REVISTA CADERNO PEDAGÓGICO – Studies Publicações Ltda.
ISSN: 1983-0882

Seasonal dynamics of chemical soil properties under native Brazil-nut *(Bertholletia Excelsa)* groves in the Tapajós National Forest, brazilian Amazon

Dinâmica sazonal das propriedades químicas do solo em áreas naturais de castanhais (*Bertholletia Excelsa)* na floresta nacional do Tapajós, Amazônia brasileira

Dinámica estacional de las propiedades químicas del suelo en rodales naturales de castaño de Brasil (*Bertholletia Excelsa)* en el bosque nacional del Tapajós, amazonia brasileña

DOI: 10.54033/cadpedv23n1-216

Originals received: 12/15/2025
Acceptance for publication: 1/12/2026

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ABSTRACT
Seasonal fluctuations in soil chemical properties play a central role in regulating biogeochemical processes and fertility in Amazonian forests. This study evaluated how rainy and dry seasons influence soil organic carbon (C), total nitrogen (N), and pH under native *Bertholletia excelsa* groves in the Tapajós National Forest, Pará, Brazil. Thirty soil samples (0–20 cm) were collected during each season and analyzed individually using standardized laboratory procedures and appropriate statistical tests. Significant seasonal differences were detected for C ($p = 0.0001$) and N ($p = 0.013$), whereas pH remained stable across periods ($p > 0.05$). Organic carbon increased markedly during the dry season, reflecting the accumulation of partially decomposed litter and humic substances under reduced moisture and slower decomposition. In contrast, total nitrogen decreased slightly but significantly, suggesting enhanced microbial immobilization during drought. Together, these patterns indicate that hydrological seasonality modulates the balance between nutrient release in the wet season and organic matter preservation in the dry season. From a management perspective, maintaining litter cover and minimizing soil disturbance during the dry season are essential to sustaining nutrient retention, soil structure, and ecosystem resilience. By integrating seasonal contrasts in C, N, and pH, this study provides empirical evidence of the mechanisms governing nutrient dynamics in soils beneath native Brazil-nut trees, advancing the understanding of biogeochemical functioning and offering a basis for sustainable management of Amazonian extractive systems.

Keywords: Biogeochemical Cycling. Seasonality. Soil Chemical Properties. Organic Carbon. Total Nitrogen. *Bertholletia Excelsa*. Amazon Rainforest.

RESUMO

As flutuações sazonais nas propriedades químicas do solo desempenham um papel central na regulação dos processos biogeoquímicos e da fertilidade nas florestas amazônicas. Este estudo avaliou como as estações chuvosa e seca influenciam o carbono orgânico (C), nitrogênio total (N) e o pH do solo sob castanhais nativos de *Bertholletia excelsa* na Floresta Nacional do Tapajós, Pará, Brasil. Trinta amostras de solo (0–20 cm) foram coletadas durante cada estação e analisadas individualmente utilizando procedimentos laboratoriais padronizados e testes estatísticos apropriados. Diferenças sazonais significativas foram detectadas para o C ($p = 0{,}0001$) e o N ($p = 0{,}013$), enquanto o pH se manteve estável entre os períodos ($p > 0{,}05$). O carbono orgânico aumentou acentuadamente durante a estação seca, refletindo o acúmulo de serapilheira parcialmente decomposta e substâncias húmicas sob condições de menor umidade e decomposição mais lenta. Em contraste, o nitrogênio total diminuiu ligeiramente, mas de forma significativa, sugerindo uma maior imobilização microbiana durante a seca. Juntos, esses padrões indicam que a sazonalidade hidrológica modula o equilíbrio entre a liberação de nutrientes na estação úmida e a preservação da matéria orgânica na estação seca. Sob uma perspectiva de manejo, manter a cobertura de serapilheira e minimizar a perturbação do solo durante a estação seca são essenciais para sustentar a retenção de nutrientes, a estrutura do solo e a resiliência do ecossistema. Ao integrar os contrastes sazonais em C, N e pH, este estudo fornece evidências empíricas dos mecanismos que regem a dinâmica de nutrientes em solos sob castanheiras nativas, avançando a compreensão do funcionamento biogeoquímico e oferecendo uma base para o manejo sustentável dos sistemas extrativistas amazônicos.

Palavras-chave: Ciclagem Biogeoquímica. Sazonalidade. Propriedades Químicas Do Solo. Carbono Orgânico. Nitrogênio Total. *Bertholletia Excelsa*. Floresta Amazônica.

