



OPEN ACCESS

EDITED BY

Calogero Schillaci,
Joint Research Centre, Italy

REVIEWED BY

Rosa Ana Rodríguez,
Facultad de Ingeniería–Universidad
Nacional de San Juan, Argentina
Mauro De Feudis,
University of Bologna, Italy

*CORRESPONDENCE

Carlos Abanto-Rodríguez
✉ cabanto@iiap.gob.pe

RECEIVED 07 November 2025

REVISED 10 February 2026

ACCEPTED 12 February 2026

PUBLISHED 05 March 2026

CITATION

Abanto-Rodríguez C, Blas JCG,
Torres DdC, Ramírez-Flores N,
Soria DGG, Ambrosio MFM,
Arévalo HG, Arévalo WFG, Nieto JAB,
Tenazoa NMP, Sakasaki RT,
Neto JLLM, Revilla-Chávez JM and
Murga-Orrillo H (2026) Soil functioning
indicators decline with land-use
intensification in the Peruvian Amazon:
evidence from Ucayali.
Front. Soil Sci. 6:1741629.
doi: 10.3389/fsoil.2026.1741629

COPYRIGHT

© 2026 Abanto-Rodríguez, Blas, Torres,
Ramírez-Flores, Soria, Ambrosio, Arévalo,
Arévalo, Nieto, Tenazoa, Sakasaki, Neto,
Revilla-Chávez and Murga-Orrillo. This is
an open-access article distributed under
the terms of the [Creative Commons
Attribution License \(CC BY\)](#). The use,
distribution or reproduction in other
forums is permitted, provided the
original author(s) and the copyright
owner(s) are credited and that the
original publication in this journal is
cited, in accordance with accepted
academic practice. No use, distribution
or reproduction is permitted which does
not comply with these terms.

Soil functioning indicators decline with land-use intensification in the Peruvian Amazon: evidence from Ucayali

Carlos Abanto-Rodríguez^{1*}, Juan Carlos Guerra Blas²,
Dennis del Castillo Torres¹, Noe Ramírez-Flores¹,
Diego Gonzalo García Soria¹, María Fernanda Moya Ambrosio¹,
Héctor Guerra Arévalo¹, Wilson Francisco Guerra Arévalo¹,
John Alison Bravo Nieto¹, Nadia Masaya Panduro Tenazoa³,
Roberto Tadashi Sakasaki⁴, João Luiz Lopes Monteiro Neto⁴,
Jorge Manuel Revilla-Chávez¹ and Hipolito Murga-Orrillo⁵

¹Peruvian Amazon Research Institute (IIAP), Iquitos, Loreto, Peru, ²National Institute for Space Research (INPE), São José dos Campos, São Paulo, Brazil, ³National Intercultural University of the Amazon (UNIA), Pucallpa, Ucayali, Peru, ⁴Federal University of Roraima (UFRR), Boa Vista, Roraima, Brazil, ⁵National Autonomous University of Alto Amazonas (UNAAA), Yurimaguas, Loreto, Peru

Introduction: Rapid land-use change in the Peruvian Amazon threatens soil processes that sustain productivity and ecosystem resilience. This study assessed soil functioning indicators along a land-use intensification gradient in Ucayali, Peru.

Methods: We evaluated physicochemical (texture fractions, pH, organic matter, cation-exchange capacity, carbon, and micronutrients) and biological indicators (cultivable microbial groups, microbial biomass carbon, respiration, and macrofauna) from 54 independent composite topsoil samples (0–20 cm) across seven land-use systems, multiple localities, and soil texture classes. Principal component analysis and univariate tests were applied to identify multivariate gradients and significant differences among groups.

Results: PCA revealed a dominant texture–fertility gradient contrasting sand-rich soils with finer-textured soils associated with higher CEC, organic matter, total carbon, and micronutrients (notably Mn and Cu). Significant differences among land-use systems were detected for CEC, OM, Mn, pH, Cu, SOC, and sand. Cacao agroforestry differed from pasture and oil palm systems in key fertility indicators. Biological indicators showed weaker global separation, although macrofauna differed significantly among land uses.

Conclusion: Soil texture modulated baseline fertility and the expression of land-use impacts. Cacao agroforestry and secondary forests occupied transitional

positions between forests and intensive systems. A reduced monitoring set including texture fractions, OM, CEC, pH, Mn, and selected biological metrics is recommended for tracking soil degradation in heterogeneous Amazonian landscapes.

KEYWORDS

cacao agroforestry, cation-exchange capacity, land-use intensification, macrofauna, oil palm, Peruvian Amazon, soil health, soil organic carbon

1 Introduction

The Peruvian Amazon is experiencing one of the most rapid territorial transformations in recent decades, driven by land-use and land-cover change (including deforestation for agriculture and pasture expansion) and demographic growth. These dynamics threaten biodiversity, global climate regulation, food security, and rural livelihoods that depend on well-functioning soils that sustain key biogeochemical and biological processes (1, 2). The Ucayali region, located in the central Peruvian Amazon, encompasses 102,411 km² (8% of Peru and 13% of the national Amazon) (3). Historically, its landscape was dominated by primary (85%) and secondary forests (10%) (4). However, between 2001 and 2023, Ucayali lost approximately 7.7% of its forest cover (~790,000 ha), becoming the most deforested region in the country, especially in Padre Abad and Coronel Portillo province (5, 6).

Land-use change from forest to crops and pastures triggers cascading effects on soils by reducing organic matter inputs and altering biogeochemical cycles, which accelerates nutrient losses (N, P, K, Ca²⁺, Mg²⁺) and drives soil acidification and degradation (2, 7, 8). These changes reduce agricultural productivity and weaken the resilience of local food systems. Recent evidence confirms this trend: primary forests store the highest soil carbon stocks, followed by secondary forests, whereas degraded pastures store substantially less carbon (1, 6, 9). This loss of carbon reduces ecosystem resilience and contributes to global warming through CO₂ emissions (10, 11).

Land-use change also affects soil physical properties (structure, aggregation, porosity) and biological attributes (microbial communities and soil fauna), altering core soil functions (12–14). However, most Amazonian soil studies still emphasize chemical indicators only (15, 16), and integrated assessments remain rare. Although emerging multifunctionality indices show promise (17), their application in the Peruvian Amazon is still limited.

In this context, the concept of soil functioning is used to refer to the integrated capacity of soils to sustain key physical, chemical, and biological processes that underpin ecosystem stability and productivity. Rather than quantifying individual soil functions directly (e.g., water regulation or primary production), the study evaluates soil functioning through an indicator-based framework that integrates physical (e.g., texture fractions), chemical (e.g., pH, organic matter, cation-exchange capacity, micronutrients), and biological (e.g., microbial biomass, respiration, cultivable microbial groups, and soil macrofauna) variables, following an approach sensu Bastida et al. (15) Naval et al. (17) Trejo et al. (18). Declines in these indicators can be interpreted as evidence of

reduced functional integrity and soil resilience under land-use intensification.

Therefore, this study aims to assess indicators of soil functioning by integrating chemical, physical, and biological variables across a land-use intensification gradient in Ucayali, Peru. Specifically, the study (i) quantifies how soil indicators differ among disturbed primary and secondary forests, cacao-based agroforestry, oil palm plantations of contrasting ages, and degraded pastures, and (ii) evaluates the extent to which soil texture modulates these indicators across land use systems. It provides locally relevant evidence to inform agroecological management and sustainability policies in the Peruvian Amazon.

2 Materials and methods

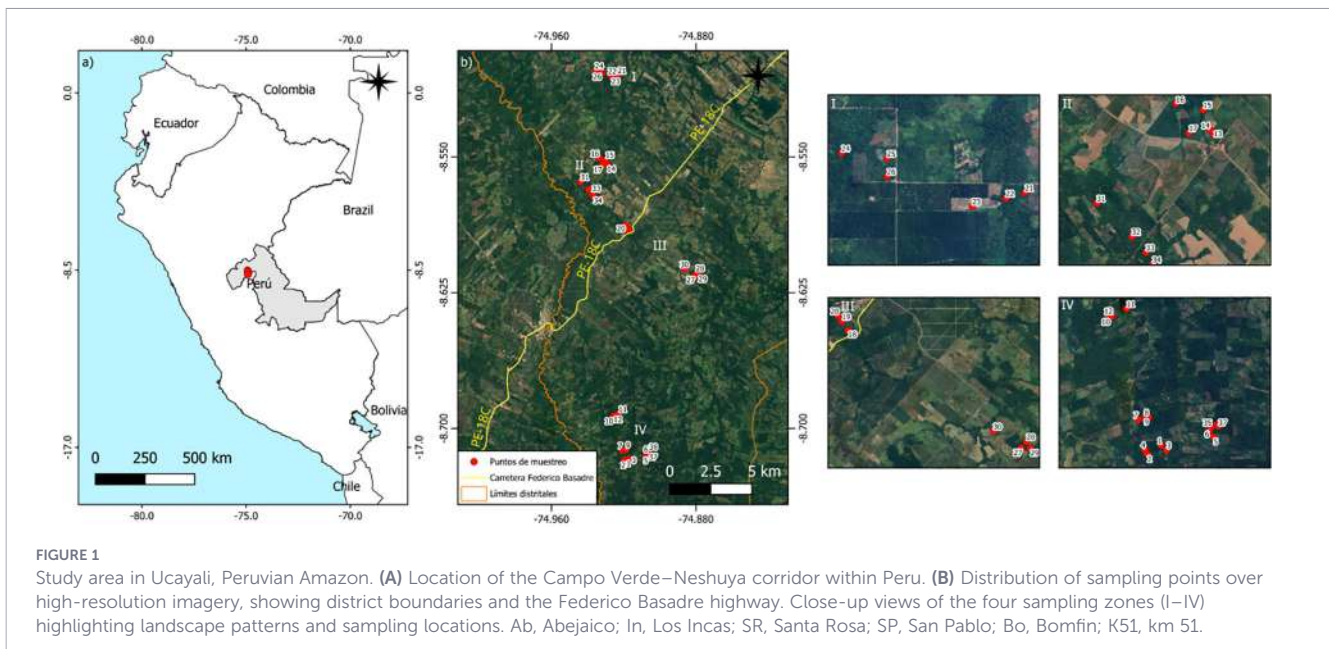
2.1 Study area and land-use systems

Field sampling was conducted between June and October 2024 in agricultural landscapes along the Federico Basadre highway, between the districts of Campo Verde and Neshuya, within the provinces of Coronel Portillo and Padre Abad, Ucayali, Peru (Figure 1). The region has a warm, humid tropical climate (B(r) A), with mean annual precipitation of approximately 2,090 mm concentrated between December and April, and mean temperatures ranging from 19 °C (July–August) to 33 °C (September–October) (Servicio Nacional de Meteorología e Hidrología del Perú (19).

