Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

Nutrient dynamics in the organic cacao agroforestry systems in the eastern Brazilian Amazon

Taoramoio Neto Cicreta

taoramoio.cicreta@icb.ufpa.br

Universidade Federal de Pará (UFPA)

Maria de Lourdes Pinheiro Ruivo

Museu Paraense Emilio Goeldi (MPEG)

Michelliny Pinheiro Matos Bentes

Empresa Brasileira de Pesquisa Agropecuária – Embrapa Amazônia Oriental (Embrapa)

Aldair de Souza Medeiros

Universidade Federal do Piauí

Moisés Mourão Jr

Empresa Brasileira de Pesquisa Agropecuária – Embrapa Amazônia Oriental (Embrapa)

José Eulário Lampi Dique

Universidade Federal de Lavras (UFLA)

Braian Saimon Frota Silva

Universidade Federal de Pará (UFPA)

Research Article

Keywords: Eastern Amazon, Soil fertility, Macro- and micronutrients, Tropical soils, Cocoa agroforestry

Posted Date: August 6th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-10562318/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License.
Read Full License

Additional Declarations: No competing interests reported.

Abstract

Amazonian tropical soils are characterized by high acidity, intense weathering, and low natural fertility, making nutrient dynamics essential for the sustainability of land-use systems. This study evaluated macro- and micronutrient dynamics and soil chemical properties in organic cocoa agroforestry systems and secondary forest areas in the Brazilian Amazon. Twelve land-use systems were evaluated in Pará State, Brazil, including ten organic cocoa agroforestry systems and two secondary forest areas distributed across the Tomé-Açu and Transamazon regions. Soil samples were collected at four depths (0–10, 10–20, 20–30, and 30–40 cm) and analyzed for macronutrients, micronutrients (copper, zinc, manganese, and iron), potential acidity, sum of bases, cation exchange capacity, and pH. Data were analyzed using analysis of variance, Tukey's test ($p < 0.05$), principal component analysis, hierarchical cluster analysis, Spearman's correlation, and linear regression. Older agroforestry systems, particularly RT-AFS5 in the Transamazon region and TA-AFS5 in the Tomé-Açu region, exhibited higher concentrations of Ca^{2+}, Mg^{2+}, K^{+}, zinc, manganese, sum of bases, and cation exchange capacity, reflecting enhanced nutrient cycling and organic matter accumulation. Principal component analysis explained 72.1% of the total variability, indicating a clear soil fertility gradient, whereas hierarchical cluster analysis showed that system similarity was more strongly associated with soil chemical characteristics and management practices than with system age alone. Linear regression indicated progressive nutrient accumulation with increasing system age. Overall, organic cocoa agroforestry systems demonstrated the potential to improve soil chemical quality, supporting ecological restoration and sustainable soil management in the Amazon.

Introduction

Tropical soils, particularly those in the Amazon, are characterized by advanced weathering, low natural fertility, and significant chemical constraints, mainly related to low phosphorus (P) availability, high acidity, and the presence of exchangeable aluminum (Al^{3+}) (Quesada et al. 2011; Souza et al. 2025). Under these conditions, macro- and micronutrient dynamics play a fundamental role in agricultural productivity and the sustainability of agroecosystems (Lal 2020). However, ongoing deforestation in the Amazon, driven by agricultural expansion, livestock production, and natural resource exploitation, has contributed substantially to environmental degradation, the loss of ecosystem functions, and changes in nutrient dynamics and soil quality across the region (Aragão et al. 2018; Beuchle et al. 2022; Miranda et al. 2021).

In this context, ecological restoration efforts in the Amazon have focused on the recovery of degraded lands (Beuchle et al. 2022; da Cruz et al. 2021), particularly through increasing soil organic matter (SOM) and improving soil chemical properties, such as pH and cation exchange capacity (CEC), which enhance nutrient retention and availability (Schroth et al. 2016). Nutrient availability and maintenance are therefore closely associated with biogeochemical cycling, SOM inputs, and soil–plant interactions within agroecosystems (Rolo et al. 2023). Among sustainable land-use strategies, agroforestry systems (AFSs)

have gained increasing attention because they integrate ecological, productive, and economic benefits (Nunes et al. 2020; Wartenberg et al. 2017).

For example, cocoa agroforestry systems (Theobroma cacao L.) (CAFSs) established on previously deforested land converted to agricultural use in Pará State, Brazil, have been recognized as promising strategies for restoring soil quality because of their efficient nutrient use during ecological and productive restoration (Gama-Rodrigues et al. 2010; Nair et al. 2009; Venturieri et al. 2022). In addition, the integration of native tree species and perennial crops into these AFSs increases organic residue inputs, improves soil aggregate stability, and enhances nutrient cycling, thereby improving soil chemical properties such as the sum of bases (SB) and cation exchange capacity (CEC) (Huera-Lucero et al. 2025; Pauletto et al. 2023; Tinoco-Jaramillo et al. 2024; Tscharntke et al. 2011).

Pará State is among the region's most severely affected by deforestation in the Eastern Amazon (Alves, 2021; Moura et al. 2021). This context justifies its selection for investigating nutrient dynamics in organic CAFSs, as it represents a critical landscape where forest loss and agricultural expansion are particularly pronounced (Mucova et al. 2021; Venturieri et al. 2022). The study focuses on two contrasting regions: Tomé-Açu, a national reference for AFSs since the 1970s, and the Transamazon region, where intense anthropogenic pressure has created opportunities to evaluate different trajectories of productive restoration and soil management (Catuxo et al. 2024; Santos et al. 2017). Therefore, organic CAFSs represent a promising strategy for restoring degraded lands while promoting a sustainable bioeconomy in the Brazilian Amazon (Schroth et al. 2016).

Despite the reported improvements in soil quality associated with organic CAFSs in the Brazilian Amazon, important knowledge gaps remain regarding nutrient dynamics and soil chemical properties among these systems, particularly across the soil profile and under different management conditions. Comparative studies integrating macro- and micronutrient dynamics at different soil depths are therefore essential to improve the understanding of nutrient distribution, retention, and availability in tropical soils (Arthur et al. 2022; Rofner et al. 2022).

Against this background, this study addressed the following research question: How do nutrient dynamics and soil chemical properties differ between organic CAFSs and secondary native vegetation (VS) areas in the Eastern Amazon? We hypothesized that properly managed organic CAFSs improve soil chemical properties, resulting in greater nutrient availability than VS areas due to increased organic residue inputs and enhanced nutrient cycling. Accordingly, the objective of this study was to evaluate the dynamics of soil chemical properties, macronutrients, and micronutrients in organic CAFSs and VS areas across different soil depths in the Eastern Brazilian Amazon.

Materials and methods

Study Area

The study was conducted in Pará State, located in the Eastern Brazilian Amazon, encompassing 12 land-use systems. Ten organic CAFSs, established between 12 and 28 years ago, were evaluated, together with two VS areas used as reference sites for the natural regeneration of soil quality (Table 1).

Table 1
Characteristics of the organic CAFSs and VS areas regarding system age, tree species diversity, and mean soil texture in the 0–40 cm soil layer in the Tomé-Açu and Transamazon region, Pará State, Brazil

Land-use system	Age (years)	Number of tree species	Sand (%)	Clay (%)	Silt (%)	Textural class
			.....g kg-1.....			0–40 cm
Tomé-Açu region						
Ta- AFS 1	18	VI	638	269	93	Sand
Ta- AFS 2	15	VIII	616	298	86	Sand
Ta- AFS 3	12	IX	390	504	106	Clay
Ta- AFS 4	23	VI	685	267	48	Sand
Ta- AFS 5	28	VIII	768	224	8	Very Sand
Ta- VS	28	-	474	478	48	Clay
Transamazon region						
RT- AFS 1	15	VIII	415	455	130	Clay
RT- AFS 2	12	VIIII	780	167	53	Sand
RT- AFS 3	18	VIII	708	208	84	Sand
RT- AFS 4	23	VII	650	218	132	Sand
RT- AFS 5	28	X	227	568	205	Very Clay
RT- VS	25	-	495	409	96	Clay

TA - Tomé-Açu; TR - Transamazon region; AFS- agroforestry system; VS- secondary vegetation. Sand, Clay, and Silt values represent the mean percentages for the 0–40 cm soil layer.

The study sites were distributed across two regions in the Eastern Brazilian Amazon, namely the municipality of Tomé-Açu and the Transamazon region, both located in Pará State, Brazil. In Tomé-Açu, five organic cocoa agroforestry systems (CAFSs) and one secondary native vegetation (VS) area were selected. The VS, with approximately 28 years of natural regeneration, was used as a reference site for soil quality. In the Transamazon region, five additional organic CAFSs and one VS area, with approximately 25 years of natural regeneration, were also evaluated as a reference site for soil quality.

Tomé-Açu (2°05' S, 47°55' W) and the Transamazon region (3°28' S, 52°40' W) differ in their land-use history and agroforestry management practices, providing an opportunity to evaluate nutrient dynamics and soil chemical properties under contrasting edaphoclimatic and management conditions in the Eastern Brazilian Amazon (Table 1).

The soils in the study area are predominantly classified as Oxisols and Ultisols, according to the Brazilian Soil Classification System (SiBCS), and are characterized by advanced weathering and a high degree of pedogenic development (Santos et al. 2018). These soils are dominated by secondary minerals, particularly kaolinite, and contain high concentrations of iron and aluminum oxides, which strongly influence soil chemical properties by affecting nutrient retention and availability, cation exchange capacity (CEC), and phosphorus adsorption (Quesada et al. 2011; Souza et al. 2025).

The regional climate is classified as Am (tropical monsoon climate) according to the Köppen classification and is characterized by consistently high mean annual temperatures (27°C), high relative humidity, and a well-distributed rainfall regime with no well-defined dry season. Annual precipitation ranges from 1.900 to 2.700 mm (Alvares et al. 2013; de Lima et al. 2023).

Soil sampling and experimental design

Soil samples were collected at four depths (0–10, 10–20, 20–30, and 30–40 cm) in each of the 12 land-use systems evaluated. At each system and sampling depth, five subsamples were collected using a Dutch auger from previously established sampling points. The subsamples were then thoroughly homogenized to form one composite sample per depth. In total, 48 composite samples (12 systems × 4 depths) were obtained, comprising 240 subsamples.

Laboratory analyses

Sample preparation

The soil samples were placed in properly labeled plastic bags and transported to the laboratory. They were subsequently air-dried under protected conditions, gently crushed, and passed through a 2-mm sieve to remove plant residues, roots, and other coarse materials. The processed samples were then stored under appropriate conditions until chemical analyses were performed following standardized laboratory procedures described by Teixeira et al. (2017).