RESUMEN

Las fluctuaciones estacionales en las propiedades químicas del suelo desempeñan un papel central en la regulación de los procesos biogeoquímicos y la fertilidad en los bosques amazónicos. Este estudio evaluó cómo las estaciones lluviosa y seca influyen en el carbono orgánico (C), nitrógeno total (N) y el pH del suelo bajo rodales nativos de *Bertholletia excelsa* en el Bosque Nacional del Tapajós, Pará, Brasil. Se recolectaron treinta muestras de suelo (0-20 cm) durante cada estación y se analizaron individualmente utilizando procedimientos de laboratorio estandarizados y pruebas estadísticas apropiadas. Se detectaron diferencias estacionales significativas para el C ($p = 0{,}0001$) y el N ($p = 0{,}013$), mientras que el pH se mantuvo estable entre los períodos ($p > 0{,}05$). El carbono orgánico aumentó marcadamente durante la estación seca, lo que refleja la acumulación de hojarasca parcialmente descompuesta y sustancias húmicas bajo condiciones de menor humedad y una descomposición más lenta. Por el contrario, el nitrógeno total disminuyó ligeramente pero de manera significativa, lo que sugiere una mayor inmovilización microbiana durante la sequía. En conjunto, estos patrones indican que la estacionalidad hidrológica modula el equilibrio entre la liberación de nutrientes en la estación húmeda y la preservación de la materia orgánica en la estación seca. Desde una perspectiva de manejo, mantener la cobertura de hojarasca y minimizar la perturbación del suelo durante la estación seca es esencial para sostener la retención de nutrientes, la estructura del suelo y la resiliencia del ecosistema. Al integrar los contrastes estacionales en C, N y pH, este estudio proporciona evidencia empírica de los mecanismos que gobiernan la dinámica de nutrientes en suelos bajo castaños de Brasil nativos, avanzando en la comprensión del funcionamiento biogeoquímico y ofreciendo una base para el manejo sostenible de los sistemas extractivos amazónicos.

Palabras clave: Ciclos Biogeoquímicos. Estacionalidad. Propiedades Químicas Del Suelo. Carbono Orgánico. Nitrógeno Total; *Bertholletia Excelsa*. Bosque Amazónico.

1 INTRODUCTION

The Brazil nut tree (*Bertholletia excelsa* Humb. & Bonpl.), a keystone species of Amazonian forests, plays a central ecological and socioeconomic role across its broad distribution. Its long lifespan, emergent canopy stature, and dependence on intact forest structure make the species particularly sensitive to environmental change, especially in regions subject to seasonal climatic fluctuations. Brazil-nut harvesting provides an essential source of income for traditional and local communities, reinforcing the cultural and economic importance of conserving these native groves (Scoles *et al*., 2011; Tourne *et al*., 2019).

The economic relevance of *B. excelsa* stems largely from its non-timber forest products, especially the highly valued edible seeds used in global food markets, cosmetics, and artisanal crafts (Instituto Socioambiental, 2020; Andrade *et al*., 2023). In this context, recent initiatives such as the “Mapping of Native Brazil Nut Groves in the Amazon” have advanced the ecological understanding of these systems, highlighting their importance for biodiversity, ecosystem functioning, and long-term socioecological resilience under changing climatic conditions.

The distribution of *B. excelsa* covers nearly one-third of the Amazon Basin, spanning regions with marked hydrological seasonality. These climatic gradients influence soil processes, vegetation structure, and the functioning of extractive systems, directly affecting productivity and ecological stability. Soil organic matter (SOM) is a central indicator of soil quality and ecosystem functioning, modulating nutrient supply, moisture retention, and microbial activity under variable environmental conditions (Xu *et al*., 2012; Kant, 2018). The availability of carbon (C) and nitrogen (N) is strongly influenced by soil pH, which governs nutrient solubility, microbial processes, and plant nutrient acquisition (Shetty *et al*., 2021; Delgado-Baquerizo *et al*., 2018).

The Tapajós National Forest (FLONA do Tapajós), located in western Pará, exemplifies a landscape where climatic seasonality strongly shapes soil biogeochemistry. Two well-defined periods—the rainy and dry seasons—drive contrasting soil moisture and temperature regimes typical of the region's tropical monsoon climate. Understanding the seasonal variability of soil C, N, and pH within *B. excelsa* groves is thus essential for evaluating nutrient cycling, ecosystem resilience, and the sustainability of extractive practices (Schaap *et al*., 2022; Souza *et al*., 2022; Peguero *et al*., 2019).

Despite the ecological and socioeconomic importance of *B. excelsa*, limited information exists on how seasonal hydrological patterns influence soil chemical properties beneath native groves, particularly under the dystrophic Yellow Latosols that dominate the region. Addressing this gap is crucial for informing sustainable management practices in Amazonian extractive systems. Accordingly, this study addresses the following research questions: (i) How do soil C, N, and pH vary between rainy and dry seasons? (ii) What seasonal patterns emerge in the interdependence among these chemical properties? and (iii) How do these dynamics relate to the inherent acidity of dystrophic Yellow Latosols typical of the region?