According to national soil maps, soils across the Campo Verde–Neshuya corridor (lowland Peruvian Amazon, Pucallpa region) are predominantly Entisols and Inceptisols, characterized by weak to incipient horizon development, with Ultisols occurring locally to a lesser extent (20, 21). Although all sites belong to the same regional soil group, they differ in surface texture (clay loam, loam, sandy clay loam, and sandy loam).

The study followed a non-experimental, correlational, explanatory design to evaluate indicators of *soil functioning* associated with land-use change. Stratified sampling was used to represent the dominant land-use systems in the landscape. Seven systems were included: degraded primary forest (DPF), secondary forest (DSF), cacao-based agroforestry (Tc), oil palm plantations aged 1–9 years (Eg1), 10–18 years (Eg2), and 19–35 years (Eg3), and pasturelands dominated by *Brachiaria decumbens* (Pas) (Figure 2).

Land-use history and stand age were characterized by integrating farmer and landowner interviews with land-cover trajectories derived from MapBiomass Peru Collection 3 (1985–



2024). Degraded primary forests correspond to areas selectively logged or partially disturbed mainly during the 1990s and early 2000s, without sustained conversion to agriculture. Secondary forests represent regenerating stands following clear-cutting or shifting cultivation, with recovery periods of approximately 15–20 years. Cacao agroforestry systems were established on previously forested soils mainly between 2005 and 2015, whereas pasturelands have been under continuous grazing for approximately two

decades. Oil palm plantations were established on former forest soils and classified into age classes according to the first year of persistent oil palm detection in MapBiomass (Table 1).

2.2 Soil sampling design

A total of 54 independent composite soil samples were collected across six localities: Abejaico (Ab), Los Incas (In), Santa Rosa (SR),



FIGURE 2
Representative land-use systems sampled in Campo Verde–Neshuya, Ucayali, Peru: **(A)** disturbed primary forest (DPF), **(B)** secondary forest (DSF), **(C)** cacao-based agroforestry (Tc), **(D)** oil palm plantations 1–9 years old (Eg1), **(E)** oil palm 10–18 years old (Eg2), **(F)** oil palm 19–35 years old (Eg3), and **(G)** pasture (Pas) dominated by *Brachiaria decumbens*.

TABLE 1 Land-use history summary for each land-use system and locality in Campo Verde–Neshuya, Ucayali, Peru, based on farmer/landowner interviews and MapBiomass Peru Collection 3 (1985–2024) land-cover trajectories.

System	Locality	<i>n</i>	Dominant prior land cover	First non-forest year (median)	Age range (years)	Dominant trajectory
DPF	Ab, SR, K51	6	Forest	1995	20–30	Forest → Mosaic → Forest
DSF	Ab, SP, Bo	10	Forest	1990	20–35	Mosaic → Forest
Tc	Ab	6	Forest	2005	10–20	Forest → Mosaic
Pas	Ab, SR, In	5	Forest	2000	15–25	Forest → Mosaic/Pasture
Eg1	SP, In	5	Forest	2016	1–9	Forest → Mosaic → Oil palm
Eg2	Ab, SR, Bo	19	Forest	2004	10–18	Forest → Mosaic → Oil palm
Eg3	SP, Bo	3	Forest	1992	19–35	Forest → Mosaic → Oil palm

Sample size (*n*) per land-use system.

San Pablo (SP), Bomfin (Bo), and km 51 (K51). Each sampling unit consisted of a single polygon (3–5 ha) representing one land-use system within a given locality. Within each polygon, the area was divided into four quadrants, and a zigzag transect was established. Multiple subsamples were collected at approximately 30-step intervals using a V-shaped pit at 0–20 cm depth. Subsamples from each polygon were composited into a single sample, which was treated as the independent replicate for statistical analyses. This strategy minimizes microscale heterogeneity while avoiding pseudo-replication.

Sampling was carried out under dry conditions and avoided saturated soils, recently fertilized areas, and proximity to roads, dwellings, wetlands, burned zones, or other localized disturbances. All tools were disinfected with 90% ethanol between sampling points. Samples were stored in sterile bags, labeled, and transported to the laboratory under controlled conditions. All samples and associated metadata are publicly available in Zenodo (22).

2.3 Management practices

Overall management intensity across the study area is low. In oil palm plantations, soil disturbance is generally restricted to the planting phase, with no routine tillage thereafter. Fertilization is sporadic and non-standardized, typically involving occasional NPK applications. In some plantations, *Pueraria thomsonii* is used as a cover crop; however, most sites exhibit either bare soil or spontaneous vegetation that is periodically slashed. Pruned fronds and fruit bunch residues are usually left on the soil surface or piled between planting rows.

Cacao agroforestry systems are managed with minimal soil disturbance, limited to planting holes. Shade trees are retained, and litter and pruning residues are left on the soil surface. Pastures are managed under continuous grazing with low stocking density and receive neither fertilization nor mechanical soil preparation after establishment. A summary of management characteristics and land-use history is provided in Table 1.

2.4 Laboratory analyses

Soil chemical and physical analyses were carried out at the Soil, Plant, Water and Fertilizer Analysis Laboratory (LASPAF–

UNALM) following the laboratory’s standardized routine protocols (Table 2). Soil texture (sand, silt, and clay) was determined by the hydrometer method. Soil salinity was assessed as electrical conductivity (EC), measured either in a 1:1 soil:water extract or in the saturation-paste extract, depending on sample requirements. Soil reaction (pH) was measured potentiometrically in a 1:1 soil:water suspension and, when required, in KCl (soil: solution 1:2.5). Calcium carbonate content (CaCO₃) was quantified by a gas-volumetric method using a calcimeter.

Organic matter content (OM) was determined by the Walkley–Black wet oxidation method and converted to organic carbon using the factor 1.724. Total nitrogen content was measured by the micro-Kjeldahl method. Available phosphorus (P) was extracted using the (modified) Olsen procedure (0.5 M NaHCO₃, pH 8.5) and subsequently quantified according to the laboratory’s standard colorimetric determination described in Table 2. Exchangeable base cations, including K⁺ (as well as Ca²⁺, Mg²⁺ and Na⁺, where applicable), were extracted with 1 N ammonium acetate (NH₄OAc) at pH 7.0 and quantified following the procedures in Table 2. Cation exchange capacity (CEC) was determined by ammoniumacetate saturation at pH 7.0. Exchangeable acidity (H + Al) was measured by the Yuan method using KCl extraction. Soluble ions (Ca²⁺, Mg²⁺, K⁺, Na⁺, Cl[−], CO₃^{2−}, HCO₃[−], NO₃[−], SO₄^{2−}), as well as soluble boron and gypsum, were quantified following the procedures listed in Table 2.

2.5 Microbiological indicators and soil macrofauna

Microbiological analyses were performed at the IIAP laboratory. Cultivable bacteria, fungi, and actinomycetes were quantified by the dilution–plating method using selective culture media and incubation at 28 °C. Gravimetric soil moisture was determined by oven-drying at 105 °C. Microbial respiration was quantified as CO₂ evolution during incubation and expressed as mg CO₂ g^{−1} dry soil day^{−1}. Microbial biomass carbon (MBC) was determined by the fumigation–extraction method and expressed as mg C g^{−1} dry soil.

Soil macrofauna was sampled using 70 soil monoliths (25 × 25 × 30 cm) following Anderson and Ingram (23). Monoliths were stratified into 0–10, 10–20, and 20–30 cm layers. Macrofauna

TABLE 2 Analytical methodologies used for soil physicochemical indicators, according to the routine procedures listed in the document “Methods followed in the soil analysis” (p. 1).

Variable	Method/extractant	Key conditions/determination	Units
Texture (sand, silt, clay)	Hydrometer method	Particle-size distribution by sedimentation	%
Salinity (EC)	Electrical conductivity	Aqueous extract (soil:water 1:1) or saturation-paste extract (ECe/ECes)	dS m ⁻¹
Soil reaction (pH)	Potentiometry	Soil:water 1:1; alternatively KCl, soil:solution 1:2.5	–
Calcium carbonate (CaCO ₃)	Gas-volumetric (calciometer)	Volumetric determination with a calciometer	% or g kg ⁻¹
Organic matter (OM)	Walkley–Black	Wet oxidation; OM = %O.M. = %C × 1.724	% or g kg ⁻¹
Total nitrogen (N)	Micro-Kjeldahl	Digestion–distillation–titration	g kg ⁻¹
Available phosphorus (P)	Modified Olsen	NaHCO ₃ 0.5 M, pH 8.5; colorimetry	mg kg ⁻¹
Available potassium (K)	Ammonium acetate extraction	CH ₃ COONH ₄ (neutral), pH 7.0	mg kg ⁻¹ or cmol _c kg ⁻¹
CEC (CIC/CTC)	Ammonium acetate saturation	CH ₃ COONH ₄ , pH 7.0 (saturation method)	cmol _c kg ⁻¹
Exchangeable Ca, Mg, K, Na	Ammonium acetate displacement	Replacement with CH ₃ COONH ₄ (pH 7.0); flame photometry and/or AAS	cmol _c kg ⁻¹
Exchangeable acidity (H+Al)	Yuan method	KCl extraction; N (normal) solution; titration	cmol _c kg ⁻¹
Soluble ions: Ca ²⁺ , Mg ²⁺ , K ⁺ , Na ⁺	Soluble fraction	Flame photometry and/or AAS	mmol _c L ⁻¹
Soluble ions: Cl ⁻ , CO ₃ ²⁻ , HCO ₃ ⁻ , NO ₃ ⁻	Soluble fraction	Volumetry and/or colorimetry	mmol _c L ⁻¹
Soluble sulfate (SO ₄ ²⁻)	Turbidimetry	BaCl ₂ turbidimetry	mg L ⁻¹
Soluble boron (B)	Water extraction	Quantification with curcumin	mg L ⁻¹
Soluble gypsum	Water solubilization	Precipitation with acetone	g L ⁻¹

were manually sorted, preserved in 4% formaldehyde, and identified at the IIAP Bioterium Laboratory.

2.6 Data analysis

This approach was chosen to avoid overparameterization and loss of power given the unbalanced design across land-use systems, localities, and texture classes.

Univariate differences in soil properties were tested separately for each grouping factor (land-use system, sampling locality, and soil texture class) using one-factor-at-a-time models, in order to isolate the marginal effects of each factor and facilitate interpretation across heterogeneous sampling strata. One-way analysis of variance (ANOVA) was applied when residual normality and homoscedasticity were not rejected (Shapiro–Wilk test on model residuals and Levene’s test, respectively; $p \geq 0.05$). When at least one assumption was violated, Kruskal–Wallis tests (rank-based) were used. *Post-hoc* pairwise comparisons were conducted using Tukey’s HSD following ANOVA, or Dunn’s test with Holm adjustment following Kruskal–Wallis. Pairwise contrasts were interpreted in relation to the corresponding global test, and statistical significance was set at $p \leq 0.05$.