Chemical analyses

Available phosphorus (P), potassium (K), sodium (Na), and micronutrients (Cu, Zn, Mn, and Fe) were extracted using the Mehlich-1 solution. Phosphorus was determined by UV-Vis spectrophotometry (SP 1105), whereas the other nutrients were determined by flame atomic absorption spectrometry (Thermo Scientific, iCE 3000 Series) (Silva 2018; Teixeira et al. 2017).

Calcium (Ca), magnesium (Mg), and exchangeable aluminum (Al^{3+}) were extracted using 1 mol L^{-1} KCl solution. Calcium and magnesium were determined by flame atomic absorption spectrometry (Thermo Scientific, iCE 3000 Series), whereas exchangeable aluminum (Al^{3+}) was quantified by volumetric titration (Prezotti & Guarçoni M, 2013; Teixeira et al. 2017). Potential acidity ($H^+ + Al^{3+}$) was determined by extraction with 1 mol L^{-1} calcium acetate solution, followed by titration. Soil pH was determined potentiometrically in a soil–water suspension.

The sum of exchangeable bases (SB), expressed in Cmolc kg^{-1}, was calculated as the sum of Ca^{2+}, Mg^{2+}, Na^+, and K^+, according to Eq. (1) (Teixeira et al. 2017).

$$\mathrm{SB} = \mathrm{Ca}^{2+} + \mathrm{Mg}^{2+} + \mathrm{Na}^{+} + \mathrm{K}^{+}$$

1

where SB is the sum of exchangeable bases (Cmolc kg^{-1}), and Ca^{2+}, Mg^{2+}, Na^+, and K^+ are the concentrations of exchangeable calcium, magnesium, sodium, and potassium in the soil, respectively.

Cation exchange capacity (CEC) was calculated as the sum of SB and exchangeable Al^{3+}, according to Eq. (2).

$$\mathrm{CEC} = \mathrm{SB} + \mathrm{Al}^{3+}$$

2

where CEC is the effective cation exchange capacity (Cmolc kg^{-1}), SB is the sum of exchangeable bases (Cmolc kg^{-1}), and Al^{3+} is the concentration of exchangeable aluminum in the soil (Cmolc kg^{-1}).

Physical analysis

Soil particle-size analysis was performed using the pipette method, as described by Teixeira et al. (2017). Soil texture was determined from the sand, silt, and clay fractions, which were previously chemically dispersed with 1 mol L^{-1} NaOH solution and subjected to mechanical agitation using a soil disperser.

Statistical analysis

Initially, the soil macro- and micronutrient data were subjected to analysis of variance (ANOVA) to evaluate the effects of land-use systems and soil depths. When significant differences were detected, means were compared using Tukey's test at the 5% significance level ($p \leq 0.05$).

To explore multivariate patterns and relationships among soil chemical properties, principal component analysis (PCA) was performed to reduce data dimensionality and identify the main gradients of variation (Filgueiras & Borges, 2021). Additionally, hierarchical cluster analysis (HCA) was used to classify the systems based on the similarity of their soil chemical properties, using Euclidean distance and an

appropriate linkage method, allowing the identification of groups with similar edaphic characteristics (Granato et al. 2018).

The relationship between system age and soil chemical properties was evaluated using linear regression, whereas the associations between macro- and micronutrients were analyzed using Spearman's correlation coefficient, which is appropriate for non-parametric data (Reimann et al. 2008). All statistical analyses were performed using R software (R Core Team, 2024).

Results

Soil chemical dynamics

Significant variations in soil macronutrients were observed among land-use systems and soil depths, as indicated by Tukey's test ($p \leq 0.05$) (Table S1). Phosphorus (P) concentrations also varied according to land-use systems and the evaluated soil depths (Fig. 1). In the surface layer (0–10 cm), the highest values were observed in TA-AFS4 and TA-AFS5 in Tomé-Açu, whereas RT-AFS3 showed the highest value in the Transamazon region. At the 30–40 cm depth, P concentrations decreased markedly, reaching 0.12 mg kg^{-1} in RT-AFS4, a value close to that observed in the TA-VS reference area.

The concentrations of Ca^{2+}, Mg^{2+}, Na^{+}, and K^{+} varied significantly among land-use systems and soil depths, with the highest values observed in TA-AFS5 in Tomé-Açu and RT-AFS5 in the Transamazon region, particularly in the surface layer (0–10 cm), where they were similar to those found in the TA-VS area. In contrast, RT-AFS2 and RT-AFS3 in the Transamazon region, as well as TA-AFS1 and TA-AFS2 in Tomé-Açu, exhibited lower values in the deeper soil layers, showing a pattern similar to that observed in the RT-VS area (Table S1).

Exchangeable Al^{3+} and potential acidity (H^{+} + Al) also differed significantly among land-use systems and soil depths (Table S1). The highest Al^{3+} concentrations were observed in TA-AFS3 in the Tomé-Açu and RT-AFS3 in the Transamazon region, particularly in the 30–40 cm layer, and were frequently exceeded by the RT-VS area at most soil depths. In contrast, RT-AFS5 and TA-AFS4 exhibited lower Al^{3+} concentrations throughout the soil profile (Fig. 2).

For H^{+} + Al, the highest values were observed in RT-AFS1 in the Transamazon region and TA-AFS3 in Tomé-Açu in the surface layer (0–10 cm), with the RT-VS area again showing the highest values at the same depth. In contrast, TA-AFS4 in Tomé-Açu and RT-AFS4 in the Transamazon region exhibited lower H^{+} + Al values throughout the soil profile (Fig. 2 and Table S1).

The sum of exchangeable bases (SB) and cation exchange capacity (CEC) also differed significantly among the evaluated systems, with the highest values observed in RT-AFS5 in the Transamazon region and TA-AFS5 in Tomé-Açu. SB values ranged from 5.46 to 12.54 Cmolc kg^{-1}, whereas CEC ranged from 2.32 to 8.05 Cmolc kg^{-1}, with values similar to those observed in the VS areas. In contrast, TA-AFS1

exhibited SB values ranging from 1.78 to 4.83 Cmolc kg^{-1}, whereas RT-AFS1 ranged from 1.52 to 2.91 Cmolc kg^{-1}, representing the lowest values across all evaluated soil profiles (Table S1 and Fig. 2).

Micronutrient concentrations differed significantly among land-use systems and soil depths ($p \leq 0.05$) (Table S2). Copper (Cu), zinc (Zn), and manganese (Mn) concentrations varied among systems and soil depths, with the highest values observed in RT-AFS4 and RT-AFS5 in the Transamazon region and TA-AFS4 and TA-AFS5 in Tomé-Açu, which showed concentrations close to those observed in the TA-VS area. In contrast, systems such as TA-AFS3 and RT-AFS2 exhibited the lowest concentrations of these micronutrients, showing patterns similar to those observed in the RT-VS area (Fig. 3 and Table S2).

Iron (Fe) concentrations showed wide variation among land-use systems and soil depths. The highest values were observed in RT-AFS5 in the Transamazon region and TA-AFS3 in Tomé-Açu, particularly in the surface layer (0–10 cm), with concentrations close to those recorded in the RT-VS area. In contrast, the lowest Fe concentrations in the surface layer (0–10 cm) were observed in RT-AFS2 (146.11 mg kg^{-1}) and TA-AFS5 (190.33 mg kg^{-1}), respectively (Table S2 and Fig. 4).

Multivariate analyses

Principal component analysis (PCA) showed that the first two principal components explained a substantial proportion of the variability in soil chemical properties. The first principal component (PC1) accounted for 52.2% of the total variance, whereas the second principal component (PC2) explained 19.9%, resulting in a cumulative explained variance of 72.1% (Fig. 6). The PCA loadings indicated that PC1 was positively associated with Ca, Mg, Na, K, SB, CEC, Cu, Zn, and Mn, whereas negative loadings were mainly associated with Al and $H^+ + Al$. Iron (Fe) also showed negative loadings, although with lower magnitude (Table 2).

Table 2
Principal component analysis (PCA) loadings for soil chemical properties at the 0–10, 10–20, 20–30, and 30–40 cm soil depths in organic CAFSs and VS areas in the Tomé-Açu and Transamazon regions. The values indicate the magnitude and direction of the association between soil chemical properties and the first (PC1) and second (PC2) principal components

Factor	Direction	Variance (%)	0–10 cm	10–20 cm	20–30 cm	30–40 cm
PCA I	(-)	Al	-0,359	-0,395	-0,551	-0,677
		Fe				-0,450
		H + Al			-0,325	-0,508
	(+)	Ca	0,937	0,849	0,908	0,911
		CTC	0,799	0,724	0,654	0,516
		Cu	0,926	0,928	0,927	0,925
		K	0,794	0,891	0,894	0,760
		Mg	0,898	0,876	0,814	0,877
		Mn	0,649	0,623	0,392	0,890
		Na	0,464	0,654	0,708	0,791
		Sb	0,978	0,918	0,948	0,958
		Zn	0,981	0,978	0,963	0,964
PCA II	(-)	Al	-0,825	-0,834	-0,694	-0,596
		CTC	-0,520	-0,488	-0,665	-0,757
		Fe	-0,894	-0,844	-0,710	-0,477
		H + AL	-0,872	-0,876	-0,868	-0,788
	(+)	Mn			0,488	
		P	0,450	0,389	0,358	

For PC2, negative loadings were associated with Al, CEC, H^+ + Al, and Fe, whereas positive loadings were mainly associated with P and Mn (Table 2). The distribution of the samples in the biplot showed a clear separation among the systems along the principal component axes (Fig. 5).

Hierarchical cluster analysis (HCA) revealed the formation of five distinct major groups (G1–G5), considering a cutoff point close to a normalized Euclidean distance of 4 (Fig. 6). The systems RT-AFS5, RT-AFS1, RT-VS, and TA-VS showed greater dissimilarity from the other systems, were assigned to groups G1, G2, and G3 only at higher Euclidean distances (> 8–10).

In contrast, the systems RT-AFS2, TA-AFS1, TA-AFS2, and TA-AFS3 clustered at lower Euclidean distances (< 4), forming group G4, indicating greater similarity in their soil chemical properties. Group G5, comprising TA-AFS5, TA-AFS4, RT-AFS3, and RT-AFS4, showed an intermediate similarity pattern, being positioned between the more homogeneous groups and those with a higher degree of dissimilarity among the evaluated systems (Fig. 6).