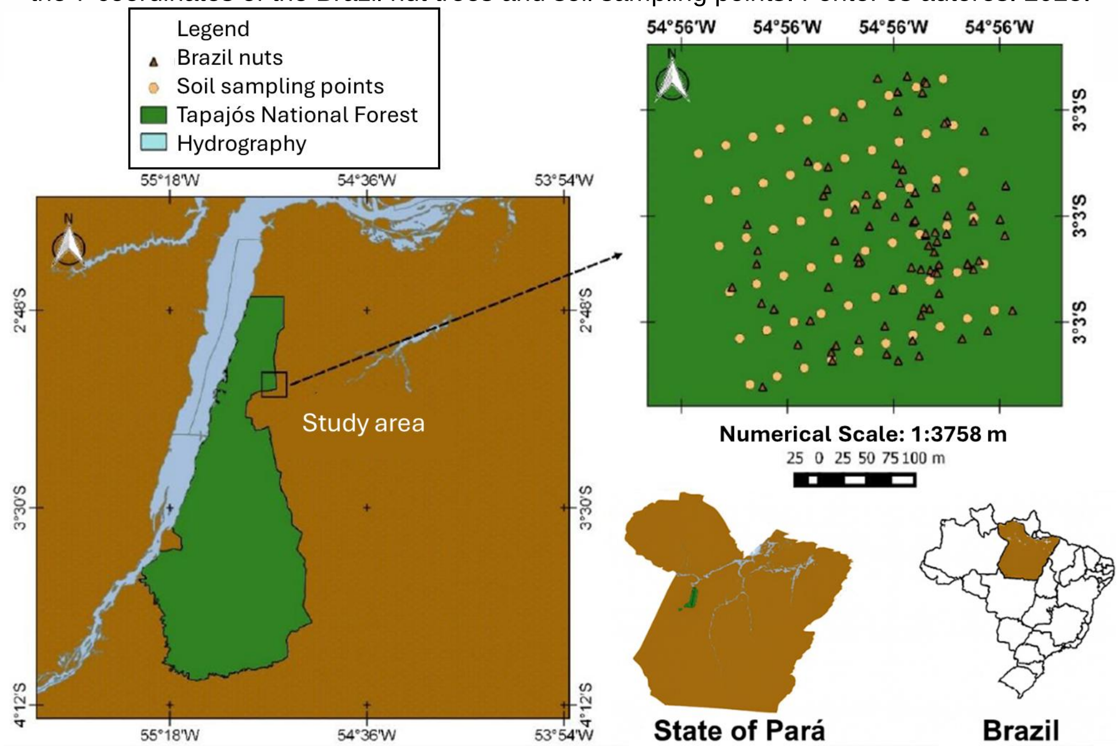
2 MATERIAL AND METHODS

In this study, the term *soil properties* refers to measurable chemical characteristics (pH, organic carbon, and total nitrogen) that vary seasonally and are sensitive to environmental conditions, following the conceptual framework of Embrapa (2017) and the IUSS Working Group WRB (2015).

2.1 STUDY AREA

The study was conducted in the Tapajós National Forest (FLONA do Tapajós), located in the western region of Pará State, Brazil, between 02°45′ and 04°10′ S and 54°45′ and 55°30′ W (Espírito-Santo *et al*., 2017; ICMBio, 2019) (figure 1). This sustainable-use conservation unit covers more than 500,000 hectares of primarily undisturbed tropical forest and represents an important area for biodiversity conservation, non-timber forest product extraction, and ecotourism (IBAMA, 2005; Brasil, 2004).

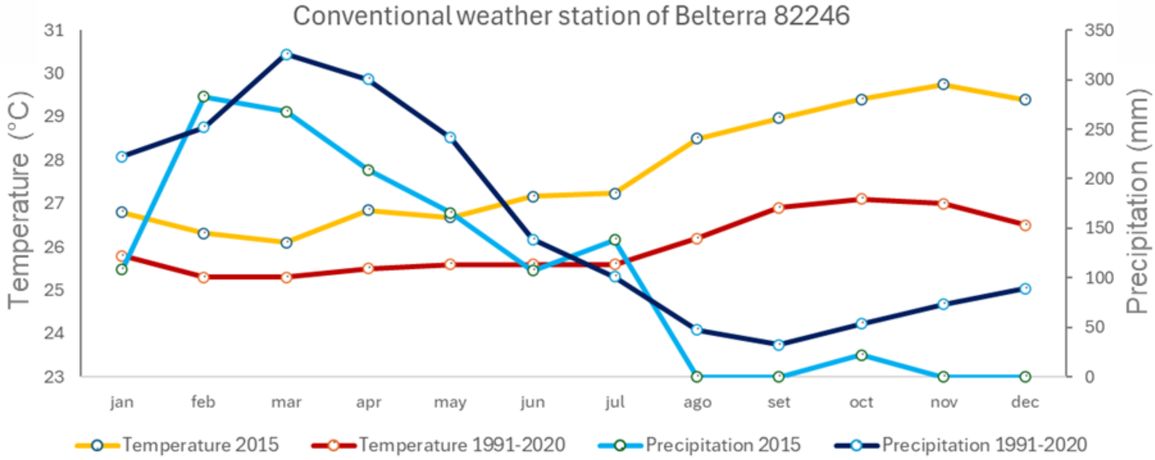
Figure 1. Location of the study site in the Tapajós National Forest, in Belterra - PA, as well as the 7 coordinates of the Brazil nut trees and soil sampling points. Fonte: os autores. 2025.