To explore multivariate patterns, we performed Principal Component Analysis (PCA) separately on three functional blocks of variables: (i) soil physicochemical properties, (ii) soil biological indicators, and (iii) microbial respiration and associated variables. Prior to PCA, variables were inspected for skewness; microbial counts (CFU) were log₁₀-transformed when appropriate, and all variables were centered and scaled to unit variance. Records with missing values were excluded on a per-analysis basis. To reduce

noise and avoid overweighting highly redundant indicators, variables showing near-zero association with the global correlation structure ($|r| < 0.01$) or near-redundancy ($|r| > 0.98$) were removed during data pre-processing, following Caruso and Cliff (24) Mardia et al. (25). PCA loadings for Dim1–Dim2 are summarized in Table 3. For visualization and interpretation, we focused on the first two components, which captured the dominant multivariate gradients within each variable block.

To further explore the joint influence of land-use systems and soil texture, key soil indicators (CEC, organic matter, manganese, and microbial biomass carbon) were stratified by texture class and summarized using boxplots. These plots depict medians, interquartile ranges, and extreme values, allowing visual comparison of land-use effects within each texture class. This exploratory analysis was interpreted in conjunction with the corresponding global and pairwise inferential tests.

Additional biological indicators, including soil macrofauna abundance, cultivable microbial groups (bacteria, fungi, and actinomycetes), microbial biomass carbon (MBC), soil respiration, and the metabolic quotient (qCO₂), were analyzed separately to assess functional responses to land-use change. Cultivable microbial abundances were log₁₀-transformed prior to analysis. Differences among land-use systems were evaluated using one-way ANOVA or Kruskal–Wallis tests, depending on data distribution and variance homogeneity, followed by appropriate *post-hoc* comparisons. These indicators were summarized graphically to illustrate system-level trends in soil biological structure and function.

Using the same set of retained variables, group-level variation was summarized by estimating mean values and 95% confidence intervals (CI) for land-use systems (Figure 3), sampling localities

TABLE 3 PCA loadings for the first two dimensions (Dim1–Dim2) by variable block (physicochemical, biological, and respiration indicators) in Campo Verde–Neshuya, Ucayali, Peru.

Block	Variable	Dim1	Dim2
Biological	Bacteria	-0.6673	0.1199
Biological	Actinomycetes	-0.5784	0.3675
Biological	Fungi	-0.4554	-0.4414
Biological	Macrofauna	-0.1130	-0.8098
Physicochemical	Sand	0.3643	-0.0191
Physicochemical	OM	-0.3636	-0.1612
Physicochemical	Clay	-0.3613	0.1181
Physicochemical	tC	-0.3560	0.0440
Physicochemical	CEC	-0.3540	-0.1131
Physicochemical	Silt	-0.2937	-0.0647
Physicochemical	Mn	-0.2924	-0.2235
Physicochemical	K	-0.2906	0.1747
Physicochemical	Cu	-0.2420	0.1969
Physicochemical	P	-0.1206	0.0480
Physicochemical	Fe	-0.1160	0.6502
Physicochemical	pH	-0.0984	-0.6297
Respiration	Gmoisture	0.7153	0.2482
Respiration	mgC	0.6972	-0.3169
Respiration	CO ₂ d	0.0474	0.9154

Positive/negative values indicate the direction and strength of each variable's contribution to each axis.

(Figure 3), and texture classes (Figure 3). Confidence intervals were computed around the mean as mean $\pm$ 1.96 $\times$ SE using the normal approximation.

Associations between microbiological indicators and physicochemical properties were evaluated using Pearson correlation analysis. Correlation significance was assessed at $p \leq 0.05$; when multiple correlations were evaluated simultaneously, p -values were adjusted using the Benjamini–Hochberg false discovery rate (FDR) procedure ($q \leq 0.05$).

All analyses were conducted in R (26) using the packages tidyverse, rstatix, broom, FactoMineR, factoextra, corrplot, and ggplot2.

3 Results

3.1 Multivariate structure of soil properties and functional indicators

The principal component analyses (PCA) summarized in Figure 4 reveal consistent multivariate gradients across land-use systems, localities, and soil texture classes. The contribution of individual variables to these gradients is quantified by the PCA loadings presented in Table 3, which describe the direction and strength of each variable along the first two dimensions (Dim1–Dim2).

For physicochemical properties (Figures 4a–c), the first two components explained 63.5% of the total variance. The first dimension (Dim1) represents a dominant texture–fertility gradient. Negative loadings were observed for CEC, OM, tC, clay, silt, and micronutrients such as Mn and Cu, whereas sand showed a strong positive loading (Table 3). This opposing contribution indicates that Dim1 captures the contrast between finer-textured, nutrient-associated soil properties and sand-dominated conditions. The second dimension (Dim2) was primarily structured by iron (Fe; positive loading) and pH (negative loading), reflecting a secondary gradient related to soil chemical conditions. In the PCA biplot, DPF clustered with Cu, tC, K, and clay content, and showed a secondary association with OM, CEC, and silt. This ordination supported a separation between forest/agroforestry systems and the most sand-associated land uses, with oil palm plantations (Eg1–Eg3) and pastures positioned toward the sand vector (Figure 4a).

In the biological block (Figures 4d–f), Dim1 was mainly driven by negative loadings of bacteria, actinomycetes, and fungi (Table 3). Dim2 was strongly influenced by macrofauna, which showed a high negative loading, separating samples according to differences in macrofaunal association. These loadings account for the ordination patterns in Figures 4d–f, where forest and agroforestry samples align with microbial and macrofaunal indicators, whereas oil palm and pasture samples are displaced in multivariate space.

For the respiration-related variables (Figures 4g–i), Dim1 was strongly associated with gravimetric soil moisture and microbial biomass carbon (mgC), both showing high positive loadings (Table 3). In contrast, Dim2 was almost exclusively driven by CO₂ efflux (CO₂d), which exhibited a very strong positive loading. This indicates that the two dimensions capture complementary aspects of microbial functioning, with Dim1 reflecting substrate- and moisture-related conditions and Dim2 representing metabolic activity. These relationships explain the dispersion of groups observed in Figures 4g–i across land-use systems, localities, and texture classes.

3.2 Variation in soil properties across land use, localities, and soil texture

Univariate analyses and confidence interval (CI) plots consistently supported the multivariate gradients identified by the PCA across land-use systems, localities, and soil texture classes (Figures 4, 3; Table 4). Across land-use systems, significant differences were detected for CEC (Kruskal–Wallis, $p = 0.004$), Cu (ANOVA, $p = 0.014$), Mn (ANOVA, $p < 0.001$), OM (ANOVA, $p = 0.004$), SOC (Kruskal–Wallis, $p = 0.040$), pH (Kruskal–Wallis, $p = 0.010$), and sand content (Kruskal–Wallis, $p = 0.041$). *Post-hoc* comparisons indicated that cacao agroforestry (Tc) differed from pasture (Pas) for CEC (Dunn, $p_{\text{adj}} = 0.012$) and Cu (Tukey, $p_{\text{adj}} = 0.046$), and from oil palm systems for OM (Eg1–Tc: $p_{\text{adj}} = 0.040$; 226 Eg2–Tc: $p_{\text{adj}} = 0.009$; Eg3–Tc: $p_{\text{adj}} = 0.026$). Tc also differed from both disturbed primary forest (DPF) and pasture for pH (Dunn, $p_{\text{adj}} = 0.008$ and 0.028, respectively). Manganese concentrations showed strong differentiation among land uses, with significant contrasts between Eg1 and both DPF and Tc, and between Pas and both DPF and Tc (all $p_{\text{adj}} < 0.01$). Confidence



interval plots showed clear separation among land-use systems for pH, OM, CEC, Cu, and Mn. In contrast, sand content exhibited substantial overlap among pasture and oil palm systems, indicating limited differentiation among these land uses, despite a significant global test driven mainly by contrasts with forest systems (Figure 3). At the locality level, inferential tests revealed significant differences for CEC (Kruskal–Wallis, $p = 0.003$), Mn ($p < 0.001$), OM ($p < 0.001$), SOC ($p < 0.001$), clay (ANOVA, $p < 0.001$), and sand (ANOVA, $p < 0.001$), whereas Cu and pH did not differ significantly among localities. Pairwise tests consistently showed that Abejaico differed from Bomfin for CEC, Mn, OM, SOC, clay, and sand (all $p_{adj} \leq 0.015$). These contrasts were reflected by non-overlapping confidence intervals for the same variables (Figures 3, 4b). Soil texture classes also exhibited strong univariate differentiation. Significant effects were observed for CEC

(Kruskal–Wallis, $p < 0.001$), Cu (ANOVA, $p = 0.025$), Mn (Kruskal–Wallis, $p = 0.012$), OM (Kruskal–Wallis, $p < 0.001$), SOC (ANOVA, $p < 0.001$), clay (Kruskal–Wallis, $p < 0.001$), and sand (Kruskal–Wallis, $p < 0.001$). *Post-hoc* tests indicated that fine-textured soils (clay loam and loam) differed from sandy loam for CEC, OM, and SOC (all $p_{adj} \leq 0.003$), while Mn differed significantly between clay loam and sandy loam (Dunn, $p_{adj} = 0.014$). Confidence intervals showed minimal overlap between fine-textured and sandy soils for these variables (Figures 3, 4c).