Spearman's correlation analysis revealed consistent patterns of association among soil chemical properties (Fig. 7). Strong positive correlations were observed between Ca and SB (r = 0.97), Ca and Mg (r = 0.76), Mg and Zn (r = 0.86), Mg and Mn (r = 0.75), as well as between SB and CEC (r = 0.63). In contrast, Al showed negative correlations with Ca (r = − 0.75), Mg (r = − 0.63), SB (r = − 0.65), Zn (r = − 0.65), and Mn (r = − 0.63), highlighting the adverse effect of soil acidity on nutrient availability and soil fertility. H^+ + Al also showed moderate negative correlations with several attributes related to soil fertility. The micronutrients Zn, Cu, and Mn showed moderate positive correlations with one another and with attributes associated with soil fertility, suggesting a relationship among these elements within the soil environment (Fig. 7).

Linear regression analysis revealed significant relationships between the establishment age of the land-use systems and some soil chemical properties, with variations among regions and soil depths ($p \leq 0.05$) (Table 3). In Tomé-Açu, a positive effect of system age on P and Zn concentrations was observed. The positive regression coefficients indicated an increase in P concentrations at the 10–20 cm and 30–40 cm soil depths as system age increased, whereas Zn concentrations increased in the surface layer (0–10 cm). In contrast, Fe showed a negative relationship with system age in the 0–10 cm layer (b_1 = −25.860; R^2 = 0.86; $p \leq 0.05$), indicating a decrease in its concentration with increasing age of the organic CAFSs.

Table 3
Linear regression models between the establishment age of the land-use systems (years) and soil chemical properties in the Tomé-Açu and Transamazon regions at different soil depths. The regression coefficients (b_0 and b_1), coefficient of determination (R^2), and statistical significance level ($p \leq 0.05$) are presented

Region	Regression with land-use system age (AGE)					
	Soil depth	Property	b_0	b_1	R^2	p
TA	10–20 cm	P	-3.484	0.344	0.78	0.03075
TA	30–40 cm	P	-4.055	0.306	0.84	0.01787
TA	0–10 cm	Zn	-1.95	0.217	0.75	0.03724
TA	0–10 cm	Fe	979.439	-25.86	0.86	0.01544
RT	30–40 cm	Na	-0.1	0.021	0.8	0.02575
RT	0–10 cm	Mg	-0.42	0.082	0.97	0.00124
RT	10–20 cm	Mg	-0.43	0.062	0.98	0.00076
RT	20–30 cm	Mg	-0.17	0.041	0.92	0.00643
RT	30–40 cm	Mg	-0.18	0.039	0.92	0.0068
RT	10–20 cm	Cu	-31.44	2.179	0.73	0.04113
RT	20–30 cm	Cu	-29.7	2.076	0.78	0.02956
RT	30–40 cm	Cu	-26.65	1.881	0.81	0.02428
RT	0–10 cm	Zn	-16.03	1.125	0.8	0.02657
RT	10–20 cm	Zn	-10.1	0.702	0.72	0.04273
RT	30–40 cm	Mn	-22.63	1.987	0.96	0.00203

In the Transamazon region, significant increases in Na, Mg, Cu, Zn, and Mn concentrations were observed with increasing system age (Table 3). Sodium showed a significant increase only at the 30–40 cm soil depth, whereas Mg exhibited a positive relationship with system age at all evaluated soil depths, with high coefficients of determination (R^2 ranging from 0.92 to 0.98; $p \leq 0.01$). Copper concentrations increased significantly at the 10–20 cm, 20–30 cm, and 30–40 cm soil depths. Zinc showed positive relationships with system age at the 10–20 cm and 30–40 cm depths, whereas Mn exhibited a significant increase only at the 30–40 cm depth.

Discussion

Nutrient dynamics and soil chemical properties

The distribution of nutrients and soil chemical properties in the Tomé-Açu and Transamazon regions followed both the typical patterns of highly weathered Amazonian soils and the influence of land use and vegetation cover on the dynamics of soil chemical properties (Tables S1 and S2). The higher P concentrations observed in the surface layers of the organic CAFSs, particularly in TA-AFS4 and TA-AFS5 in Tomé-Açu and RT-AFS3 in the Transamazon region, are associated with the low mobility of this nutrient within the soil profile, its adsorption by iron and aluminum oxides, which are characteristic of the predominant soil types in the Brazilian Amazon, and the greater input of organic residues through litterfall (Agbeshie et al. 2025; Arthur et al. 2022; Marques et al. 2025).

However, this pattern was not observed in RT-AFS5, which, despite its longer establishment period, exhibited low P concentrations. These results may be explained by the influence of additional factors, such as differences in soil texture (Table S1) and greater P adsorption associated with soil mineralogy, a pattern also reported by Santos et al. (2023) in the Tomé-Açu region. Furthermore, the reduction in P concentrations with increasing soil depth reflects the low mobility of this element within the soil profile, a characteristic typical of highly weathered tropical environments (Souza et al. 2018; Souza et al. 2025; Zaia et al. 2012).

The high concentrations of exchangeable Al^{3+} and potential acidity (H^{+} + Al) observed in RT-VS and RT-AFS1 in the Transamazon region, as well as in TA-AFS3 in Tomé-Açu, reflect the naturally high acidity of Amazonian soils, which is often intensified by the leaching of base cations under conditions of high rainfall, as found in the regions evaluated in this study. Similar results were reported by Chaves et al. (2020) and Santos et al. (2023), who observed higher concentrations of these properties in VS areas than in organic CAFSs.

Based on the soil acidity results (Table S1), it is important to note that high concentrations of Al^{3+} reduce the availability of Ca^{2+} and Mg^{2+}, limit nutrient uptake by plants, and contribute to unfavorable chemical conditions for plant growth (Ofoe et al. 2023; Ur Rahman et al. 2024). This behavior is consistent with the findings reported by Souza et al. (2025), who observed an association between higher soil acidity, higher Al^{3+} concentrations, and lower soil chemical fertility in Amazonian soils under AFSs.

Conversely, the higher concentrations of Ca^{2+}, Mg^{2+}, Na^{+}, and K^{+}, together with the higher values of the sum of exchangeable bases (SB) and cation exchange capacity (CEC) observed in RT-AFS5 in the Transamazon region and TA-AFS5 in Tomé-Açu, indicate improvements in soil fertility associated with agroforestry management and the longer establishment age of the evaluated systems. These results indicate more favorable soil chemical conditions in these AFSs than in the VS areas. Similar findings were reported by Butzke et al. (2020); Marques et al. (2025) and Suárez et al. (2021), who observed gradual improvements in soil fertility in organic CAFSs, which were attributed to the accumulation of organic material and enhanced nutrient cycling. In the present study, the improvement in soil fertility observed in some agroforestry systems (RT-AFS5 and TA-AFS5) is probably associated with greater litterfall input, enhanced nutrient cycling, and increased organic residues (Asigbaase et al. 2021), factors that contribute to greater cation retention and increased CEC (Rofner et al. 2022).

However, Martial et al. (2026) evaluated a chronosequence of organic CAFSs ranging from 7 to 52 years under low-input management and observed reductions in Ca^{2+} and Mg^{2+} in the older systems, together with the partial maintenance of K^{+} and Na^{+}, indicating that the response of soil fertility to the establishment age of organic CAFSs may vary according to the management practices adopted, the input of organic residues, and local soil and climatic conditions. In contrast, Wartenberg et al. (2017) found that increasing the diversity of shade trees in organic CAFSs established for up to 15 years did not promote significant improvements in soil properties such as CEC, pH, and aggregate stability. Therefore, the differences observed among the land-use systems in the Tomé-Açu and Transamazon regions further suggest a strong influence of edaphoclimatic conditions and land-use history on nutrient dynamics (Gama-Rodrigues et al. 2021; Takoutsing et al. 2016).

The higher concentrations of Cu, Zn, and Mn observed in RT-AFS5 in the Transamazon region and TA-AFS4 and TA-AFS5 in Tomé-Açu indicate greater availability of these micronutrients in environments with higher soil fertility. These results are consistent with those reported by Vasconcelos et al. (2020) and Pinho et al. (2012), who associated these micronutrients with management quality and the efficiency of biogeochemical nutrient cycling in organic CAFSs in the state of Pará. In contrast, structurally less complex systems, such as RT-AFS2 in the Transamazon region and TA-AFS3 in Tomé-Açu, exhibited lower concentrations of these micronutrients, possibly due to less efficient nutrient cycling and greater susceptibility to leaching in highly weathered tropical soils, such as those of the Brazilian Amazon, as discussed by Chaves et al. (2020). Despite this, Santos et al. (2023) observed that, even in organic CAFSs with improved soil fertility properties, the spatial distribution of nutrients remained heterogeneous, indicating a strong influence of land-use history, soil texture, and management practices on soil chemical dynamics.

The high Fe concentrations observed in RT-AFS5 in the Transamazon region and TA-AFS3 in Tomé-Açu, although lower than those in the reference system (VS), reflect the nature of highly weathered tropical soils, in which this element occurs predominantly in the form of stable oxides (Santos et al. 2018). Similar findings were reported by Chaves et al. (2020) in a study conducted in the Tomé-Açu region, Pará, where higher Fe concentrations were observed in VS areas than in organic CAFSs. This behavior indicates that Fe dynamics are more closely related to soil mineralogy and the advanced degree of weathering than exclusively to management practices, a pattern also discussed by Santos et al. (2023) for highly weathered soils of the Eastern Amazon.

Multivariate analyses

The results of the principal component analysis (PCA) revealed a soil fertility gradient in which Ca, Mg, Na, K, SB, CEC, Cu, Zn, and Mn were positively associated, whereas exchangeable Al^{3+}, potential acidity (H^{+} + Al), and Fe tended to be positioned in the opposite direction. This pattern indicates a separation between properties related to soil fertility and variables associated with soil acidity, as reported in other studies conducted on tropical soils (Dawoe et al. 2014; Marques et al. 2025; Rousseau et al. 2012; Souza et al. 2025). However, Suárez et al. (2021), evaluating different land-use systems in the Colombian

Amazon, observed a different distribution of some nutrients in the PCA, suggesting that the multivariate organization of soil chemical properties may vary according to vegetation composition as well as edaphic, climatic, and management factors.

Spearman's correlation analysis (Fig. 7) partially reinforced this pattern, mainly through the negative correlations of exchangeable Al^{3+} with Ca, Mg, SB, Zn, and Mn, whereas potential acidity (H^{+} + Al) showed variable relationships with the other properties, indicating that soil acidity acts as a limiting factor for soil fertility, although its influence depends on the property evaluated (Martial et al. 2026; Souza et al. 2018; Souza et al. 2025). This behavior is consistent with the findings of Marques et al. (2025), who reported negative correlations between exchangeable Al^{3+} and the basic nutrients, as well as a positive association among pH, Ca, Mg, and P.