Legend: Map showing the location of sampling sites in the Tapajós National Forest, Pará, Brazilian Amazon. The map highlights forest typologies, elevation gradients, and access routes within the study area. Sampling plots were distributed under native *Bertholletia excelsa* groves, covering representative soil and topographic conditions across the site. Geographic coordinates with Datum SIRGAS 2000. Fonte: os autores. 2025.

The local climate is classified as Am (tropical monsoon) according to Köppen, with a mean annual temperature of 25.5 °C and an average annual precipitation of approximately 1,820 mm (Marengo; Souza, 2021). The region experiences a well-defined rainy season from December to May and a dry season from June to November (Figure 2). Rainfall variability is strongly influenced by El Niño–Southern Oscillation (ENSO) events, which periodically alter precipitation regimes (Sousa *et al*., 2015; Limberger & Silva, 2016).

Figure 2. Conventional weather station in Belterra 82246, with averages for the year 2015 and climatological normals from 1991 to 2020.



Fonte: os autores. 2025.

The dominant soils are Dystrophic Yellow Latosols (Oxisols), highly weathered, acidic, and characterized by low natural fertility and cation exchange capacity (MMA, 2004; Embrapa, 2018). Representative soil samples collected in the study plot indicate a clayey texture (63.5% clay, 20.2% silt, 16.3% sand) and an average bulk density of 1.25 g cm^{-3}, as determined by Embrapa (2017). These features are typical of deep tropical soils under humid forest conditions.

The sampling area corresponds to the permanent plot established by the MapCast Project at kilometer 84 of the BR-163 highway (Santarém–Cuiabá), in the municipality of Belterra, Pará. The 300 × 300 m plot contains a natural population of *Bertholletia excelsa* and is subdivided into six parallel transects, each 300 m long and spaced 50 m apart, with 25 m margins on each side.

2.2 SOIL SAMPLING

Soil samples were collected during two field campaigns in 2015, representing contrasting seasonal conditions: April (middle rainy season) and October (middle dry season). Thirty sampling points were established along the six transects, with five points per transect spaced 60 m apart. At each point, soil was collected at a depth of 0–20 cm using a Dutch auger, corresponding to the layer of highest root biomass, organic matter accumulation, and microbial activity. All vegetal material were retired from the soil before saves in plastic bags.

Each of the 30 soil samples per season was analyzed individually, not composited, in order to capture the spatial variability within the permanent plot. Samples were stored in labeled polyethylene bags and transported to the Soil Laboratory of the Museu Paraense Emílio Goeldi (MPEG) in Belém, Pará.

In the laboratory, samples were air-dried, gently crushed, homogenized in a porcelain mortar, and passed through a 2 mm sieve to obtain the fine-earth fraction (TFSA) following the procedures recommended by Embrapa (2017).

2.3 CHEMICAL ANALYSES

Organic carbon (C) was determined by the modified Walkley–Black method, which involves oxidation of soil organic matter using potassium dichromate ($K_2Cr_2O_7$) in a sulfuric acid medium. The unreacted dichromate was titrated with a standardized ferrous ammonium sulfate (FAS) solution (Embrapa, 2017).

Total nitrogen (N) was measured using the micro-Kjeldahl method. Soil samples were digested in a mixture of concentrated H_2SO_4 with $CuSO_4$ and Na_2SO_4 catalysts, converting organic N into ammonium sulfate. The released ammonia was distilled by steam and quantified by titration with a standard boric acid solution (Embrapa, 2017).

Soil pH was determined potentiometrically in a 1:2.5 soil-to-water suspension using a combined electrode, following Embrapa (2017). This procedure provides a direct measure of active soil acidity.

2.4 DATA ANALYSIS

Descriptive statistics (minimum, maximum, mean, standard deviation, and coefficient of variation) were calculated for each variable. Data normality was tested using the Shapiro–Wilk test at a 5% significance level. Seasonal comparisons of soil attributes (C, N, and pH) were conducted using Student's *t*-test for independent samples. When assumptions of normality or homogeneity of variance were not met, the non-parametric Mann–Whitney test was applied.