3.3 Texture-stratified patterns of soil indicators

Figure 5 summarizes texture-stratified variation across land-use systems. CEC differed among land uses in L soils (ANOVA,

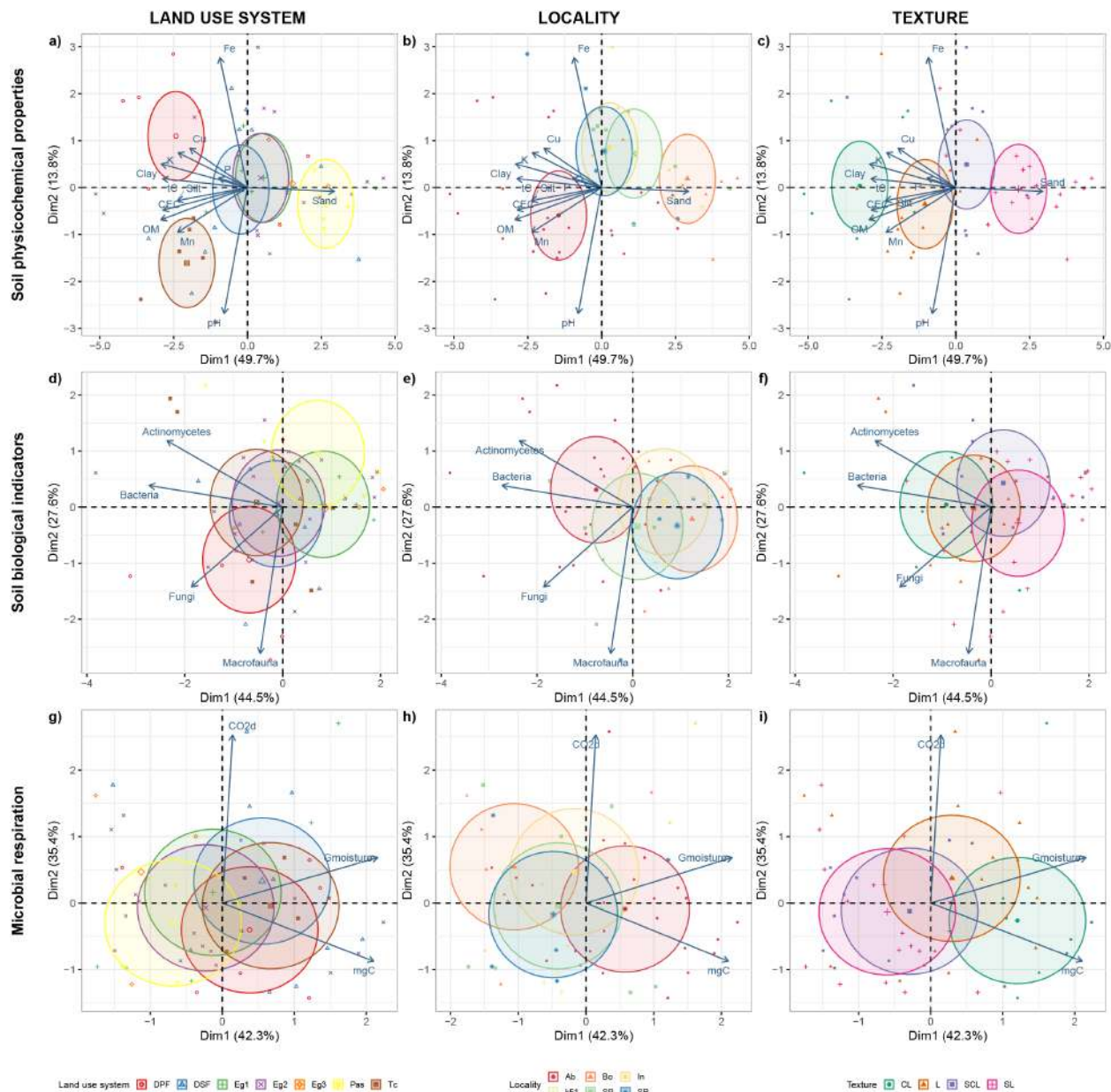


FIGURE 4

Principal component analysis (PCA) of soil multifunctionality indicators in Campo Verde–Neshuya, Ucayali, Peru. Top row (a–c) soil physicochemical properties grouped by (a) land-use system, (b) sampling locality, and (c) texture class. Middle row (d–f) soil biological indicators (bacteria, fungi, actinomycetes, and macrofauna) grouped by (d) land-use system, (e) sampling locality, and (f) texture class. Bottom row (g–i) microbial respiration and associated soil attributes grouped by (g) land-use system, (h) sampling locality, and (i) texture class. Arrows represent variable loadings and axis labels report the percentage of variance explained by each dimension. Land-use systems: DPF, disturbed primary forest; DSF, secondary forest; Tc, cacao agroforestry; Eg1, oil palm 1–9 years; Eg2, 10–18 years; Eg3, 19–35 years; Pas, pasture. Localities: Ab, Abejaico; In, Los Incas; SR, Santa Rosa; SP, San Pablo; Bo, Bomfin; K51, km 51. Texture classes: CL, clay loam; L, loam; SCL, sandy clay loam; SL, sandy loam.

$p < 0.001$), with significant contrasts separating Eg1/Eg2/Eg3/Pas from both DPF and Tc (all $p_{adj} \leq 0.029$; Figure 5a; Table 5). In SL soils, CEC also differed among land uses (ANOVA, $p = 0.012$), with Tc differing from Eg1/Eg2/Eg3/Pas ($p_{adj} = 0.004$ – 0.026) and from DPF/DSF ($p_{adj} = 0.008$ – 0.026 ; Figure 5a; Table 5).

OM differed among land-use systems within sandy clay loam (SCL) soils (ANOVA, $p = 0.007$), with separations relative to DPF (DSF–DPF: $p_{adj} = 0.023$; Eg1–DPF: $p_{adj} = 0.012$; Eg2–DPF: $p_{adj} = 0.004$; Pas–DPF: $p_{adj} = 0.013$; Figure 5b; Table 5). No significant

land-use contrasts for OM were retained in other texture classes under the same within-texture testing scheme (Figure 5b).

Mn exhibited marked within-texture dispersion across land-use systems (Figure 5c); however, under the within-texture univariate testing summarized in Table 5, no significant pairwise contrasts for Mn were retained after adjustment ($p_{adj} \geq 0.05$ across comparisons). pH showed comparatively limited within-texture separation among land-use systems in the stratified panel (Figure 5d), and no significant within-texture contrasts were retained under the same testing framework ($p_{adj} \geq 0.05$).

TABLE 4 Global tests for differences in key soil properties among land-use systems, sampling localities, and soil textures in Campo Verde–Neshuya, Ucayali, Peru.

Factor	Block	Variable	Test	<i>p</i> -value	Shapiro <i>p</i>	Levene <i>p</i>
Land-use system	Chemical	CEC	Kruskal–Wallis	0.004	< 0.001	0.780
Land-use system	Chemical	Cu	ANOVA	0.014	0.097	0.435
Land-use system	Chemical	Mn	ANOVA	< 0.001	0.218	0.309
Land-use system	Chemical	OM	ANOVA	0.004	0.093	0.339
Land-use system	Chemical	SOC	Kruskal–Wallis	0.040	0.003	0.364
Land-use system	Chemical	pH	Kruskal–Wallis	0.010	0.929	0.001
Land-use system	Physical	Clay	ANOVA	0.060	0.328	0.244
Land-use system	Physical	Sand	Kruskal–Wallis	0.041	< 0.001	0.602
Land-use system	Biological	MBC	ANOVA	0.061	0.953	0.528
Land-use system	Biological	Resp	ANOVA	0.667	0.350	0.874
Locality	Chemical	CEC	Kruskal–Wallis	0.003	0.015	0.052
Locality	Chemical	Cu	ANOVA	0.729	0.337	0.104
Locality	Chemical	Mn	Kruskal–Wallis	< 0.001	0.750	0.027
Locality	Chemical	OM	Kruskal–Wallis	< 0.001	0.363	0.036
Locality	Chemical	SOC	Kruskal–Wallis	< 0.001	0.005	0.567
Locality	Chemical	pH	ANOVA	0.117	0.535	0.754
Locality	Physical	Clay	ANOVA	< 0.001	0.488	0.462
Locality	Physical	Sand	ANOVA	< 0.001	0.564	0.353
Locality	Biological	MBC	ANOVA	0.005	0.831	0.188
Locality	Biological	Resp	ANOVA	0.581	0.064	0.492
Texture	Chemical	CEC	Kruskal–Wallis	< 0.001	0.241	0.016
Texture	Chemical	Cu	ANOVA	0.025	0.993	0.605
Texture	Chemical	Mn	Kruskal–Wallis	0.012	0.014	0.494
Texture	Chemical	OM	Kruskal–Wallis	< 0.001	0.011	0.504
Texture	Chemical	SOC	ANOVA	< 0.001	0.053	0.252
Texture	Chemical	pH	ANOVA	0.190	0.072	0.926
Texture	Physical	Clay	Kruskal–Wallis	< 0.001	0.008	0.767
Texture	Physical	Sand	Kruskal–Wallis	< 0.001	0.039	< 0.001
Texture	Biological	MBC	ANOVA	0.043	0.430	0.309
Texture	Biological	Resp	ANOVA	0.370	0.086	0.937

One-way ANOVA was used when assumptions were met; otherwise, Kruskal–Wallis tests were applied. Shapiro and Levene *p*-values refer to residual normality and homoscedasticity diagnostics, respectively. CEC (cmolc kg⁻¹), Cu (mg kg⁻¹), Mn (mg kg⁻¹), OM (%), SOC (%), Clay (%), Sand (%), MBC (mg C g⁻¹ dry soil), Resp (g CO₂ m⁻² d⁻¹).

3.4 Biological indicators across land-use systems and localities

Compared with physicochemical properties, biological indicators showed weaker separation in the global univariate tests (Table 4). Nevertheless, ordination analyses consistently captured spatial and land-use structure (Figures 4d–f), suggesting a biological gradient associated with forest cover and increasing management intensity. At the land-use level, macrofauna abundance differed significantly among systems (Figure 6A; Kruskal–Wallis, $p = 0.047$). *Post hoc* comparisons indicated lower macrofauna values in pasture relative to disturbed primary forest (Dunn, $p_{adj} < 0.05$). In contrast, cultivable microbial abundances did not show significant global differences among land uses, although confidence-interval plots suggested lower mean values in oil palm plantations and pastures (Figures 6b–e). Microbial respiration also did not differ across land-use systems (ANOVA, $p = 0.667$; Table 4) (Figure 6f). Microbial biomass carbon (MBC; mgC_{mg}C_g soil) showed a marginal land-use effect (ANOVA, $p = 0.061$), with a tendency toward

lower values in long-established oil palm plantations (Figure 6g). The metabolic quotient qCO_2 did not differ significantly among land uses (Figure 6h). Beyond land use, locality effects were pronounced for MBC (ANOVA, $p = 0.005$), driven mainly by lower values in Bo compared with Ab (Tukey, $p_{adj} = 0.004$; Table 6). This contrast was consistent with the reduced biotic signal observed for Bo in the multivariate space (Figure 4e).