The distinct position of P in the biplot (Fig. 5) suggests a different behavior compared with the other nutrients, which may be associated with its low mobility and strong interaction with Fe and Al^{3+} oxides, responsible for controlling its adsorption and availability in highly weathered tropical soils (Kongor et al. 2018). In this regard, Huera-Lucero et al. (2025) and Vera-Vélez et al. (2021) also reported a distinct behavior of P in multivariate analyses of Amazonian soils under different land-use systems. Likewise, Cu, Zn, and Mn showed positive correlations mainly with some basic cations and soil fertility properties, indicating that their availability tends to be greater in environments with more favorable chemical conditions and a higher nutrient retention capacity (Agbeshie et al. 2025).

The formation of distinct clusters in the hierarchical cluster analysis (HCA), particularly for systems such as RT-AFS5 in the Transamazon region and TA-AFS5 and TA-VS in Tomé-Açu (Fig. 6), despite having similar establishment ages, indicates marked differences in the edaphic characteristics of these environments. In contrast, systems with similar physicochemical characteristics formed clusters at shorter Euclidean distances (< 4), reflecting greater chemical similarity among the areas and a possible influence of management practices and vegetation composition (Oliveira et al. 2015; Souza et al. 2025).

The HCA showed that the similarity among the systems is more closely related to soil chemical conditions and management practices than exclusively to the establishment age of the systems, corroborating the findings of Agbeshie et al. (2025), who highlighted the role of agroforestry management in improving soil quality. Furthermore, the formation of distinct groups between the systems in the Tomé-Açu and Transamazon regions suggests a strong influence of environmental characteristics and management practices on the chemical structure of the systems and nutrient dynamics in the soil (Miccolis et al. 2016).

The regression analysis showed that the establishment age of the systems significantly influences nutrient dynamics, with marked differences between the evaluated regions (Table 3). In Tomé-Açu, P and Zn concentrations increased with increasing system age, indicating the progressive accumulation of these nutrients over time, possibly related to greater litterfall input and enhanced biogeochemical nutrient cycling (Vanhove et al. 2016). In contrast, Fe concentrations decreased in the surface layer with

increasing system age, suggesting redistribution within the soil profile or interaction with SOM, a pattern similar to that reported by Alberto Quesada et al. (2020) and Vanhove et al. (2016).

In the Transamazon region, the effect of system establishment age was more pronounced, with significant increases in Na, Mg, Cu, Zn, and Mn concentrations, indicating progressive soil enrichment over the establishment period of the organic CAFSs (Table 3). This pattern suggests that older systems promote greater nutrient accumulation and gradual improvements in soil fertility, particularly in environments with greater inputs of plant residues and enhanced biogeochemical nutrient cycling (Arthur et al. 2022; Suárez et al. 2021). This response differs from that reported by Martial et al. (2026) in a chronosequence of organic CAFSs ranging from 7 to 52 years under low-input management in Cameroon. The organic CAFSs evaluated in the present study showed a progressive increase in nutrient concentrations with increasing establishment age, suggesting that differences in management, vegetation composition, and environmental conditions may modulate soil fertility dynamics in organic CAFSs in tropical regions.

Mg exhibited a positive relationship with system establishment age at all evaluated soil depths (Table 3). Copper concentrations increased at the 10–20 cm, 20–30 cm, and 30–40 cm soil depths, whereas Zn concentrations increased at the 0–10 cm and 10–20 cm depths, both with high coefficients of determination ($R^2 > 0.71$), reinforcing the strong relationship between system age and the gradual improvement of soil chemical properties (Schroth et al. 2016; Suárez et al. 2021). In turn, Mn showed a significant increase at greater soil depth, suggesting possible vertical mobility associated with pedogenetic processes and soil management (Adiyah et al. 2022; Fonkeng et al. 2024).

These results indicate that, although system establishment age is an important factor, its influence is modulated by edaphoclimatic conditions, being more pronounced in the Transamazon region than in Tomé-Açu (Table 3). Previous studies have attributed this pattern to the progressive accumulation of SOM and the enhancement of nutrient cycling over time in tropical organic CAFSs (Alberto Quesada et al. 2020; Arthur et al. 2022). Similarly, Biloa et al. (2025) demonstrated that improvements in soil chemical properties in organic CAFSs result from the interaction among management practices, establishment age, and environmental conditions, reinforcing the role of these systems in restoring soil fertility and promoting ecosystem services.

Conclusions

Organic CAFSs promote significant improvements in soil chemical properties compared with VS areas and less structurally complex systems, highlighting their potential for restoring deforested areas and enhancing soil fertility in highly weathered Amazonian soils. The older systems exhibited greater nutrient availability and fewer chemical constraints related to soil acidity, indicating that longer establishment age, together with agroforestry management, enhances biogeochemical nutrient cycling.

Multivariate analyses demonstrated that soil chemical dynamics are strongly influenced by the interaction among management practices, soil conditions, and system establishment age, resulting in

distinct fertility patterns between the evaluated regions. Furthermore, the organic CAFSs contributed to greater soil chemical stability and higher nutrient retention, particularly in the Transamazon region, reinforcing their role as a sustainable strategy for restoring degraded areas and maintaining ecosystem services in the Amazon.

Therefore, organic CAFSs have considerable potential to reconcile agricultural production with environmental conservation in tropical environments. However, future studies should integrate soil physical and biological properties, as well as soil carbon stocks, to improve the understanding of the long-term sustainability of these systems on the Amazon.

Declarations

Funding:

This study was supported by the Coordination for the Improvement of Higher Education Personnel (CAPES) through a doctoral scholarship and by the National Council for Scientific and Technological Development (CNPq).

Competing Interests: The authors declare that they have no competing interests.

Data Availability: The datasets generated and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Author Contribution

T.N.C. conceived the study, curated the data, performed the formal analyses, conducted the investigation, developed the methodology, validated the results, prepared the visualizations, and wrote the original manuscript draft. M.L.P.R. contributed to the conceptualization, formal analysis, funding acquisition, investigation, methodology, resources, project administration, supervision, validation, and manuscript review and editing. M.P.M.B. contributed to the conceptualization, formal analysis, investigation, methodology, validation, and manuscript review and editing. A.S.M. contributed to the formal analysis, validation, and manuscript review and editing. M.M.J. contributed to the software, formal analysis, visualization, and manuscript review and editing. J.E.L.D. contributed to the data curation, formal analysis, validation, and manuscript review and editing. B.S.F.S. contributed to the formal analysis, visualization, and manuscript review and editing. All authors read and approved the final manuscript.

Acknowledgements

The authors gratefully acknowledge the Museu Paraense Emílio Goeldi (MPEG), particularly the Soil Laboratory, for providing laboratory facilities, equipment, and technical support for the processing and

analysis of the soil samples.

References

1. Adiyah, F., Micheli, E., Csorba, A., Weldmichael, T. G., Gyuricza, C., Ocansey, C. M., Dawoe, E., Owusu, S., & Fuchs, M. (2022). Effects of landuse change and topography on the quantity and distribution of soil organic carbon stocks on Acrisol catenas in tropical small-scale shade cocoa systems of the Ashanti region of Ghana. *CATENA*, *216*. https://doi.org/10.1016/j.catena.2022.106366
2. Agbeshie, A. A., Asei, R., & Awuah, R. (2025). Age-dependent variations in soil carbon stocks and biogeochemical attributes under cocoa agroforests in Bono, Ghana. *Agroforestry Systems*, *99*(8). https://doi.org/10.1007/s10457-025-01349-8
3. Alberto Quesada, C., Paz, C., Oblitas Mendoza, E., Lawrence Phillips, O., Saiz, G., & Lloyd, J. (2020). Variations in soil chemical and physical properties explain basin-wide Amazon forest soil carbon concentrations. *SOIL*, *6*(1), 53–88. https://doi.org/10.5194/soil-6-53-2020
4. Alvares, C. A., Stape, J. L., Sentelhas, P. C., De Moraes Gonçalves, J. L., & Sparovek, G. (2013). Köppen's climate classification map for Brazil. *Meteorologische Zeitschrift*, *22*(6), 711–728. https://doi.org/10.1127/0941-2948/2013/0507
5. Alves, V. da P. (2021). *Determinantes do desmatamento no estado do Pará: uma análise com regressões quantílicas para dados em painel*. www.rbgdr.net
6. Aragão, L. E. O. C., Anderson, L. O., Fonseca, M. G., Rosan, T. M., Vedovato, L. B., Wagner, F. H., Silva, C. V. J., Silva Junior, C. H. L., Arai, E., Aguiar, A. P., Barlow, J., Berenguer, E., Deeter, M. N., Domingues, L. G., Gatti, L., Gloor, M., Malhi, Y., Marengo, J. A., Miller, J. B., … Saatchi, S. (2018). 21st Century drought-related fires counteract the decline of Amazon deforestation carbon emissions. *Nature Communications*, *9*(1). https://doi.org/10.1038/s41467-017-02771-y
7. Arthur, A., Acquaye, S., Cheng, W., Dogbatse, J. A., Konlan, S., Domfeh, O., & Quaye, A. K. (2022). Soil carbon stocks and main nutrients under cocoa plantations of different ages. *Soil Science and Plant Nutrition*, *68*(1), 99–103. https://doi.org/10.1080/00380768.2022.2029219
8. Asigbaase, M., Dawoe, E., Lomax, B. H., & Sjogersten, S. (2021). Temporal changes in litterfall and potential nutrient return in cocoa agroforestry systems under organic and conventional management, Ghana. *Heliyon*, *7*(10). https://doi.org/10.1016/j.heliyon.2021.e08051
9. Beuchle, R.., Achard, F., Bourgoin, C., & Vancutsem, C. (2022). *Deforestation and forest degradation in the Amazon: status and trends up to year 2021*. Publications Office of the European Union.
10. Biloa, J. B., Monique, A., Giweta, M. H., Fiaboe, K. K. M., Samuel, N. N., Mandah, P. V., Essobo, J. D., Onana, A., & Cargele, M. (2025). Influence of cocoa farm age and slope, and shade rate on cocoa soils fertility. *Environmental Challenges*, *19*. https://doi.org/10.1016/j.envc.2025.101115
11. Butzke, A. G., De Oliveira, T. K., De Paula, A. E. B., & Da Silva Fiuza, S. (2020). Soil fertility and organic carbon in two decades of agroforestry systems composed of Brazil nut, cupuaçuzeiro and peach palm in the Western Amazon. *Cientifica*, *48*(2), 160–169. https://doi.org/10.15361/1984-5529.2020v48n2p160-169