All analyses were performed using the software PAST v. 3.14 (Hammer *et al*., 2001), which is widely used for ecological and environmental data analysis. Statistical significance was considered at $p < 0.05$.

To evaluate the interrelationships among soil chemical properties, Pearson's correlation coefficients (r) were calculated between soil organic carbon, total nitrogen, and pH for both seasonal periods (rainy and dry). The normality of the data was verified using the Shapiro–Wilk test prior to correlation analysis. A correlation matrix was generated and visualized as a heatmap, where color intensity represents the magnitude and direction of the correlations, and significance levels ($p < 0.05$) are indicated by asterisks. This approach allowed identifying the degree of covariation among soil properties and assessing whether seasonal dynamics influenced their chemical associations. All analyses and graphical representations were performed using the statistical software PAST 4.03 (Hammer *et al*., 2001) and R 4.3.1 (R Core Team, 2023).

3 RESULTS AND DISCUSSIONS

3.1 OVERVIEW

The statistical analysis revealed significant seasonal differences in soil organic carbon (C) and total nitrogen (N), whereas soil pH showed no detectable variation between seasons (Table 1). Organic carbon displayed a marked increase in the dry season (t= – 6.58; p= 0.0001), while total nitrogen exhibited a smaller but still significant seasonal shift (t= –2.58; p= 0.013). In contrast, soil pH remained stable across periods (p= 0.184), indicating strong buffering capacity characteristic of dystrophic Yellow Latosols.

3.2 DESCRIPTIVE STATISTICS AND SEASONAL ANALYSIS

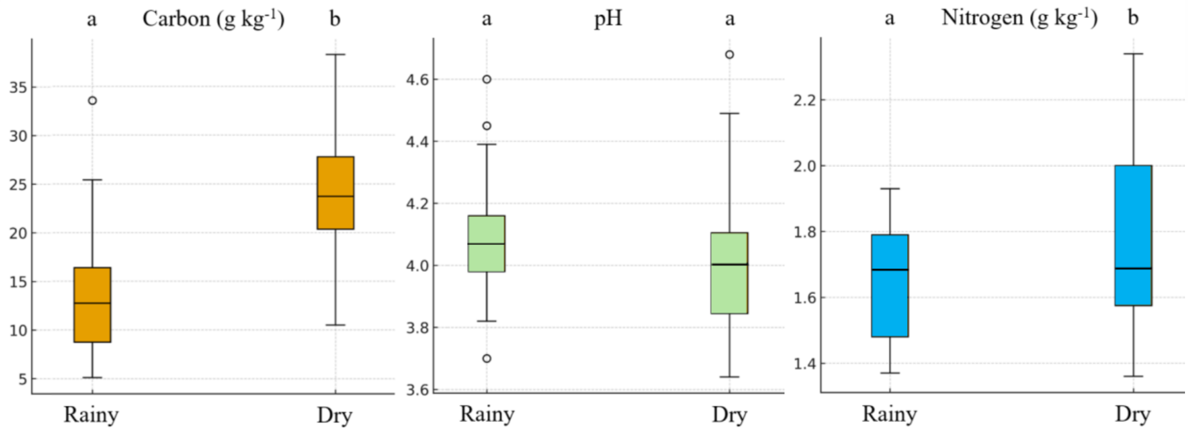
Table 1. Descriptive statistics of soil chemical attributes in native Brazil nut groves of the Tapajós National Forest during the rainy and dry seasons.

Period	Attribute	Average (X)	Standard Deviation (SD)	Coefficient of Variation (CV%)	Minimum	Maximum
Rainy	C ($g.kg^{-1}$)	13.30	6.14	46.15	5.10	33.54
	N ($g.kg^{-1}$)	1.88	0.17	10.88	1.40	1.93
	pH	4.07	0.19	4.73	3.70	4.60
Dry	C ($g.kg^{-1}$)	24.08	6.22	25.49	10.50	38.28
	N ($g.kg^{-1}$)	1.77	0.26	14.73	1.36	2.34
	pH	4.00	0.23	5.72	3.64	4.68

Legend: Summary of soil properties (mean ± SD, coefficient of variation – CV %) and results of significance tests between rainy and dry seasons. Variables include soil organic carbon ($g\ kg^{-1}$), total nitrogen ($g\ kg^{-1}$), and pH (H_2O 1:2.5). Statistical differences were determined using Student's *t*-test ($\alpha = 0.05$). Fonte: os autores. 2025.

The composite boxplots (Figure 2) complement these findings by illustrating pronounced contrasts in the distribution of C and N across seasons. During the rainy season, both variables displayed greater dispersion, reflecting spatial heterogeneity associated with microtopographic moisture gradients and variable litter inputs. In the dry season, however, the medians were notably higher and the interquartile ranges narrower—particularly for C—indicating more homogeneous accumulation of organic matter under reduced decomposition conditions. Conversely, the pH boxplots exhibited nearly identical distributions in both seasons, as indicated by the shared letter "a," reinforcing the absence of seasonal influence on soil acidity.