3.5 Correlations among soil properties

Taken together, the PCA results highlight coherent covariance structures among texture fractions, functional indicators, and biological functioning. To further examine these associations in a pairwise framework, we evaluated Pearson correlations among variables (Figure 7). Pearson correlation analysis revealed strong and significant associations among soil properties (Figure 7). Sand content was negatively correlated with silt ($r = -0.91$) and clay ($r = -0.86$), while clay was positively correlated with CEC ($r = 0.80$). Organic matter was positively correlated with pH ($r = 0.35$) and

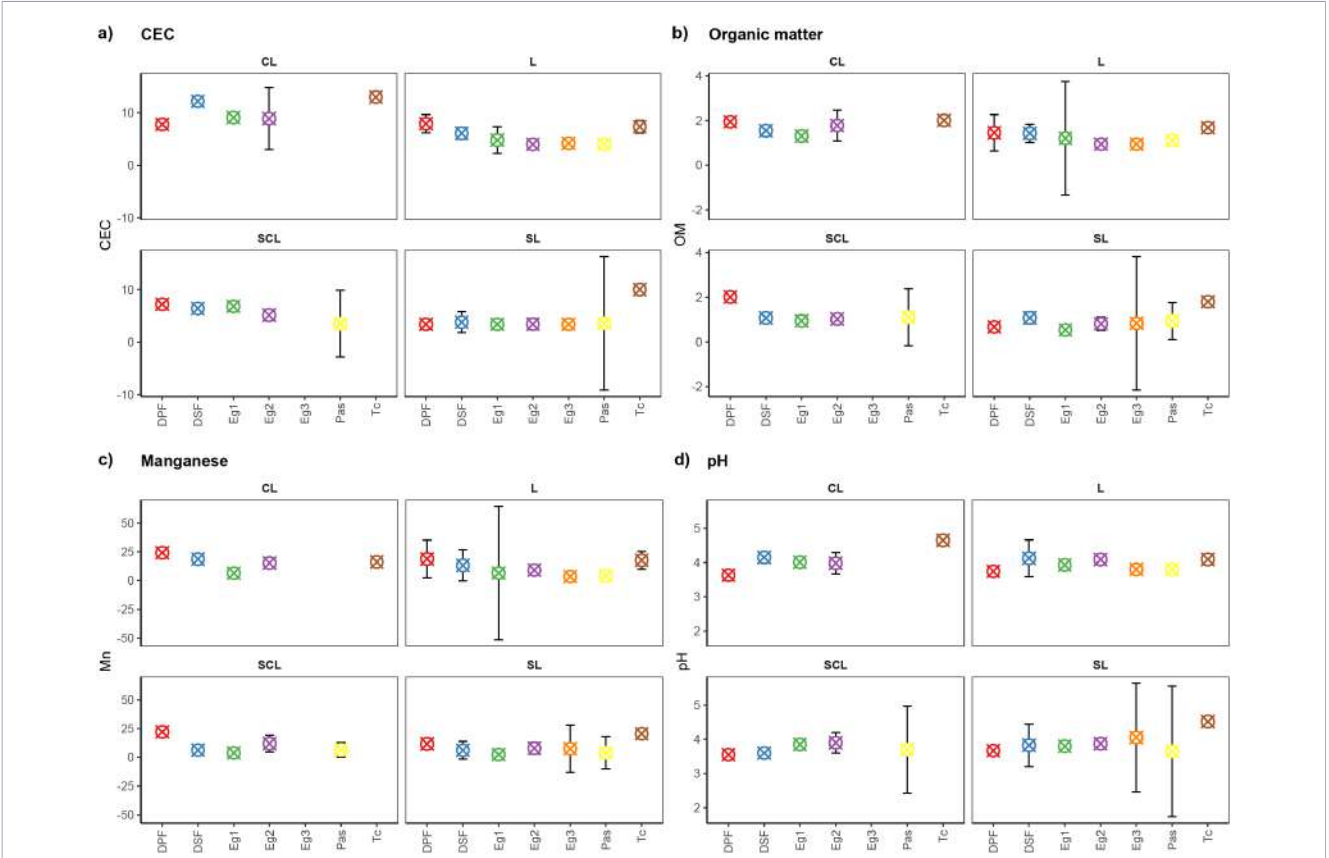
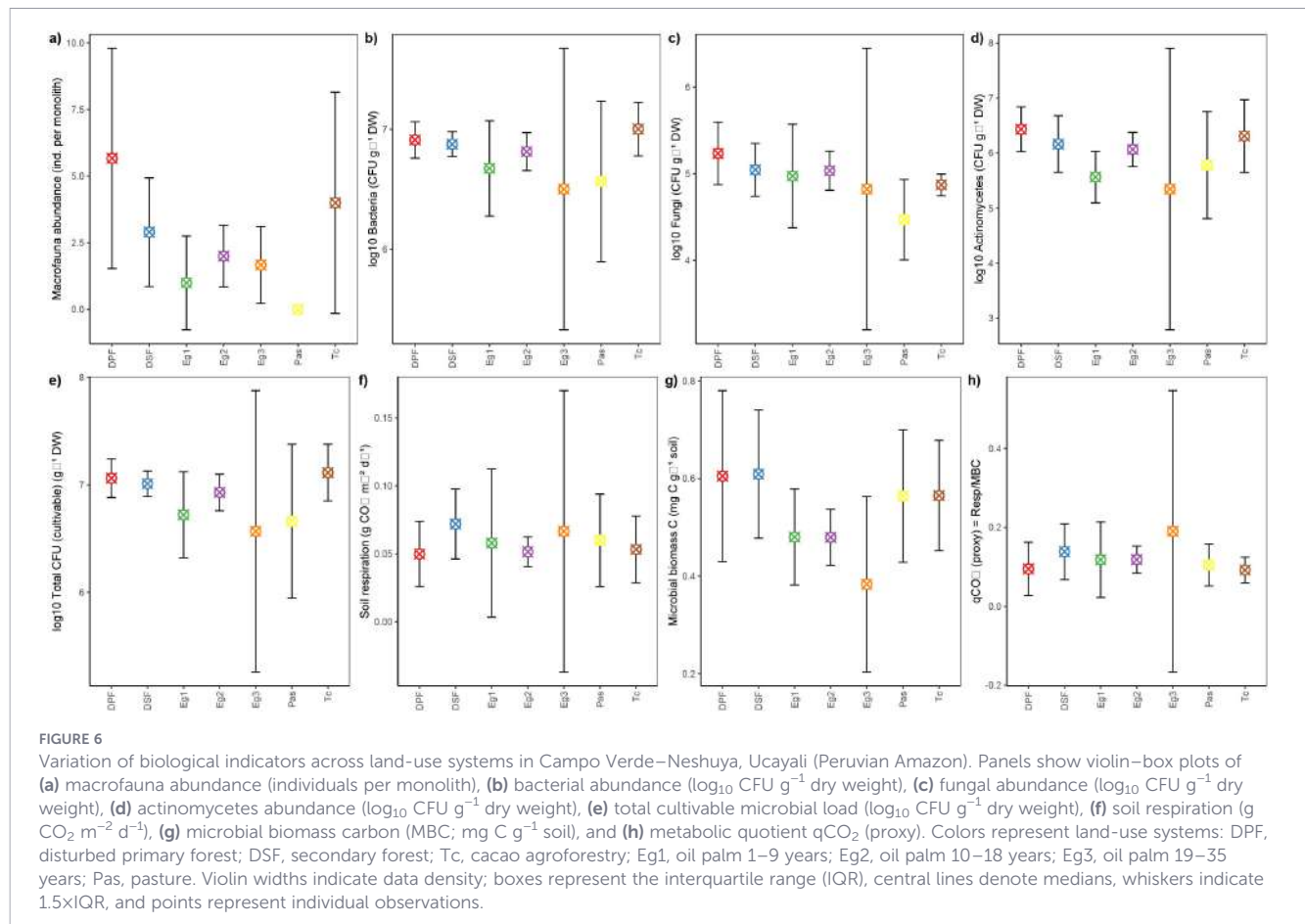


FIGURE 5
Variation of selected soil properties across land-use systems and soil texture classes in Campo Verde–Neshuya, Ucayali (Peruvian Amazon). Panels show boxplots of (a) cation-exchange capacity (CEC), (b) organic matter (OM), (c) manganese (Mn), and (d) microbial biomass carbon (MBC), stratified by soil texture classes: clay loam (CL), loam (L), sandy clay loam (SCL), and sandy loam (SL). Colors represent land-use systems: DPF, disturbed primary forest; DSF, secondary forest; Tc, cacao agroforestry; Eg1, oil palm 1–9 years; Eg2, oil palm 10–18 years; Eg3, oil palm 19–35 years; Pas, pasture. Boxes indicate interquartile range (IQR), central lines represent medians, whiskers denote 1.5×IQR, and points indicate outliers.

TABLE 5 Significant within-texture pairwise comparisons ($p_{adj} < 0.05$) for some soil indicators across land-use systems in Campo Verde–Neshuya, Ucayali, Peru.

Texture	Variable	Test	Comparison	p_{adj}	Signif
L	CEC	Tukey	Eg1–DPF	0.009	**
L	CEC	Tukey	Eg1–Tc	0.023	*
L	CEC	Tukey	Eg2–DPF	0.009	**
L	CEC	Tukey	Eg2–Tc	0.020	*
L	CEC	Tukey	Eg3–DPF	0.013	*
L	CEC	Tukey	Eg3–Tc	0.029	*
L	CEC	Tukey	Pas–DPF	0.009	**
L	CEC	Tukey	Pas–Tc	0.020	*
SCL	OM	Tukey	DSF–DPF	0.023	*
SCL	OM	Tukey	Eg1–DPF	0.012	*
SCL	OM	Tukey	Eg2–DPF	0.004	**
SCL	OM	Tukey	Pas–DPF	0.013	*
SL	CEC	Tukey	Eg1–Tc	0.026	*
SL	CEC	Tukey	Eg2–Tc	0.004	**
SL	CEC	Tukey	Eg3–Tc	0.010	*
SL	CEC	Tukey	Pas–Tc	0.012	*
SL	CEC	Tukey	Tc–DPF	0.026	*
SL	CEC	Tukey	Tc–DSF	0.008	**

Pairwise tests were Tukey HSD following ANOVA, as indicated. The significance symbols correspond to adjusted p-value thresholds (p_{adj}) as follows: * $p_{adj} < 0.05$; ** $p_{adj} < 0.01$.



with clay ($r = 0.72$). In the biological component, silt was positively correlated with bacteria ($r = 0.34$) and fungi ($r = 0.31$), whereas sand showed negative correlations with these microbial groups ($p \leq 0.05$).

4 Discussion

This study applies an indicator-based framework to evaluate soil functioning across a land-use intensification gradient in the Peruvian Amazon (Ucayali). Multivariate analyses showed that soil texture is the dominant factor structuring soil indicators, opposing sand-rich soils to finer-textured conditions associated with higher CEC, OM, Ct, and micronutrients. Within this strong edaphic gradient, land-use effects were consistently detected in a limited set of sensitive physicochemical indicators (CEC, OM, Mn, pH, Cu, and SOC), whereas biological indicators exhibited weaker univariate separation but coherent organization in multivariate space. Cacao agroforestry and secondary forests occupied intermediate positions between forest systems and intensive land uses, indicating transitional soil conditions under land-use intensification. Together, these results demonstrate that land-use impacts on soil functioning indicators must be interpreted within a texture-aware framework in heterogeneous Amazonian landscapes.