12. Catuxo, V. T. da S., Vieira, M. E., & Gonçalves, C. da S. (2024). Evaluation of deforestation in the municipality of Brasil Novo in the state of Pará - Brazil, using machine learning techniques. *Mercator*, *23*(2024), 1–15. https://doi.org/10.4215/rm2024.e23029
13. Chaves, S. F. da S., Gama, M. A. P., Alves, R. M., de Oliveira, R. P., Pedroza Neto, J. L., & Lima, V. M. N. (2020). Evaluation of physicochemical attributes of a yellow latosol under agroforestry system as compared to secondary forest in the Eastern Amazon. *Agroforestry Systems*, *94*(5), 1903–1912. https://doi.org/10.1007/s10457-020-00513-6
14. da Cruz, D. C., Benayas, J. M. R., Ferreira, G. C., Santos, S. R., & Schwartz, G. (2021). An overview of forest loss and restoration in the Brazilian Amazon. In *New Forests* (Vol. 52, Issue 1). Springer Science and Business Media B.V. https://doi.org/10.1007/s11056-020-09777-3
15. Dawoe, E. K., Quashie-Sam, J. S., & Oppong, S. K. (2014). Effect of land-use conversion from forest to cocoa agroforest on soil characteristics and quality of a Ferric Lixisol in lowland humid Ghana. *Agroforestry Systems*, *88*(1), 87–99. https://doi.org/10.1007/s10457-013-9658-1
16. de Lima, R. F., de Oliveira Aparecido, L. E., Torsoni, G. B., & de Souza Rolim, G. (2023). Climate Change Assessment in Brazil: Utilizing the Köppen-Geiger (1936) Climate Classification. *Revista Brasileira de Meteorologia*, *38*. https://doi.org/10.1590/0102-77863810001
17. de Souza, J. C., Pereira, M. A., da Costa, E. N. D., & da Silva, D. M. L. (2018). Nitrogen dynamics in soil solution under different land uses: Atlantic forest and cacao–cabruca system. *Agroforestry Systems*, *92*(2), 425–435. https://doi.org/10.1007/s10457-017-0077-6
18. de Vasconcelos, W. L. F., Rodrigues, D. de M., Silva, R. O. C., & Alfaia, S. S. (2020). Diversity and abundance of soil macrofauna in three land use systems in Eastern Amazonia. *Revista Brasileira de Ciencia Do Solo*, *44*, 1–16. https://doi.org/10.36783/18069657rbcs20190136
19. Dos Santos, C. R. C., Matsunaga, A. T., Costa, L. R. R., Dos Santos, M. L., Brasil Neto, A. B., Rodrigues, R. P., Maciel, M. de N. M., & DE MELO, V. S. (2023). Spatial variability of soil fertility under agroforestry system and native forest in Eastern Amazonia, Brazil. *Bioscience Journal*, *39*. Https://doi.org/10.14393/bj-v39n0a2023-62830
20. dos Santos, D. M., da Silva, K. A., dos Santos, J. M. F. F., & Araújo, E. de L. (2018). Soil seed bank and its importance in the natural regeneration of degraded areas. In *Ethnobiology and Conservation* (Vol. 7). Universidade Federal Rural de Pernambuco. https://doi.org/10.15451/ec2018-03-07.05-1-7
21. Dos Santos, R. S., Costa, A. de B. S., Gonçalves, B. S., & Ribeiro, S. da C. A. (2023). Sistemas agroflorestais e a produção de alimentos: uma experiência na cooperativa d'Irituia. *Revista de Gestão e Secretariado (Management and Administrative Professional Review)*, *14*(9), 15020–15026. https://doi.org/10.7769/gesec.v14i9.1705
22. Filgueiras, M. F., & Borges, E. M. (2021). Principal Component Analysis (PCA) and Statistical Tests Using Factoshiny and R Commander. In *Journal of Chemical Education*.
23. Fonkeng, E. E., Chevallier, T., Sauvadet, M., Enock, S., Rakotondrazafy, N., Chapuis-Lardy, L., Takoutsing, B., Tabi Fritz, O., & Harmand, J. M. (2024). Dynamics of soil organic carbon pools

following conversion of savannah to cocoa agroforestry systems in the Centre region of Cameroon. *Geoderma Regional*, *36*. https://doi.org/10.1016/j.geodrs.2024.e00758

24. Gama-Rodrigues, A. C., Müller, M. W., Gama-Rodrigues, E. F., & Mendes, F. A. T. (2021). Cacao-based agroforestry systems in the Atlantic Forest and Amazon Biomes: An ecoregional analysis of land use. In *Agricultural Systems* (Vol. 194). Elsevier Ltd. https://doi.org/10.1016/j.agsy.2021.103270
25. Gama-Rodrigues, E. F., Nair, P. K. R., Nair, V. D., Gama-Rodrigues, A. C., Baligar, V. C., & Machado, R. C. R. (2010). Carbon storage in soil size fractions under Two cacao agroforestry systems in Bahia, Brazil. *Environmental Management*, *45*(2), 274–283. https://doi.org/10.1007/s00267-009-9420-7
26. Granato, D., Santos, J. S., Escher, G. B., Ferreira, B. L., & Maggio, R. M. (2018). Use of principal component analysis (PCA) and hierarchical cluster analysis (HCA) for multivariate association between bioactive compounds and functional properties in foods: A critical perspective. In *Trends in Food Science and Technology* (Vol. 72, pp. 83–90). Elsevier Ltd. https://doi.org/10.1016/j.tifs.2017.12.006
27. Huera-Lucero, T., Lopez-Piñeiro, A., & Bravo-Medina, C. (2025). Soil Quality Indicators for Different Land Uses in the Ecuadorian Amazon Rainforest. *Forests*, *16*(8). https://doi.org/10.3390/f16081275
28. Kongor, J. E., Boeckx, P., Vermeir, P., Van de Walle, D., Baert, G., Afoakwa, E. O., & Dewettinck, K. (2018). Assessment of soil fertility and quality for improved cocoa production in six cocoa growing regions in Ghana. *Agroforestry Systems*, 1–13. https://doi.org/10.1007/s10457-018-0253-3
29. Lal, R. (2020). Soil Organic Matter and Water Retention. *Agronomy Journal*, *112*, n. *5*, 3265–3277. https://doi.org/10.1002/agj2.20282.This
30. Marques, J. D., Dias, V. H. R., Gomes, M. F., Sampaio, I. M. G., Borges, G. B., Fiel, L. G., da Silva Júnior, M. L., & de Melo, V. S. (2025). Soil quality in an agroforestry system in the scenario of family farming in the eastern Amazon. *Agroforestry Systems*, *99*(6). https://doi.org/10.1007/s10457-025-01272-y
31. Martial, N. G., Zhao, Z., Gao, R., Yvana, M. M., Mubolo, J. K., Napoléon, A. K., Landry, T. A., Evarist, M., Mamert, A. T., Xue, B., & Meersmans, J. (2026). Soil Carbon and Nutrient Trajectories Across A 52–Year Cocoa Agroforestry Chronosequence Under Low–Input Smallholder Management. *Journal of Soil Science and Plant Nutrition*. https://doi.org/10.1007/s42729-026-03290-w
32. Miccolis, A., Peneireiro, F. M., Marques, H. R., Vieira, D. L. M., Arco-Verde, M. F., Hoffmann, M. R., Rehder, T., & Pereira, A. V. B. (2016). Restauração ecológica com sistemas agroflorestais: como conciliar conservação com produção. Opções para Cerrado e Caatinga. In *Centro Internacional de Pesquisa Agroflorestal*. https://www.embrapa.br/busca-de-publicacoes/-/publicacao/1069767/restauracao-ecologica-com-sistemas-agroflorestais-como-conciliar-conservacao-com-producao-opcoes-para-cerrado-e-caatinga
33. Miranda, R. S. de, Nogueira, L. da R., Rodrigues, M. S., Alves, A. M., Costa, M. S., & Amador, M. F. (2021). Analise do desmatamento nos periodos de 2016 a 2020 na Mesorregiao Sudeste Paraense. *Revista Ibero-Americana de Humanidades, Ciências e Educação*, *7*(5), 498–517. https://doi.org/10.51891/rease.v7i5.1209

34. Moura, R., Santos, D., Veríssimo, A., & Nunes, S. (2021). *Desmatamento ZERO no Pará: desafios e oportunidades* (T. C. Veríssimo (ed.)).
35. Mucova, S. A. R., Azeiteiro, U. M., Filho, W. L., Lopes, C. L., Dias, J. M., & Pereira, M. J. (2021). Approaching sea-level rise (Slr) change: Strengthening local responses to sea-level rise and coping with climate change in northern mozambique. *Journal of Marine Science and Engineering*, *9*(2), 1–17. https://doi.org/10.3390/jmse9020205
36. Nair, P. K. R., Kumar, B. M., & Nair, V. D. (2009). Agroforestry as a strategy for carbon sequestration. *Journal of Plant Nutrition and Soil Science*, *172*(1), 10–23. https://doi.org/10.1002/jpln.200800030
37. Nunes, S., Gastauer, M., Cavalcante, R. B. L., Ramos, S. J., Caldeira, C. F., Silva, D., Rodrigues, R. R., Salomão, R., Oliveira, M., Souza-Filho, P. W. M., & Siqueira, J. O. (2020). Challenges and opportunities for large-scale reforestation in the Eastern Amazon using native species. *Forest Ecology and Management*, *466*(December 2019), 118120. https://doi.org/10.1016/j.foreco.2020.118120
38. Ofoe, R., Thomas, R. H., Asiedu, S. K., Wang-Pruski, G., Fofana, B., & Abbey, Lord. (2023). Aluminum in plant: Benefits, toxicity and tolerance mechanisms. *Frontiers in Plant Science*, *13*(January), 1–24. https://doi.org/10.3389/fpls.2022.1085998
39. Oliveira, I. A. de, Campos, M. C. C., Freitas, L. de, & Soares, M. D. R. (2015). Caracterização de solos sob diferentes usos na região sul do Amazonas. *Acta Amazonica*, *45*(1), 1–12. https://doi.org/10.1590/1809-4392201400555
40. Pauletto, D., Guerreiro Martorano, L., de Sousa Lopes, L. S., Pinheiro de Matos Bentes, M., Vieira, T. A., Gomes de Sousa Oliveira, T., Santos de Sousa, V., Fernandes da Silva, Á., da Silva Ferreira de Lima, P., Santos Tribuzy, A., & Pinto Guimarães, I. V. (2023). Plant Composition and Species Use in Agroforestry Homegardens in the Eastern Amazon, Brazil. *Sustainability (Switzerland)*, *15*(14), 1–18. https://doi.org/10.3390/su151411269
41. Pinho, R. C., Miller, R. P., & Alfaia, S. S. (2012). Agroforestry and the improvement of soil fertility: A view from amazonia. In *Applied and Environmental Soil Science* (Vol. 2012). https://doi.org/10.1155/2012/616383
42. Prezotti, L. C., & Guarçoni M, A. (2013). Guia de interpretação de análise de Solo E Foliar. In *Incaper - Instituto Capixaba de Pesquisa, Assistência Técnica e Extensão Rural*.
43. Quesada, C. A., Lloyd, J., Anderson, L. O., Fyllas, N. M., Schwarz, M., & Czimczik, C. I. (2011). Soils of Amazonia with particular reference to the RAINFOR sites. *Biogeosciences*, *8*(6), 1415–1440. https://doi.org/10.5194/bg-8-1415-2011
44. Reimann, C., Filzmoser, P., Garrett, R. G., & Dutter, R. (2008). *Statistical data analysis explained: applied environmental statistics with R* (John Wiley & Sons Lt). John Wiley & Sons.
45. Rofner, N. F., Arce, M. P., Paredes Salazar, R. M., Vásquez, L. N., & Rojas, A. R. (2022). An organic management alternative that improves soil quality in cocoa plantations under agroforestry systems. *Scientia Agropecuaria*, *13*(4), 335–342. https://doi.org/10.17268/sci.agropecu.2022.030
46. Rolo, V., Rivest, D., Maillard, É., & Moreno, G. (2023). Agroforestry potential for adaptation to climate change: A soil-based perspective. In *Soil Use and Management* (Vol. 39, Issue 3, pp. 1006–1032).