Figure 2. Seasonal variation of soil properties under native Brazil-nut groves.



Legend: Composite boxplots showing the distribution of soil organic carbon (C), total nitrogen (N), and pH during the rainy (blue) and dry (orange) seasons. Boxes represent interquartile ranges; whiskers indicate 1.5 × IQR; horizontal lines mark medians; and black dots represent outliers. Significant differences between seasons ($p < 0.05$) are indicated by distinct letters above boxes. Carbon: t= -6.850, p= 0,0000; pH: t= 1.337, p= 0.1865; Nitrogen: t= -2.626, p= 0.0112. Fonte: os autores. 2025.

3.3 CORRELATIONS AMONG SOIL PROPERTIES

The seasonal shift in correlations further highlights differences in soil chemical dynamics (Table 2). During the dry season, strong positive relationships were observed among C, N, and pH, with the C–N correlation reaching r= 0.95. This pattern confirms that most nitrogen occurs in organic form and is intrinsically linked to soil organic matter. Positive correlations involving pH (pH–C= 0.81; pH–N= 0.77) suggest that samples with higher organic matter content also exhibited slightly higher pH values, likely due to enhanced buffering capacity.

In sharp contrast, the rainy season showed weak or negligible correlations among all variables (C–N= 0.13; pH correlations < 0.15). The loss of interdependence among soil properties is consistent with intensified hydrological processes during peak rainfall, which promote nutrient leaching, ion mobilization, and shifts in microbial activity—processes that disrupt the physicochemical coupling typical of the drier period.

Table 2. Pearson correlation coefficients (r) among soil properties.

Variable	Organic C	Total N	pH (H_2O)
Organic C	1.00	**0.67** (**p**< 0.01)*	– 0.12 (ns)
Total N	**0.67** (**p**< 0.01)*	1.00	– 0.09 (ns)
pH (H_2O)	– 0.12 (ns)	– 0.09 (ns)	1.00

Legend: Matrix presenting correlation coefficients and significance levels between soil organic carbon, total nitrogen, and pH for the pooled dataset (rainy + dry seasons). *p*-values below 0.05 are indicated in bold. Significant correlations (p < 0.05) are marked with an asterisk (*). (ns= not significant, *p*> 0.05). Fonte: os autores. 2025.

4 DISCUSSION

4.1 RAINY SEASON: ACCELERATED DECOMPOSITION AND NUTRIENT RELEASE

During the rainy season, increased soil moisture and temperature enhance microbial activity and the decomposition of organic matter. This leads to rapid mineralization of carbon compounds and higher nitrogen turnover rates.

Although the mean C content (13.3 ± 6.1 g kg^{-1}) was lower than in the dry season, this pattern reflects an active stage of mineralization rather than carbon depletion. The higher variability observed (CV= 46%) likely results from spatial heterogeneity in litter inputs and microtopographic moisture gradients.

Nitrogen dynamics followed a similar trend during the wet period. Elevated moisture enhances microbial nitrification and increases N availability in the soil solution, resulting in faster nutrient cycling (Paul, 2015; Camenzind *et al*., 2018). However, the rapid leaching that accompanies high rainfall can reduce the retention of inorganic N in the upper soil layer, leading to moderate overall concentrations (mean= 1.88 ± 0.17 g kg^{-1}). This pattern is consistent with observations from other Amazonian forest soils, where intense rainfall generates short-lived nutrient pulses followed by losses through drainage and denitrification (Figueiredo *et al*., 2019; Nevison *et al*., 2016; Schaap *et al*., 2024).

The pH values (mean= 4.07 ± 0.19) confirm the high acidity typical of dystrophic Yellow Latosols. Despite the slightly higher hydrogen activity during the rainy season, no significant variation was detected (p> 0.05), suggesting strong buffering capacity and limited influence of seasonal precipitation on this soil chemical property (Ng *et al*., 2022; Pereira, 2020).

The correlation between C and N was substantially reduced in the wet season (r= 0.13), and relationships involving pH were nearly absent (r< 0.15). This decoupling may be attributed to intensified hydrological dynamics, leading to greater leaching of soluble nutrients or ion mobilization, as well as shifts in microbial activity that result in variable mineralization and decomposition rates.

4.2 DRY SEASON: ACCUMULATION AND IMMOBILIZATION PROCESSES

In contrast, the dry season was characterized by organic matter accumulation and reduced decomposition due to lower soil moisture. Organic carbon increased substantially (mean= 24.1 ± 6.2 g kg^{-1}), reflecting the buildup of partially decomposed litter and humic substances. This accumulation enhances cation exchange capacity (CEC) and soil structural stability, both of which are critical for nutrient retention and water storage under seasonal drought conditions (Lehmann *et al*., 2020; Quesada *et al*., 2020; Fancourt *et al*., 2022; Frare *et al*., 2023).