4.1 Physicochemical gradients and indicator behavior under land-use intensification

The dominant multivariate structure in physicochemical indicators presented a clear texture–fertility gradient, contrasting sand-dominated conditions against higher CEC, OM, tC, clay, silt, and micronutrients (notably Mn and Cu). This organization was consistently supported by PCA loadings, univariate tests, and confidence intervals, which showed significant land-use differences for CEC, OM, Mn, pH, Cu, and SOC, alongside strong texture effects for CEC, OM, SOC, clay, and sand. These patterns align with extensive evidence that fine soil fractions enhance nutrient retention and carbon stabilization through organo–mineral associations, whereas sandy soils exhibit lower CEC, higher leaching potential, and reduced buffering capacity against disturbance (15, 27, 28). The strong negative correlations between sand and fine fractions, and the positive association between clay and CEC observed here, further supported texture as a primary axis structuring soil functioning indicators.

Within this physicochemical gradient, Mn emerged as one of the most responsive indicators, showing strong differentiation across land-use systems and texture classes and contributing substantially to the fertility-associated PCA axis. Mn availability is tightly regulated by pH, redox conditions, organic matter quality, and microbial activity, and can respond rapidly to changes in soil structure, aeration, and

TABLE 6 Significant pairwise comparisons ($p_{adj} < 0.05$) for key soil properties across land-use systems, sampling localities, and soil textures in Campo Verde–Neshuya, Ucayali, Peru.

Factor	Block	Variable	Test	Comparison	p_{adj}	Signif
Land-use system	Chemical	CEC	Dunn	Tc vs Pas	0.012	*
Land-use system	Chemical	Cu	Tukey	Pas–Tc	0.046	*
Land-use system	Chemical	Mn	Tukey	Eg1–DPF	0.003	**
Land-use system	Chemical	Mn	Tukey	Eg1–Tc	0.009	**
Land-use system	Chemical	Mn	Tukey	Eg3–DPF	0.036	*
Land-use system	Chemical	Mn	Tukey	Pas–DPF	0.003	**
Land-use system	Chemical	Mn	Tukey	Pas–Tc	0.008	**
Land-use system	Chemical	OM	Tukey	Eg1–Tc	0.040	*
Land-use system	Chemical	OM	Tukey	Eg2–Tc	0.009	**
Land-use system	Chemical	OM	Tukey	Eg3–Tc	0.026	*
Land-use system	Chemical	OM	Tukey	Pas–Tc	0.040	*
Land-use system	Chemical	pH	Dunn	DPF vs Tc	0.008	**
Land-use system	Chemical	pH	Dunn	Tc vs Pas	0.028	*
Locality	Biological	MBC	Tukey	Bo–Ab	0.004	**
Locality	Chemical	CEC	Dunn	Ab vs Bo	0.015	*
Locality	Chemical	Mn	Dunn	Ab vs Bo	< 0.001	***
Locality	Chemical	Mn	Dunn	Ab vs In	0.003	**
Locality	Chemical	Mn	Dunn	Ab vs SP	0.002	**
Locality	Chemical	OM	Dunn	Ab vs Bo	< 0.001	***
Locality	Chemical	OM	Dunn	Ab vs K51	0.021	*
Locality	Chemical	SOC	Dunn	Ab vs Bo	0.002	**
Locality	Physical	Clay	Tukey	Bo–Ab	< 0.001	***
Locality	Physical	Sand	Tukey	Bo–Ab	< 0.001	***
Locality	Physical	Sand	Tukey	In–Bo	0.006	**
Locality	Physical	Sand	Tukey	SR–Bo	0.017	*
Locality	Physical	Sand	Tukey	K51–Ab	0.002	**
Locality	Physical	Sand	Tukey	K51–In	0.040	*
Texture	Biological	MBC	Tukey	SL–CL	0.028	*
Texture	Chemical	CEC	Dunn	CL vs SCL	0.038	*
Texture	Chemical	CEC	Dunn	CL vs SL	< 0.001	***
Texture	Chemical	CEC	Dunn	L vs SL	0.001	**
Texture	Chemical	Cu	Tukey	SCL–CL	0.026	*
Texture	Chemical	Cu	Tukey	SL–CL	0.032	*
Texture	Chemical	Mn	Dunn	CL vs SL	0.014	*
Texture	Chemical	OM	Dunn	CL vs SCL	0.010	**
Texture	Chemical	OM	Dunn	CL vs SL	< 0.001	***
Texture	Chemical	OM	Dunn	L vs SL	0.003	**
Texture	Chemical	SOC	Tukey	SCL–CL	0.004	**
Texture	Chemical	SOC	Tukey	SL–CL	< 0.001	***
Texture	Chemical	SOC	Tukey	SL–L	0.001	**
Texture	Physical	Clay	Dunn	CL vs L	0.015	*
Texture	Physical	Clay	Dunn	CL vs SCL	0.015	*
Texture	Physical	Clay	Dunn	CL vs SL	< 0.001	***
Texture	Physical	Clay	Dunn	L vs SL	0.002	**

(Continued)

TABLE 6 Continued

Factor	Block	Variable	Test	Comparison	<i>p</i> _{adj}	Signif
Texture	Physical	Clay	Dunn	SCL vs SL	0.006	**
Texture	Physical	Sand	Dunn	CL vs SCL	0.005	**
Texture	Physical	Sand	Dunn	CL vs SL	< 0.001	***
Texture	Physical	Sand	Dunn	L vs SL	< 0.001	***

Pairwise tests were Tukey HSD or Dunn tests, as indicated. The significance symbols correspond to adjusted *p*-value thresholds (*p*_{adj}): * *p*_{adj} < 0.05; ** *p*_{adj} < 0.01; *** *p*_{adj} < 0.001.

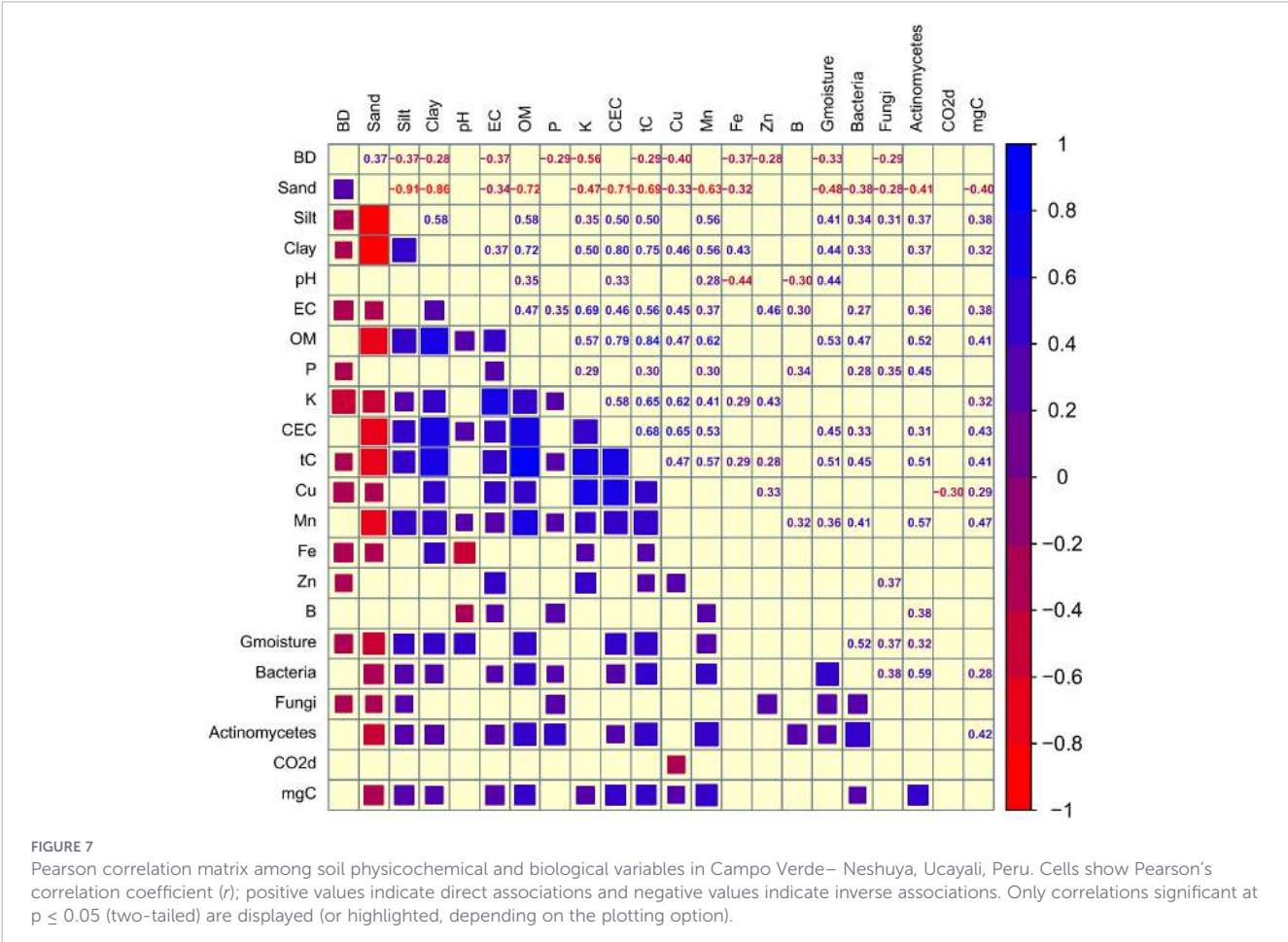
aggregation following land-use change (29, 30). This association is mechanistically plausible: forests and agroforestry maintain higher and more continuous organic inputs and a more buffered microenvironment, which can enhance Mn retention through organic complexation and redox-driven cycling, aligning Mn with the broader fertility-related indicator set.

4.2 Land-use systems along the intensification gradient

DPF clustered with higher nutrient- and fine-fraction-associated indicators, including clay, tC, K, and Cu, and showed secondary associations with OM, CEC, and silt in multivariate space. This configuration reflects the higher functional integrity of soils under forest cover, which supports nutrient retention, organo-

mineral stabilization, and resistance to physicochemical disturbance in highly weathered tropical soils (31–33). DSF generally occupied intermediate positions between disturbed primary forest and intensive land uses in both PCA ordination and confidence interval summaries, consistent with partial recovery trajectories following agricultural abandonment or shifting cultivation (34, 35). Together, these patterns underscore the role of forest cover and regrowth in maintaining soil attributes central to nutrient cycling and structural stability.