John Wiley and Sons Inc. https://doi.org/10.1111/sum.12932

47. Rousseau, G. X., Deheuvels, O., Rodriguez Arias, I., & Somarriba, E. (2012). Indicating soil quality in cacao-based agroforestry systems and old-growth forests: The potential of soil macrofauna assemblage. *Ecological Indicators*, *23*, 535–543. https://doi.org/10.1016/j.ecolind.2012.05.008
48. Santos, H. G., Jacomine, P. K. T., Anjos, L. H. C., Oliveira, V. A., Lumbreras, J. F., Coelho, M. R., Almeida, J. A., Filho, J. C. A., Oliveira, J. B., & Cunha, T. J. F. (2018). *Sistema brasileiro de classificação de solos: Vol. 5ª edição*. Embrapa Brasília, DF.
49. Santos, M. R. da S., Vitorino, M. I., & Pimentel, M. A. da S. (2017). Vulnerabilidade e mudanças climáticas: análise socioambiental em uma mesorregião da Amazônia. *Revista Ambiente e Agua*, *9*(3), 842–854. https://doi.org/10.4136/1980-993X
50. Schroth, G., Garcia, E., Griscom, B. W., Teixeira, W. G., & Barros, L. P. (2016). Commodity production as restoration driver in the Brazilian Amazon? Pasture re-agro-forestation with cocoa (Theobroma cacao) in southern Pará. *Sustainability Science*, *11*(2), 277–293. https://doi.org/10.1007/s11625-015-0330-8
51. Silva, S. B. (2018). *Análise de Solo Para Ciências Agrárias, Belém*.
52. Souza, E. S. de, Fernandes, A. R., Braz, A. M. de S., Oliveira, F. J. de, Alleoni, L. R. F., & Campos, M. C. C. (2018). *Physical, chemical and mineralogical attributes of a representative group of soils from the Eastern Amazon, Brazil*. https://doi.org/10.5194/soil-2018-3
53. Souza, F. E. D. de, Oliveira, J. de N. dos S., Santos, C. R. C. dos, Ferreira, E. V. de O., Silva, R. T. L. da, Paula, M. T. de, Alves, J. D. N., Oliveira, J. S. R. de, Rodrigues, J. I. de M., & Martins, W. B. R. (2025). Physical and chemical soil quality and litter stock in agroforestry systems in the Eastern Amazonia. *Agriculture, Ecosystems and Environment*, *382*. https://doi.org/10.1016/j.agee.2025.109479
54. Suárez, L. R., Suárez Salazar, J. C., Casanoves, F., & Ngo Bieng, M. A. (2021). Cacao agroforestry systems improve soil fertility: Comparison of soil properties between forest, cacao agroforestry systems, and pasture in the Colombian Amazon. *Agriculture, Ecosystems and Environment*, *314*(April 2020). https://doi.org/10.1016/j.agee.2021.107349
55. Takoutsing, B., Weber, J. C., Tchoundjeu, Z., & Shepherd, K. (2016). Soil chemical properties dynamics as affected by land use change in the humid forest zone of Cameroon. *Agroforestry Systems*, *90*(6), 1089–1102. https://doi.org/10.1007/s10457-015-9885-8
56. Teixeira, P. C., Donagemma, G. K., Fontana, A., & Teixeira, W. G. (2017). *Manual de Metodos de Analise de Solo* (3ª edição Embrapa,). https://www.embrapa.br
57. Tinoco-Jaramillo, L., Vargas-Tierras, Y., Habibi, N., Caicedo, C., Chanaluisa, A., Paredes-Arcos, F., Viera, W., Almeida, M., & Vásquez-Castillo, W. (2024). Agroforestry Systems of Cocoa (Theobroma cacao L.) in the Ecuadorian Amazon. *Forests*, *15*(1). https://doi.org/10.3390/f15010195
58. Tscharntke, T., Clough, Y., Bhagwat, S. A., Buchori, D., Faust, H., Hertel, D., Hölscher, D., Juhrbandt, J., Kessler, M., Perfecto, I., Scherber, C., Schroth, G., Veldkamp, E., & Wanger, T. C. (2011). Multifunctional shade-tree management in tropical agroforestry landscapes - A review. *Journal of Applied Ecology*, *48*(3), 619–629. https://doi.org/10.1111/j.1365-2664.2010.01939.x

59. Ur Rahman, S., Han, J. C., Ahmad, M., Ashraf, M. N., Khaliq, M. A., Yousaf, M., Wang, Y., Yasin, G., Nawaz, M. F., Khan, K. A., & Du, Z. (2024). Aluminum phytotoxicity in acidic environments: A comprehensive review of plant tolerance and adaptation strategies. *Ecotoxicology and Environmental Safety*, *269*(December 2023), 115791. https://doi.org/10.1016/j.ecoenv.2023.115791
60. Vanhove, W., Vanhoudt, N., & Van Damme, P. (2016). Effect of shade tree planting and soil management on rehabilitation success of a 22-year-old degraded cocoa (Theobroma cacao L.) plantation. *Agriculture, Ecosystems and Environment*, *219*, 14–25. https://doi.org/10.1016/j.agee.2015.12.005
61. Venturieri, A., Oliveira, R. R. S. de, Igawa, T. K., Fernandes, K. D. A., Adami, M.,Júnior, M., Almeida, C. A., Silva, L. G. T., Cabral, A. I. R., Pinto, J. F. K. C.,Menezes, A. J. A., & Sampaio, S. M. N. (2022). The Sustainable Expansion of the Cocoa Crop in the State of Pará and Its Contribution to Altered Areas Recovery and Fire Reduction. *Journal of Geographic Information System*, *14*(03), 294–313. https://doi.org/10.4236/jgis.2022.143016
62. Vera-Vélez, R., Cota-Sánchez, J. H., & Grijalva-Olmedo, J. (2021). Beta diversity and fallow length regulate soil fertility in cocoa agroforestry in the Northern Ecuadorian Amazon. *Agricultural Systems*, *187*(August 2020). https://doi.org/10.1016/j.agsy.2020.103020
63. Wartenberg, A. C., Blaser, W. J., Gattinger, A., Roshetko, J. M., Van Noordwijk, M., & Six, J. (2017). Does shade tree diversity increase soil fertility in cocoa plantations? *Agriculture, Ecosystems and Environment*, *248*, 190–199. https://doi.org/10.1016/j.agee.2017.07.033
64. Zaia, F. C., Gama-Rodrigues, A. C., Gama-Rodrigues, E. F., Moço, M. K. S., Fontes, A. G., Machado, R. C. R., & Baligar, V. C. (2012). Carbon, nitrogen, organic phosphorus, microbial biomass and N mineralization in soils under cacao agroforestry systems in Bahia, Brazil. *Agroforestry Systems*, *86*(2), 197–212. https://doi.org/10.1007/s10457-012-9550-4

Figures

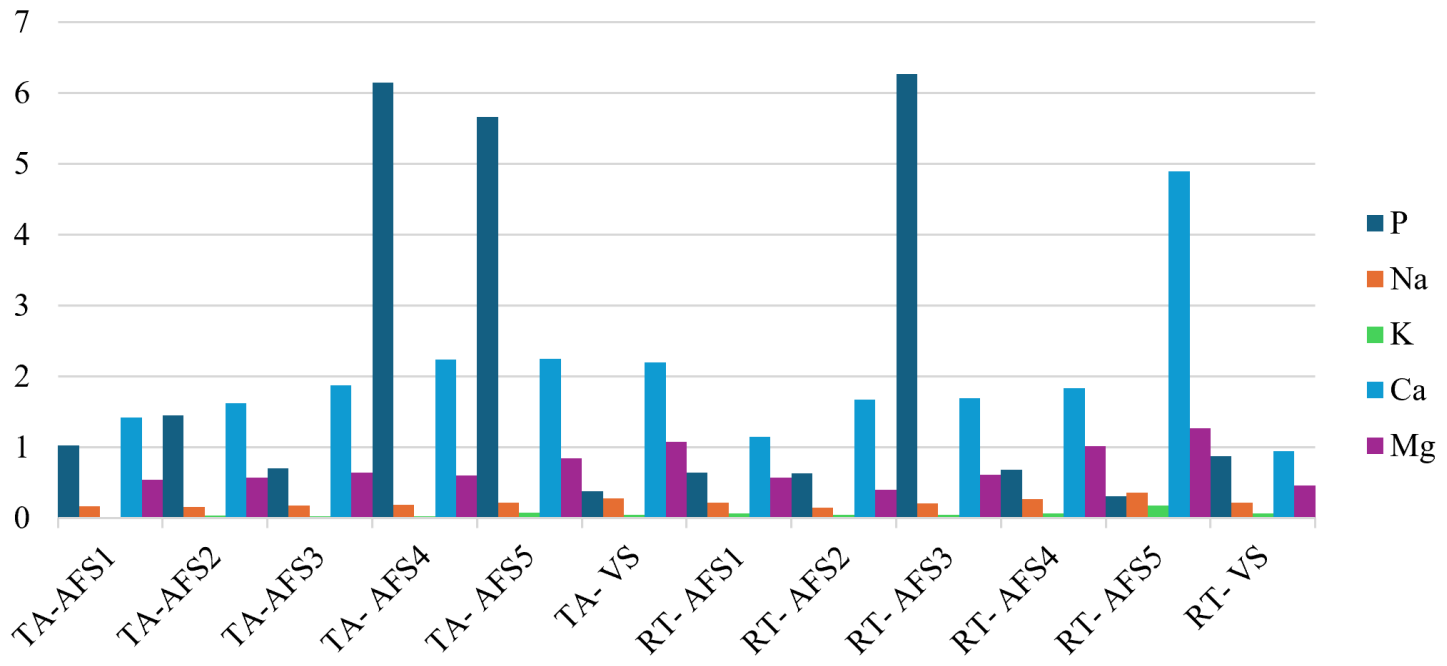

Figure 1

Distribution of macronutrient concentrations: phosphorus (P), sodium (Na), potassium (K), calcium (Ca), and magnesium (Mg) in different land-use systems in the municipality of Tomé-Açu (TA) and the Transamazon region (RT), Pará State, Brazil

