynamics in the soil, which supports the idea that the litter layer is much more dynamic than the soil, whose changes in C stocks, for instance, can take much longer than the time scale used in this study, as indicated by our findings. Thus, litter biogeochemistry can be much more susceptible than soil biogeochemistry to logging-induced changes in the forest.

Higher N input from the litter layer in recently logged forests likely derives from the tree crown left after the logs are removed, as discussed above. For instance, tropical forest litter removal had a stronger negative effect on N than on P cycling (Sayer and Tanner, 2010); this is consistent with recent findings of land-use-specific C and nutrient cycling in forest ecosystems in the tropics (Bomfim et al., 2019) and elsewhere where litter quality affects litter decomposition (Hättenschwiler and Jørgensen, 2010). Overall, the internal recycling of N from litter decomposition provides an essential resource for ecosystem productivity, especially since estimates of biological N_2 fixation in lowland tropical forests across the Amazon basin are low (Nardoto et al., 2014). However, it is noteworthy mentioning that nutrient concentration and stock in the litter layer can vary as a function tree density, individual species ability to absorb, use and redistribute nutrients, natural habitat, and tree age (Buscardo et al., 2016). Also, 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).

4.3. Links between forest regeneration and biogeochemical parameters

Even though SFMPs in Amazonia attempt to minimize impacts on the forest, changes in vegetation structure can occur. For instance, canopy cover can decrease in response to logging (Pinagé et al., 2019). Indeed, canopy cover had a decreasing trend over time since logging and was ~14% lower nine years after logging (Fig. A2). Nevertheless, regardless of logging history, canopy cover correlated strongly with soil sand and clay contents, and litter nutrient content and stoichiometric ratios (Fig. A3; Tables 2 and A4). Besides, both canopy cover and seedling density showed high variation among sampling points, which reflects the patchy nature of both soil conditions and selective logging operations in Amazon forests (Putz et al., 2019). Although the long-term monitoring of seedlings and canopy cover is a critical component for assessing forest regeneration and, therefore, the sustainability of SFMPs (Reza and Abdullah, 2011), additional metrics other than canopy cover and seedling density, such as litter and soil biogeochemical parameters, can provide a more robust assessment of the impacts of sustainable logging in Amazon forests.

Soil properties, rather than logging history, are closely related to leaf and, thus, litter C—plant trait associated with nutrient acquisition strategy (Both et al., 2019). C concentration, C:P, and C:N ratios in the litter were closely related to soil fertility (as inferred by CECe) and clay content (Fig. 4). The increase in litter C stock with time since logging did not solely covary with standing litter mass—which did not change with time since logging (Table A4; Fig. A3). Therefore, it is essential to take into account possible differences in soil sand and clay contents among unlogged and logged forests when assessing the impacts of reduced-impact logging in upland Amazon forests via comparisons with nearby protected stretches of the same forest type. Previous studies also suggested a complex interaction between anthropogenic disturbances and the variability in abiotic controls in determining the shifts in tropical forest functioning after disturbance (e.g., Both et al., 2019).

5. Conclusion

Our results have implications for efforts to improve (and expand) SFMPs in Amazonia, which is one mechanism to decrease the likelihood of forest conversion to monocropping systems. Here, we tested the hypothesis that litter and soil biogeochemical parameters serve as indicators of sustainable logging. Considering that the logged forests had similar reduced-impact logging schemes and harvesting intensity, we expected that the chronosequence spanning nine years since logging would show differences in vegetation structure (i.e., canopy cover and tree seedling density) coupled with differences in dynamic soil and litter parameters. We found that litter and soil parameters reflected differences in vegetation structure, but litter parameters (e.g., C stock and C:N ratio) were more sensitive to logging than soil parameters. Therefore, litter and soil parameters can be used by forest managers as indicators of sustainable forest management in upland evergreen forests in Central Amazonia. Overall, our results support the notion that the selective logging operations at Precious Woods Amazon, at least after the first harvest cycle, appear not to compromise litter and soil biogeochemistry and, thus, nutrient cycling in Central Amazonian forests. Future studies can benefit from testing whether the five litter and soil parameters identified in our study can be used as indicators of sustainable logging in other Amazon forests managed for timber production.

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CRediT authorship contribution statement

Barbara Bomfim: Conceptualization, Project administration, Data curation, Formal analysis, Methodology, Writing - original draft, Writing - review & editing. **Lucas C.R. Silva:** Visualization, Writing - review & editing. **Reginaldo S. Pereira:** Conceptualization, Supervision, Methodology, Funding acquisition, Project administration, Resources, Writing - original draft. **Alcides Gatto:** Supervision, Investigation, Visualization, Writing - original draft. **Fabiano Emmert:** Conceptualization, Project administration, Data curation, Formal analysis, Methodology, Visualization, Writing - original draft. **Niro Higuchi:** Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Supervision, Writing - review & editing.

Declaration of competing interest

The authors declare no conflict of interest.

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