Although nitrogen levels declined slightly (mean= 1.77 ± 0.26 g kg^{-1}), the change was significant (p= 0.013), indicating that nitrogen immobilization by soil microbes predominates under limited moisture. This behavior aligns with reduced mineralization efficiency and lower substrate diffusion during water deficit (Manzoni *et al*., 2012; Camenzind *et al*., 2018). Consequently, C:N ratios tend to increase in the dry period, reflecting the accumulation of organic matter and a temporary decoupling between carbon inputs and nitrogen release.

Soil pH remained consistently acidic (mean= 4.00 ± 0.23), showing no significant difference compared to the wet period (p= 0.184). The relative stability of pH, despite seasonal changes in organic inputs, highlights the dominance of intrinsic mineralogical controls over exchangeable bases and aluminum saturation (Weil; Brady, 2016).

In the dry season, the strong positive correlation between C and N (r= 0.95) confirms that most N is present in organic form and is intrinsically linked to organic matter. Additionally, pH showed high positive correlations with C (r= 0.81) and N (r= 0.77), suggesting that samples with higher organic matter content tended to exhibit higher pH values, possibly due to increased buffering capacity.

4.3 COMPARATIVE SEASONAL INTERPRETATION

The contrasting behavior of C and N between seasons emphasizes the tight coupling between the hydrological regime and the biogeochemical functioning of Amazonian soils. During the rainy season, decomposition and nutrient mineralization dominate, whereas the dry period promotes organic matter accumulation and microbial dormancy. This alternation creates a cyclical pattern of nutrient availability that stabilizes soil fertility over time, supporting productivity in native Brazil-nut stands (Barroco Neta; Nishiwaki, 2018; Schaap *et al*., 2024; Costa *et al*., 2022).

Statistically, these findings demonstrate a strong seasonal signal in soil carbon (C ↑ dry > wet) and a moderate but significant effect on nitrogen (N ↓ dry < wet), with pH remaining unaffected. The strong correlation between C and N (r= 0.67; p< 0.01) indicates that both are regulated by common biogeochemical processes related to organic matter dynamics and microbial activity, while pH remains relatively independent, reflecting the high buffering capacity of these dystrophic soils.

The boxplots (Fig. 2) reinforce these patterns, showing higher medians and narrower interquartile ranges for carbon during the dry period—evidence of more homogeneous accumulation—whereas nitrogen displays greater variability, reflecting localized responses of microsites.

4.4 SEASONAL CORRELATIONS

The Pearson correlation analysis of soil chemical properties revealed a marked distinction in the interdependence of variables based on seasonality (Table 2).

In the dry season, the pattern typically expected for tropical soils was observed, with strong positive correlations between carbon (C) and nitrogen (N) fractions (r = 0.95), confirming that most N occurs in organic form and is intrinsically associated with organic matter (Silva *et al*., 2018; Moraes; Guerreiro, 2022). Additionally, pH showed strong positive correlations with C (r= 0.81) and N (r= 0.77). This relationship suggests that samples with higher organic matter content (C and N) tended to exhibit higher pH values, possibly due to the increased buffering capacity provided by organic compounds.

In complete contrast, the rainy season showed correlations among C, N, and pH that were weak or nonexistent (r values near zero). The strong C–N correlation was substantially reduced (r= 0.13), and relationships involving pH were virtually absent (r< 0.15). This decoupling of the C–N relationship and the loss of correlation between pH and organic fractions may be attributed to the intensified hydrological dynamics characteristic of the wet period (Silva *et al*., 2025). Increased rainfall and water percolation may have led to: (1) greater leaching of soluble nutrients or ion mobilization, heterogeneously affecting pH and N across samples; and (2) activation or shifts in microbial activity, resulting in variable mineralization and decomposition rates (Albuquerque *et al*., 2025). Such seasonal transport and transformation processes disrupted the close physicochemical relationships observed in the soil matrix during the drier period.

Therefore, seasonal changes represent a key factor modulating the interdependence among chemical properties, which is crucial for understanding nutrient availability in the studied ecosystem.

4.5 IMPLICATIONS FOR SOIL MANAGEMENT

From a management perspective, these seasonal changes have direct implications for the sustainability of extractive systems based on *Bertholletia excelsa*.

The increase in organic carbon during the dry season improves soil structure and nutrient retention but also signals potential vulnerability to disturbance or fire during prolonged droughts. Maintaining litter cover and minimizing soil exposure are essential for preserving organic horizons and microbial habitat.