Oil palm plantations (Eg1–Eg3) and pastures tended to align with sand-associated conditions and lower fertility-related indicators, while forests and cacao agroforestry were positioned toward higher OM, CEC, and fine fractions. These interpretations are supported by statistically robust contrasts (e.g., for OM and Mn) and the consistency of multivariate structure, rather than by isolated



indicators. The tendency for older oil palm stands to occupy more sand-associated multivariate positions is consistent with cumulative effects of disturbance, residue removal, and reduced organic inputs reported in other tropical monoculture systems (36–38). Pastures represented the lowest indicator condition overall, with low CEC and OM and weaker biotic signals, in agreement with evidence that long-term pasture establishment can intensify nutrient depletion, compaction, and loss of soil structural integrity in tropical regions (1, 7, 39–41).

Cacao agroforestry consistently showed more favorable indicator profiles than oil palm and pasture systems, including higher OM and clear contrasts in CEC and pH in *post-hoc* comparisons. This pattern supports the interpretation of cacao agroforestry as a transitional, lower-impact system within the intensification gradient, likely sustained by shade trees, continuous litter inputs, and reduced soil disturbance relative to monocultures (42–45).

Strong locality-level contrasts (e.g., Abejaico versus Bomfin for key soil functioning indicators such as CEC, OM, SOC, Mn, and texture fractions) demonstrate that spatial heterogeneity is a defining feature of indicator behavior in Amazonian frontiers. These differences likely reflect variation in parent material, microtopography, drainage, and land-use history, interacting with dominant land-use matrices at the district scale. Rather than representing residual “site effects,” such contrasts identify localities where soil functioning indicators show the strongest declines and where management pressures intersect with inherently vulnerable edaphic conditions (12, 28, 31, 46).

4.3 Biological indicators and ecological implications

Compared with physicochemical properties, biological indicators showed weaker separation in global univariate tests. Macrofauna abundance differed significantly among land uses, while MBC showed only marginal land-use effects and stronger locality dependence. In contrast, soil respiration and the metabolic quotient (qCO_2) did not differ among systems. Nonetheless, PCA ordinations consistently captured structure by land use and locality, with forest and agroforestry samples aligning with microbial and macrofaunal indicators and intensive systems displaced in multivariate space. This pattern suggests that biological organization can respond to land-use change in ways that are detectable when indicators are evaluated jointly, even when individual metrics show limited univariate sensitivity (47–49).

Ecologically, these associations are consistent with shifts in resource availability and habitat structure along the intensification gradient. Forests and agroforestry systems provide more continuous organic inputs and microhabitat heterogeneity, supporting diverse microbial strategies and trophic interactions involving soil fauna (50, 51). In contrast, intensive systems characterized by reduced litter inputs, greater exposure, and physical disturbance may favor stress-tolerant assemblages and weaken biological contributions to soil functioning indicators (51, 52). While community composition and functional traits were not directly assessed here, the alignment of biotic indicators with fine fractions and OM/CEC gradients supports this mechanistic interpretation.

4.4 Implications, limitations, and future research

From an applied perspective, our results support a practical, indicator-based framework for monitoring soil functioning in Amazonian production landscapes. A reduced panel combining texture fractions, OM, CEC, pH, Mn, and complementary biological metrics such as MBC captures dominant gradients while remaining interpretable and cost-effective. This approach is consistent with broader efforts to operationalize soil health and multifunctionality assessments using integrative indicator sets in tropical systems (15, 17). The indicator patterns observed for cacao agroforestry and secondary forests suggest that these systems can contribute to maintaining key soil attributes within heterogeneous landscape mosaics, offering realistic pathways to reconcile production with soil conservation goals (34, 42, 43).

Although restoration interventions were not experimentally tested, the observed patterns in soil functioning indicators suggest that organic amendments and surface residue management could represent logical extensions to mitigate declines in organic matter and nutrient retention capacity in degraded systems. In this context, biochar and composts derived from agro-industrial residues emerge as promising circular-economy options, as demonstrated by successful applications of characterized almond-shell biochar in controlled cultivation systems (53). Translating such approaches to Amazonian soils, however, requires site-specific evaluation and should be framed as a research priority rather than a validated recommendation derived from the present dataset.

This study is constrained by its cross-sectional design and by incomplete quantification of management intensity (e.g., fertilizer inputs, machinery traffic, and residue handling), as well as by the lack of direct measurements of erosion and leaching processes. Future research should prioritize (i) chronosequence or paired-plot designs that explicitly control for soil texture while comparing forest, agroforestry, and age-structured oil palm systems; (ii) depth-resolved sampling to distinguish surface-driven management effects from intrinsic textural gradients; and (iii) mechanistic assays, including litter decomposition, extracellular enzyme activities, and redox-sensitive micronutrient dynamics, to test causal pathways linking organic matter quality, microbial activity, and manganese behavior under contrasting land uses (27, 29, 30, 50). Such approaches would strengthen inference on how land use and management alter soil functioning indicators independently of intrinsic edaphic context and would better inform targeted, texture-aware restoration strategies in Amazonian production landscapes (7, 28).

5 Conclusions

Soil functioning indicators in the Campo Verde–Neshuya landscapes are structured primarily by edaphic context, with texture defining a dominant gradient from sand-associated conditions to finer-textured, higher-fertility soils characterized by greater CEC, organic matter, carbon, and micronutrient availability.

Within this strong baseline constraint, land-use intensification produced consistent signals in a limited but sensitive set of physicochemical indicators (CEC, OM, Mn, pH, Cu, SOC), whereas biological metrics showed weaker univariate separation but coherent structure in multivariate space and a detectable decline in macrofauna under intensive systems. Cacao agroforestry and secondary forests consistently occupied intermediate (transitional) positions, indicating partial maintenance of key soil attributes relative to oil palm plantations and degraded pastures. Marked locality effects further demonstrate that spatial heterogeneity is a defining feature of soil condition in Amazonian frontiers and should be explicitly incorporated in monitoring and management. Collectively, the findings support a texture-aware, indicator-based framework for operational soil monitoring in Ucayali, prioritizing texture fractions, OM, CEC, pH, Mn (plus complementary biotic metrics such as macrofauna and/or MBC) to detect functional decline and guide sustainable land-use strategies.

Data availability statement

The datasets presented in this study can be found in online repositories. The names of the repository/repository and accession number(s) can be found in the article/[Supplementary Material](#).

Author contributions

CA-R: Investigation, Software, Writing – original draft, Conceptualization, Writing – review & editing, Supervision, Funding acquisition, Data curation, Formal analysis, Project administration, Resources, Validation, Methodology. JG: Writing – original draft, Writing – review & editing, Visualization, Investigation. DC: Writing – review & editing, Supervision, Conceptualization. NR-F: Writing – review & editing, Methodology, Data curation, Investigation. DG: Writing – review & editing, Formal analysis, Investigation, Methodology. MM: Investigation, Writing – review & editing, Methodology. HG: Methodology, Writing – review & editing, Conceptualization, Investigation. WG: Investigation, Methodology, Writing – review & editing. JB: Methodology, Investigation, Writing – review & editing. NP: Methodology, Investigation, Writing – review & editing. RT: Writing – review & editing, Methodology, Investigation. JM: Investigation, Methodology, Writing – review & editing. JR: Methodology, Supervision, Investigation, Writing – review & editing. HM-O: Writing – review & editing, Methodology, Investigation.

Funding

The author(s) declared that financial support was received for this work and/or its publication. This work was supported by the

Instituto de Investigaciones de la Amazonía Peruana (IIAP) through the Directorate for Integrated Forest Management and Ecosystem Services (Dirección de Investigación en Manejo Integral de Bosques y Servicios Ecosistémicos, BOSQUES). JG acknowledges support from CAPES (Coordenação de Aperfeiçoamento de Pessoal de Nível Superior, Brazil).

Acknowledgments

We thank the IIAP–Ucayali field and laboratory teams for technical assistance and local farmers for granting access to sampling sites. We appreciate helpful comments from colleagues at the Universidad Nacional Intercultural de la Amazonía (UNIA).

Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declared that generative AI was used in the creation of this manuscript. A generative AI tool was used only for language polishing. Specifically, ChatGPT (OpenAI; accessed Oct~2025) assisted with macro-level editing. All scientific content, analyses, figures, and references were produced and verified by the authors, who take full responsibility for the manuscript.

Any alternative text (alt text) provided alongside figures in this article has been generated by Frontiers with the support of artificial intelligence and reasonable efforts have been made to ensure accuracy, including review by the authors wherever possible. If you identify any issues, please contact us.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

Supplementary material

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fsoil.2026.1741629/full#supplementary-material>