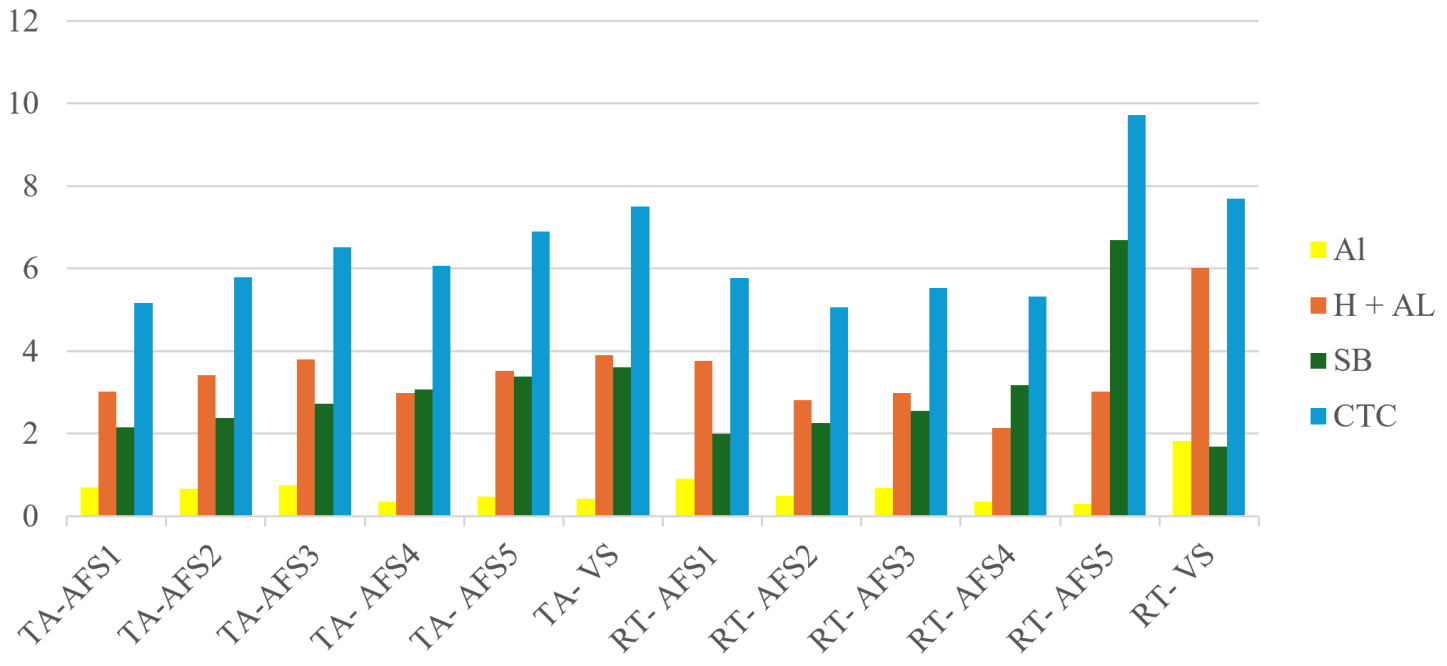

Figure 2

Distribution of exchangeable aluminum (Al^{3+}), potential acidity (H^{+} + Al), sum of exchangeable bases (SB), and cation exchange capacity (CEC) in different land-use systems in the municipality of Tomé-Açu

(TA) and the Transamazon region (RT), Pará State, Brazil

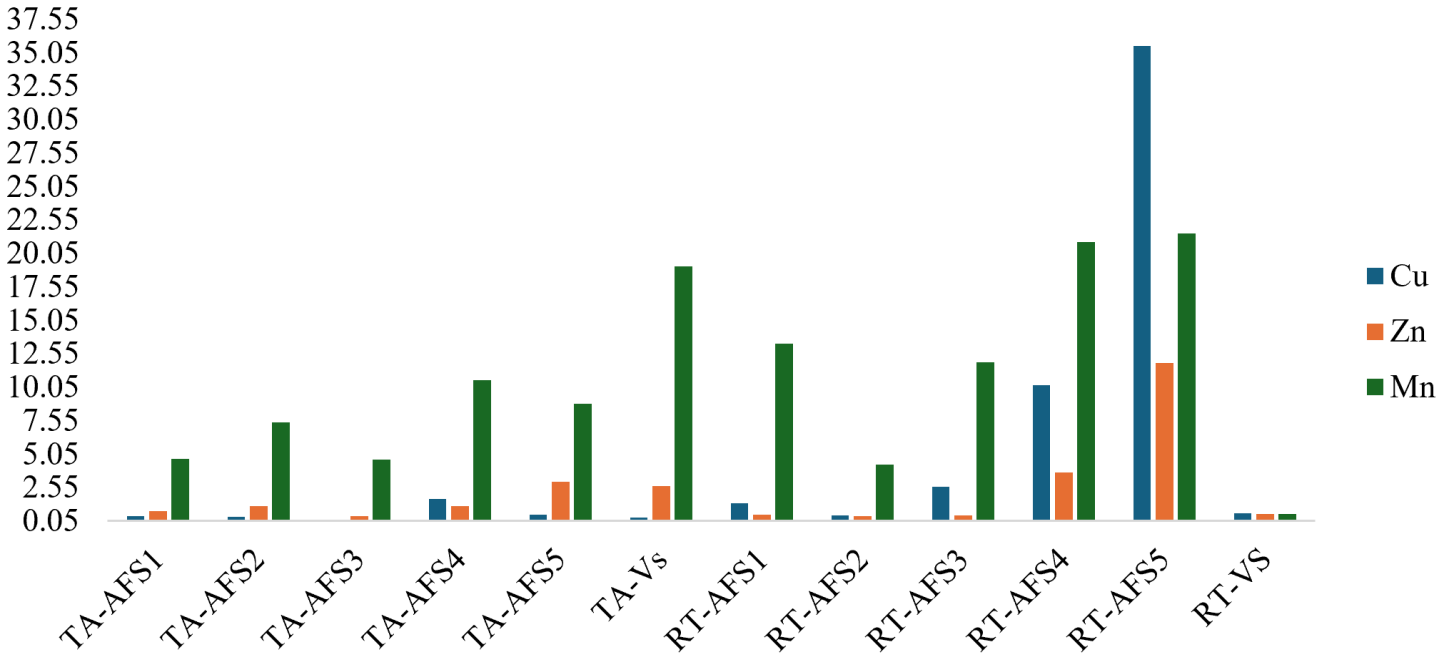

Figure 3

Distribution of micronutrient concentrations: copper (Cu), zinc (Zn), and manganese (Mn) in different land-use systems in the municipality of Tomé-Açu (TA) and the Transamazon region (RT), Brazilian Amazon

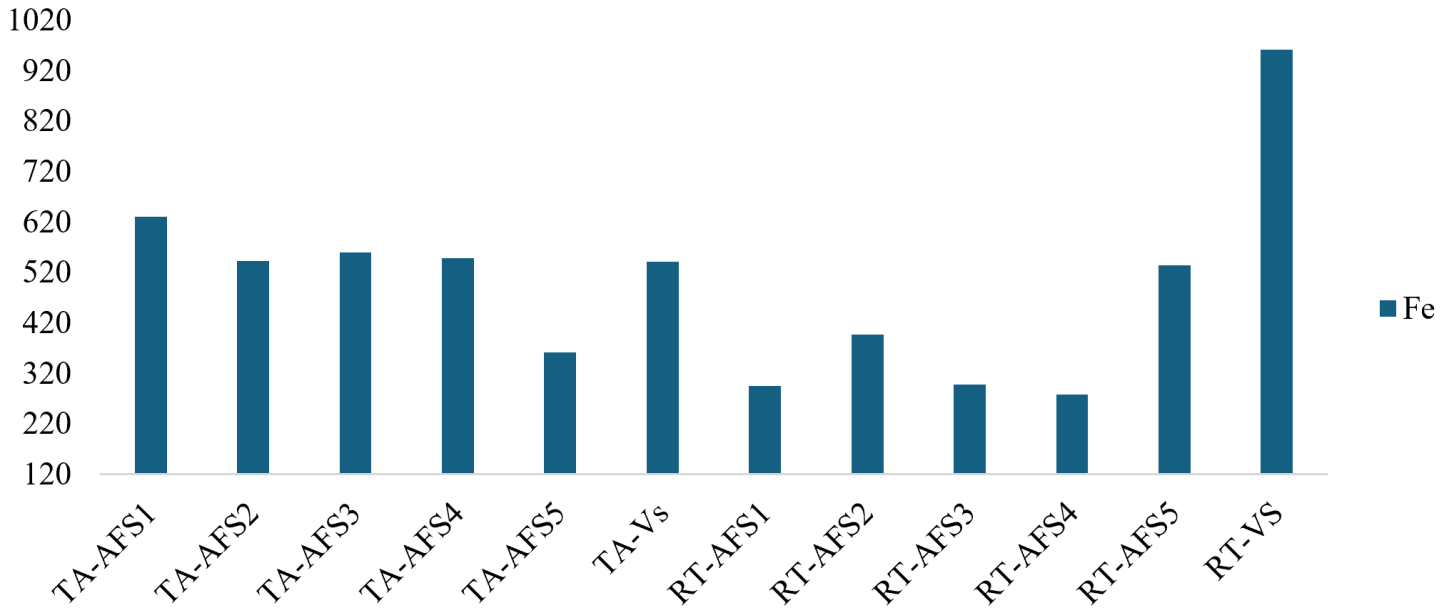

Figure 4

Distribution of iron (Fe) concentrations in different land-use systems in the municipality of Tomé-Açu (TA) and the Transamazon region (RT), Brazilian Amazon