During the rainy season, when decomposition and nutrient release are highest, management strategies should prioritize nutrient conservation—avoiding excessive soil disturbance or harvest practices prone to surface runoff—to prevent leaching losses. Recognizing the temporal rhythm of nutrient cycling enables adaptive planning of extractive and conservation activities, aligning with the natural resilience of Amazonian ecosystems (Putz *et al*., 2022; Lima; Tonello., 2023; Numazawa *et al*., 2020; Flores *et al*., 2019).

Collectively, the seasonal patterns observed in soil carbon and nitrogen dynamics highlight the crucial role of climatic seasonality in regulating nutrient availability and fertility in native Brazil-nut stands. These insights contribute to understanding the biogeochemical stability of Amazonian soils and support the development of evidence-based management strategies for sustainable use and conservation.

4.6 INTEGRATION OF SOIL PROPERTY CORRELATIONS

The Pearson correlation analysis among the soil's chemical properties revealed a sharp distinction in the interdependence of variables based on seasonality (Table 2).

In the Dry Season, the typically expected pattern for tropical soils was observed, with strong positive correlations between the carbon (C) and nitrogen (N) fractions (r = 0.95), confirming that the majority of N is found in the organic form and is intrinsically linked to organic matter (Silva *et al*., 2018; Moraes; Guerreiro, 2022). Additionally, pH showed high positive correlations with both C (r= 0.81) and N (r= 0.77). This relationship suggests that samples with higher organic matter content (C and N) tended to exhibit higher pH values, possibly due to the increased buffering capacity conferred by the organic compounds.

In complete contrast, the Wet Season presented correlations among C, N, and pH classified as weak or null (r values close to zero). The strong correlation between C and N was significantly reduced (r= 0.13), and the relationships involving pH were virtually nonexistent (r< 0.15). This decoupling of the C-N relationship and the loss of correlation between pH and the organic fractions can be attributed to the intensified hydric dynamics characteristic of the wet period (Silva *et al*., 2025). Increased precipitation and water percolation may have led to: 1) greater leaching of soluble nutrients or mobilization of ions, affecting pH and N heterogeneously across the samples; and 2) activation or alteration in microbial activity, resulting in variable rates of mineralization and decomposition (Albuquerque *et al*., 2025). Such seasonal transport and transformation processes interrupted the close physicochemical relationship observed in the soil matrix during the drier period. Therefore, seasonal changes represent a key factor in the modulation of interdependence among chemical properties, which is crucial for understanding nutrient availability in the studied ecosystem.

The strong positive correlation between organic carbon and total nitrogen (r = 0.67; p < 0.01) indicates that both are regulated by common biogeochemical processes related to organic matter dynamics, whereas pH remains relatively independent, reflecting the high buffering capacity of these dystrophic soils.

5 CONCLUSÃO

This study explicitly tested how seasonal variation between the rainy and dry periods affects the availability of soil carbon, nitrogen, and pH under native *Bertholletia excelsa* groves in the Tapajós National Forest. The results confirmed the hypotheses that (i) soil organic carbon and total nitrogen contents vary significantly between seasons, and (ii) soil pH remains relatively stable, reflecting the intrinsic acidity of dystrophic Yellow Latosols.

This study explicitly tested how seasonal variation between the rainy and dry periods affects the chemical properties of soils under native *Bertholletia excelsa* groves in the Tapajós National Forest. The results confirmed the hypotheses that (i) organic carbon and total nitrogen contents vary significantly between seasons, and (ii) soil pH remains relatively stable, reflecting the intrinsic acidity of dystrophic Yellow Latosols.

Organic carbon increased markedly in the dry season due to the accumulation of partially decomposed organic matter, while nitrogen showed a smaller but significant seasonal decline, suggesting microbial immobilization under reduced moisture. These findings demonstrate that hydrological seasonality exerts strong control over short-term nutrient availability and long-term soil fertility.

By integrating chemical data with seasonal interpretation, this research provides new empirical evidence of how the chemical properties of Brazil-nut soils respond to climatic oscillations. The results emphasize the importance of maintaining surface organic layers and minimizing soil disturbance, particularly during the dry season, to preserve fertility and ecosystem resilience.

Overall, the study contributes to understanding the biogeochemical functioning and sustainable management of Amazonian forest soils, offering a soil-based perspective for conservation and adaptive management under increasing climatic variability.

AGRADECIMENTOS

We thank the Chico Mendes Institute for Biodiversity Conservation (ICMBio) for granting access to the study area in the Tapajós National Forest. This research was conducted within the framework of the MapCast Project, with logistical support from the Museu Paraense Emílio Goeldi. We also acknowledge the technical staff and scholarship holders involved in field sampling and laboratory analyses. The lead author is grateful to the funding agencies for providing research grants and supporting scientific development in the Amazon region.

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