References

- Davidson EA, de Araújo AC, Artaxo P, Balch JK, Brown IF, Bustamante MMC, et al. The Amazon basin in transition. *Nature*. (2012) 481:321–8. doi: 10.1038/nature10717
- FAO and ITPS. *Status of the world's soil resources (swsr) – main report*. Rome, Italy: FAO (2015).
- Instituto Nacional de Estadística e Informática. *Censos Nacionales 2017: Resultados definitivos —Departamento de Ucayali*. Lima, Perú: INEI (2018).
- SERFOR. *Memoria descriptiva del mapa de cobertura vegetal del Perú*. Lima, Peru: Servicio Nacional Forestal y de Fauna Silvestre, Ministerio del Ambiente (2015). Available online at: <https://www.serfor.gob.pe> (Accessed October 15, 2025).
- Institute W. R. *Ucayali, Peru: Deforestation rates & statistics (dashboard)*. Washington, DC, USA: Global Forest Watch dashboard (2025). Available online at: <https://www.globalforestwatch.org/dashboards/country/PER/26/> (Accessed October 15, 2025).
- Vela Alvarado JW, Clavo Z-M, Ramírez-Flores N, Villegas Panduro PP, Saito Villanueva C. Contribución de los fragmentos de vegetación al almacenamiento de carbono en paisajes agrícolas de la Amazonia Peruana. *Rev Peruana. Biol.* (2024) 31: e27004. doi: 10.15381/rpb.v31i2.27004
- Quesada CA, Paz C, Oblitas Mendoza E, Phillips OL, Saiz G, Lloyd J. Variations in soil chemical and physical properties explain basin-wide Amazon forest soil carbon concentrations. *SOIL*. (2020) 6:53–88. doi: 10.5194/soil-6-53-2020
- Lange DF, Schröter SA, Da Luz FM, Jankowski KJ, Neill C, Krusche AV. Cycling of dissolved organic nutrients and indications for nutrient limitations in contrasting Amazon rainforest ecosystems. *Biogeochemistry*. (2024) 167:1567–88. doi: 10.1007/s10533-024-01187-3
- Willard SJ, Liang G, Adkins S, Foley K, Murray J, Waring B. Land use drives the distribution of free, physically protected, and chemically protected soil organic carbon storage at a global scale. *Global Change Biol.* (2024) 30:e17507. doi: 10.1111/gcb.17507
- Houghton RA, House JI, Pongratz J, van der Werf GR, DeFries RS, Hansen MC, et al. Carbon emissions from land use and land-cover change. *Biogeosciences*. (2012) 9:5125–42. doi: 10.5194/bg-9-5125-2012
- Meena M, Dheebakaran J, Rangasamy A, Kaliappan SB, Kovilpillai B, Alagarswamy S, et al. Microbial carbon dynamics in tropical forests: Linking soil processes to 504 atmospheric impacts under climate stress. *Sci Tot. Environ.* (2025) 991:179918. doi: 10.1016/j.scitotenv.2025.179918
- Laurance WF, Camargo JLC, Luizão RCC, Laurance SG, Pimm SL, Bruna EM, et al. The fate of Amazonian forest fragments: A 32-year investigation. *Biol Conserv.* (2011) 144:56–67. doi: 10.1016/j.biocon.2010.09.021
- Renó V, Novo E, Escada M. Forest fragmentation in the lower Amazon floodplain: Implications for biodiversity and ecosystem service provision to riverine populations. *Remote Sens.* (2016) 8:886. doi: 10.3390/rs8110886
- Franco ALC, Sobral BW, Silva ALC, Wall DH. Amazonian deforestation and soil biodiversity. *Conserv Biol.* (2018) 33:1430–9. doi: 10.1111/cobi.13234
- Bastida F, Eldridge DJ, García C, Kenny Png G, Bardgett RD, Delgado-Baquerizo M. Soil microbial diversity–biomass relationships are driven by soil carbon content across global biomes. *ISME J.* (2021) 15:2081–91. doi: 10.1038/s41396-021-00906-0
- Souza IM, Pereira MG, Loss A, Perin A. Soil chemical quality in integrated production systems in the Brazilian eastern Amazon. *Forests*. (2024) 15:1078. doi: 10.3390/f15071078
- Naval MLM, Bieluczyk W, Alvarez F, da Silva Carvalho LC, Maracahipes-Santos L, de Oliveira EA, et al. Impacts of repeated forest fires and agriculture on soil organic matter and health in southern Amazonia. *CATENA*. (2025) 254:108924. doi: 10.1016/j.catena.2025.108924
- Trejo P, Azevedo-Ramos C, Lenti F. Forest fragmentation in the Brazilian Amazon: Trends and conservation strategies. *Perspect Ecol Conserv.* (2025) 23:104–9. doi: 10.1016/j.pecon.2025.04.001
- Servicio Nacional de Meteorología e Hidrología del Perú (SENAMHI). *Climas del Perú: Mapa de clasificación climática* (2021). Available online at: <https://www.gob.pe/institucion/senamhi/informes-publicaciones/2158106-climas-del-peru-mapa-de-clasificacion-climatica> (Accessed September 15, 2025).
- Gobierno Regional de Ucayali. *Zonificación ecológica económica de la región ucayali: Base para el ordenamiento territorial. Proyecto “Desarrollo de Capacidades para el Ordenamiento Territorial de la Región Ucayali*. Available online at: https://sinia.minam.gob.pe/sites/default/files/sinia/archivos/public/docs/estudio_de_la_propuesta_de_zee_10.pdf (Accessed 15 October 2025).
- Soil Survey Staff. *Keys to soil taxonomy (U.S. Department of agriculture, natural resources conservation service)* (2022).
- Abanto-Rodríguez C. Soil and ecosystem functioning data in productive landscapes of the Peruvian Amazon. (2025). doi: 10.5281/zenodo.17549901
- Anderson JM, Ingram JSI. *Tropical soil biology and fertility: A handbook of methods*. (Wallingford, UK: CAB international), 2 edn. (1993).
- Caruso JC, Cliff N. The factor structure of the wais-r: Replicability across age-groups. *Multivar. Behav Res.* (1998) 33:273–93. doi: 10.1207/s15327906mbr33024
- Mardia KV, Kent JT, Bibby JM. *Multivariate analysis*. London, UK: Academic Press (1979).
- R Core Team. *R: A language and environment for statistical computing*. Vienna, Austria: R Foundation for Statistical Computing (2021).
- Six J, Conant RT, Paul EA, Paustian K. Stabilization mechanisms of soil organic matter: Implications for C-saturation of soils. *Plant Soil*. (2002) 241:155–76. doi: 10.1023/A:1016125726789
- Lal R. Restoring soil quality to mitigate soil degradation. *Sustainability*. (2015) 7:5875–95. doi: 10.3390/su7055875
- Millaleo R, Reyes-Díaz M, Ivanov AG, Mora ML, Alberdi M. Manganese as essential and toxic element for plants: Transport, accumulation and resistance mechanisms. *J Soil Sci Plant Nutr.* (2010) 10:470–81. doi: 10.4067/S0718-95162010000200008
- Aponte C, García LV, Marañón T. Tree species effects on nutrient cycling and soil biota: A feedback mechanism favouring species coexistence. *For Ecol Manage.* (2013) 309:36–46. doi: 10.1016/j.foreco.2013.05.035
- Quesada CA, Lloyd J, Schwarz M, Patiño S, Baker TR, Czimczik C, et al. Variations in chemical and physical properties of Amazon forest soils in relation to their genesis. *Biogeosciences*. (2010) 7:1515–41. doi: 10.5194/bg-7-1515-2010
- Quesada CA, Lloyd J, Anderson LO, Fyllas NM, Schwarz M, Czimczik CI. Soils of Amazonia with particular reference to the rainforest sites. *Biogeosciences*. (2011) 8:1415–40. doi: 10.5194/bg-8-1415-2011
- Davidson EA, De Carvalho CJR, Figueira AMS, Ishida FY, Ometto JPHB, Nardoto GB, et al. Recuperation of nitrogen cycling in Amazonian forests following agricultural abandonment. *Nature*. (2007) 447:995–8. doi: 10.1038/nature05900
- Chazdon RL, Uriarte M. Scale-up forest and landscape restoration in the tropics. *Biotropica*. (2016) 48:716–24. doi: 10.1111/btp.12312
- Poorter L, Rozendaal DMA, Bongers F, de Almeida JS, Álvarez FS, Andrade JL, et al. Multidimensional tropical forest recovery. *Science*. (2021) 374:1370–6. doi: 10.1126/science.abb3629
- Guillaume T, Damris M, Kuzyakov Y. Losses of soil carbon by converting tropical forest to plantations: erosion and decomposition estimated by $\delta^{13}C$. *Global Change Biol.* (2015) 21:3548–60. doi: 10.1111/gcb.12907
- Guillaume T, Holtkamp AM, Damris M, Kuzyakov Y. Soil degradation in oil palm and rubber plantations under land resource scarcity. *Agric. Ecosyst Environ.* (2016) 232:110–8. doi: 10.1016/j.agee.2016.07.002
- Aini FK, Hergoualc'h K, Smith JU, Verchot L, Martius C. How does replacing natural forests with rubber and oil palm plantations affect soil respiration and methane fluxes? *Ecosphere*. (2020) 11:e03284. doi: 10.1002/ecs2.3284
- Guariguata MR, Ostertag R. Neotropical secondary forest succession: Changes in structural and functional characteristics. *For Ecol Manage.* (2001) 148:185–206. doi: 10.1016/S03781127(00)00535-1
- Neill C, Deegan LA, Thomas SM, Cerri CC. Deforestation for pasture alters nitrogen and phosphorus in small Amazonian streams. *Ecol Appl.* (2001) 11:1817–28. doi: 10.2307/3061098
- Dislich C, Keyel AC, Salecker J, Kisel Y, Meyer KM, Auliya M, et al. A review of the ecosystem functions in oil palm plantations, using forests as a reference system. *Biol Rev.* (2017) 92:1539–69. doi: 10.1111/brv.12295
- Schroth G, Harvey CA. Biodiversity conservation in cocoa production landscapes: an overview. *Biodivers. Conserv.* (2007) 16:2237–44. doi: 10.1007/s10531-007-9195-1
- Tscharntke T, Clough Y, Bhagwat SA, Buchori D, Faust H, Hertel D, et al. Multifunctional shade tree management in tropical agroforestry landscapes: A review. *J Appl Ecol.* (2011) 48:619–29. doi: 10.1111/j.1365-2664.2011.01937.x
- Eddy WC, Olander LP, Galford GL, Crowley MA, Boucher TM, Fargione JE. Improvements in soil health and soil carbon sequestration following land conversion to agroforestry: A systematic review. *For Ecol Manage.* (2022) 520:120403. doi: 10.1016/j.foreco.2022.120403
- Ngaba MJY, Li W, Peng X, Chen H, Wang D, Luo G, et al. Meta-analysis unveils differential effects of agroforestry on soil properties in different zonobiomes. *Plant Soil*. (2024) 493:1–19. doi: 10.1007/s11104-023-06385-w
- Zinn YL, Lal R, Resck DVS. Texture and organic carbon relations described by a profile pedotransfer function for Brazilian cerrado soils. *Geoderma*. (2005) 127:168–73. doi: 10.1016/j.geoderma.2005.02.010
- Fierer N, Bradford MA, Jackson RB. Toward an ecological classification of soil bacteria. *Ecology*. (2007) 88:1354–64. doi: 10.1890/05-1839
- Urbanová M, Šnajdr J, Baldrian P. Composition of fungal and bacterial communities in forest litter and soil is largely determined by dominant trees. *Soil Biol Biochem.* (2015) 84:53–64. doi: 10.1016/j.soilbio.2015.02.011
- Tedersoo L, Bahram M, Põlme S, Kõljalg U, Yorou NS, Wijesundera R, et al. Fungal biogeography: Global diversity and geography of soil fungi. *Science*. (2014) 346:1256688. doi: 10.1126/science.1256688

50. Fierer N, Schimel JP, Holden PA. Variations in microbial community composition through two soil depth profiles. *Soil Biol Biochem.* (2003) 35:167–76. doi: 10.1016/S0038-0717(02)00251-1
51. Lavelle P, Rodríguez NE, Arguello O, Bernal J, Botero C, Chaparro P, et al. Soil ecosystem services and land use in the rapidly changing orinoco river basin in Colombia. *Agric. Ecosyst Environ.* (2014) 185:106–17. doi: 10.1016/j.agee.2013.12.020
52. Rousk J, Bååth E, Brookes PC, Lauber CL, Lozupone C, Caporaso JG, et al. Soil bacterial and fungal communities across a ph gradient in an arable soil. *ISME J.* (2010) 4:1340–51. doi: 10.1038/ismej.2010.58
53. Zabaleta R, Sánchez E, Fabani P, Mazza G, Rodríguez R. Almond shell biochar: characterization and application in soilless cultivation of *Eruca sativa*. *Biomass Convers. Biorefin.* (2024) 14:18183–200. doi: 10.1007/s13399-023-04002-5