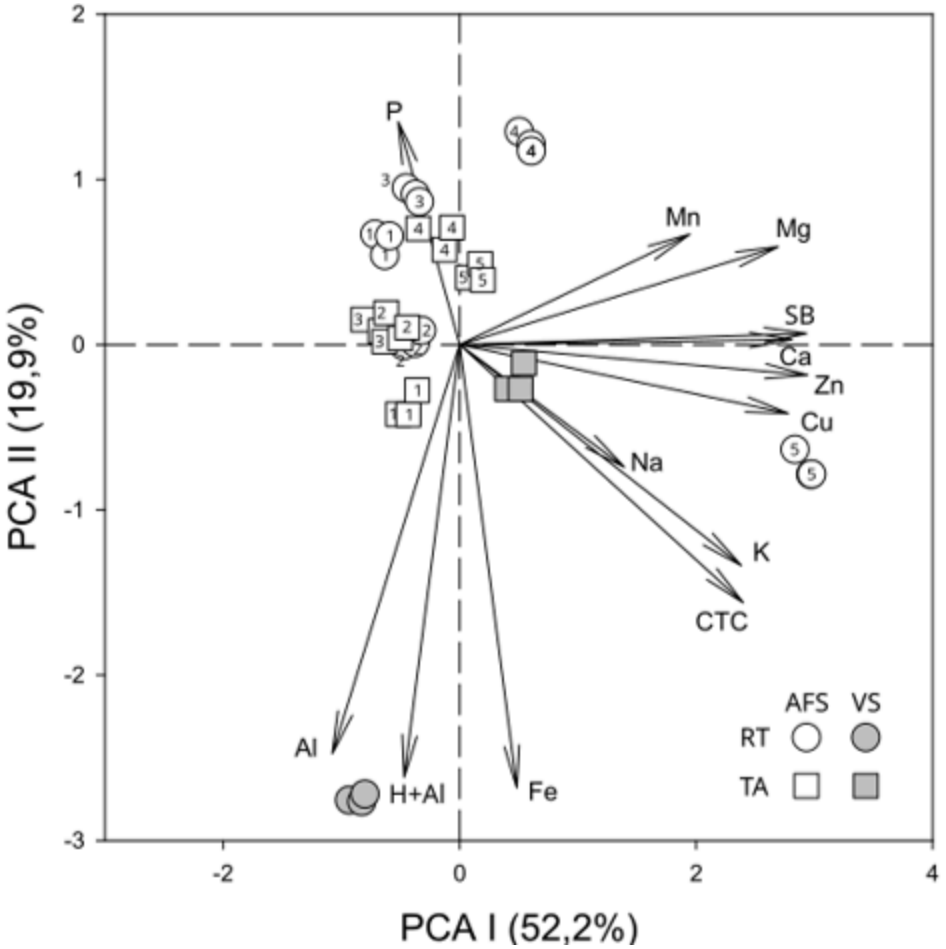

Figure 5

PCA biplot of soil chemical properties in organic CAFSs and VS areas in the Tomé-Açu and Transamazon regions. The arrows represent the soil chemical properties and their contribution to the PCA axes

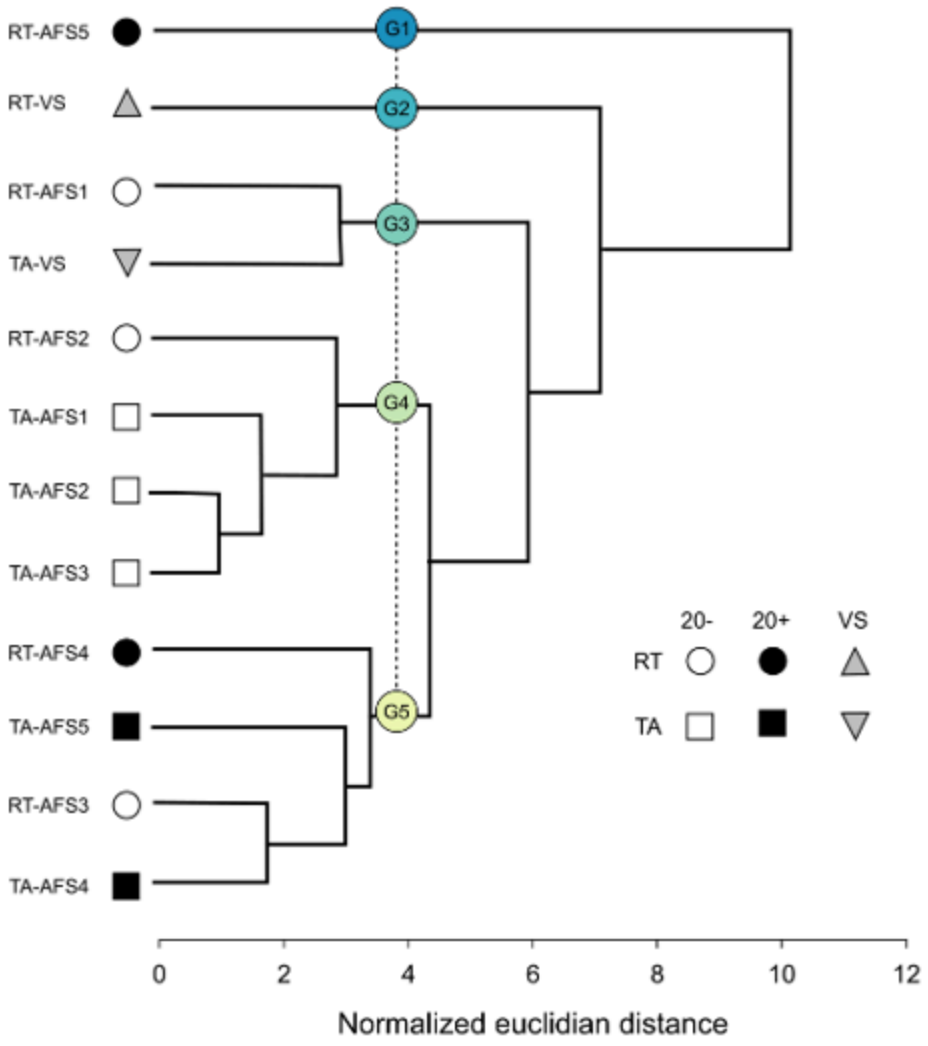

Figure 6

Hierarchical cluster analysis (HCA) of the organic CAFSs and VS areas in the Tomé-Açu and Transamazon regions, based on the similarity of soil chemical properties and system age, using normalized Euclidean distance. G, hierarchical groups (G1–G5); RT and TA (< 20, less than 20 years; ≥ 20, 20 years or more), age of the organic CAFSs

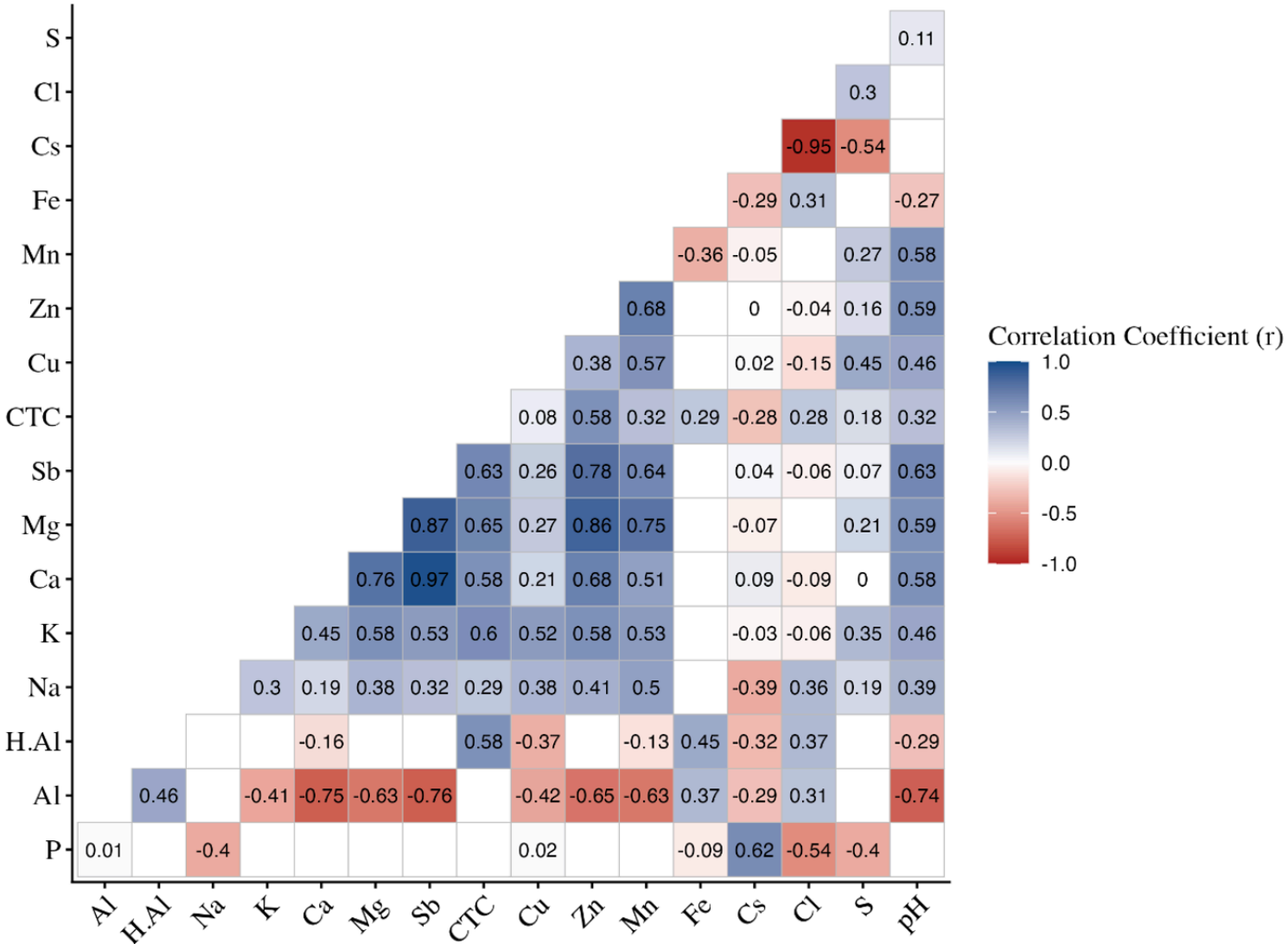

Figure 7

Spearman's correlation matrix of soil chemical properties in organic CAFSs and VS areas in the Tomé-Açu and Transamazon regions. The values represent Spearman's correlation coefficients (r) among the evaluated soil chemical properties

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- SuplementalS1.docx