frontiers in Soil Science

TYPE Original Research
PUBLISHED 14 April 2026
DOI 10.3389/fsoil.2026.1737123

Climate, carbon, and soil stability: a key link in coffee-growing landscapes of the Peruvian Amazon

Lorena Estefani Romero-Chávez[1], Nilton A. Hermoza Ayme[2], Rodolfo Chuchon-Remon[3], Uriel Aldava-Pardave[4], Rosa K. Arroyo-Isuiza[1], Richard Solórzano Acosta[2,5] and Geomar Vallejos-Torres[3,6]*

[1]Estación Experimental Agraria Pichanaki, Dirección de Servicios Estratégicos Agrarios, Instituto Nacional de Innovación Agraria (INIA), Pichanaqui, Junín, Peru, [2]Centro Experimental La Molina, Dirección de Servicios Estratégicos Agrarios, Instituto Nacional de Innovación Agraria (INIA), La Molina, Lima, Peru, [3]Estación Experimental Agraria El Porvenir, Dirección de Servicios Estratégicos Agrarios, Instituto Nacional de Innovación Agraria (INIA), Juan Guerra, San Martín, Peru, [4]Estación Experimental Agraria Pucallpa, Dirección de Servicios Estratégicos Agrarios, Instituto Nacional de Innovación Agraria (INIA), Pucallpa, Ucayali, Peru, [5]Facultad de Ciencias Ambientales, Universidad Científica del Sur (UCSUR), Chorrillos, Lima, Peru, [6]Facultad de Ciencias Agrarias, Universidad Nacional de San Martín, Tarapoto, San Martín, Peru

OPEN ACCESS

EDITED BY
Martin A.N. Anikwe,
Enugu State University of Science and Technology, Nigeria

REVIEWED BY
Cristina Chinchilla-Soto,
University of Costa Rica, Costa Rica
Akas Anggita,
Sebelas Maret University, Indonesia

*CORRESPONDENCE
Geomar Vallejos-Torres
gvallejos@unsm.edu.pe

RECEIVED 01 November 2025
REVISED 26 February 2026
ACCEPTED 20 March 2026
PUBLISHED 14 April 2026

CITATION
Romero-Chávez LE, Hermoza Ayme NA, Chuchon-Remon R, Aldava-Pardave U, Arroyo-Isuiza RK, Solórzano Acosta R and Vallejos-Torres G (2026) Climate, carbon, and soil stability: a key link in coffee-growing landscapes of the Peruvian Amazon. *Front. Soil Sci.* 6:1737123. doi: 10.3389/fsoil.2026.1737123

Introduction: Coffee cultivation in the Central Peruvian Amazon, one of the country's most important production regions, faces increasing challenges from soil degradation and climate change impacts. This study aimed to evaluate the influence of the altitudinal gradient on soil organic carbon (SOC) stocks and soil erodibility (K index) in coffee-growing systems.

Methods: Three altitudinal zones were established for sampling (0–20 cm depth): zone 1 (900–1200 m.a.s.l.), zone 2 (1201–1400 m.a.s.l.), and zone 3 (1401–1600 m.a.s.l.). Within these zones, physical and chemical soil properties were analyzed, and SOC and soil erodibility (K index) values were calculated.

Results: The results revealed a direct and statistically significant relationship between altitude and carbon sequestration capacity. Zone 3 exhibited the highest SOC (63.19 $t \cdot ha^{-1}$) and organic matter (OM) content (5.49%), compared with zone 1 (37.56 $t \cdot ha^{-1}$). This difference is attributable to the climatic conditions at higher elevations, characterized by greater precipitation and lower temperatures. Structural equation modeling (SEM) indicated that increasing altitude enhances SOC (b = 0.42), which in turn improves the soil structural stability index (SI) (R^2 = 0.87) and reduces the K index (b = −0.38). Overall, the findings demonstrate that organic carbon acts as a key mediator between topography, soil texture, and susceptibility to erosion. The altitudinal gradient thus represents a major controlling factor influencing the health and structural stability of coffee soils.

Discussion: These results highlight the need to implement site-specific soil management practices, emphasizing intensive conservation strategies in low-altitude coffee-growing systems to mitigate accelerated erosion and ensure long-term production sustainability under changing climatic conditions.

KEYWORDS

altitudinal gradient, coffee cultivation, Peruvian Amazon, soil erodibility, soil organic carbon, structural stability, sustainable land management

1 Introduction

Slight variations in soil organic carbon (SOC) content may significantly reduce atmospheric CO_2 concentrations, as soil functions both as a source and a sink for CO_2 exchange, facilitating carbon sequestration. Agricultural management practices affect soil water dynamics and the carbon cycle by altering soil CO_2 emission and absorption rates (1). Globally, the top one meter of soil stores approximately twice as much carbon as the atmosphere and three times as much as terrestrial vegetation (1417 Pg, where one petagram = 10^{15} g or 10^9 t) (2). SOC sequestration is fundamental to maintaining soil fertility and ecosystem resilience; thus, enhancing SOC storage is regarded as a sustainable strategy for mitigating environmental change (3). Stored carbon is widely recognized as a key indicator of soil health Bünemann et al. (4) due to its critical role in promoting soil structural stability, quality, and fertility, as well as supporting the overall health of ecosystems (5, 6).

Factors such as vegetation type, land management practices, soil classification, sampling depth, and slope susceptibility to erosion significantly influence soil carbon storage (7, 8). Among these, slope erosion represents one of the greatest threats to the stability of SOC, as it leads to the transport or removal of carbon-rich particles, particularly on slopes ranging from 15° to 35° (9). In addition, climatic factors associated with altitudinal gradients play a key role in determining both the quantity of soil carbon and the inherent physicochemical properties of the soil (10).

SOC reserves show a positive correlation with altitude, with concentrations tending to increase at higher elevations (8, 11, 12). Similarly, Vallejos-Torres et al. (13) reported that secondary forests in the Peruvian Amazon exhibited the highest SOC average (225.28 t ha^{-1}) at an altitude of 1,332 m.a.s.l., in contrast to monoculture coffee soils without shade trees, which contained only a SOC of 28.02 t ha^{-1} at 772 m.a.s.l. This pattern can be explained by the fact that native litter decomposition slows down depending on environmental conditions (14). Additional factors, including vegetation type and increased precipitation, also contribute to this trend (15). Moreover, altitudinal variation influences microbial activity (7), emphasizing the role of microbial residues in the upper soil horizons, which originate from the interaction between organic and mineral layers (16).

However, anthropogenic activities such as deforestation and land-use change have led to substantial reductions in SOC (17). This decline is particularly pronounced in forested areas converted to agricultural use, especially for export-oriented crops such as coffee. In Peru, the area under coffee cultivation expanded from 399,600 ha in 2013 to 422,000 ha in 2022 (11). This ongoing expansion across the national territory has led to the loss of primary forests, contributing to the deforestation of over 3 million hectares of Amazonian and dry forests between 2021 and 2023 for various land-use purposes (18). Although Peruvian Arabica coffee ranks fifth globally, representing 3.9% of world demand (19), its relatively low yields have encouraged the clearing of new areas, making coffee cultivation a key driver of deforestation (20). This process is most evident at elevations around 1,900 m.a.s.l., where cultivation is favored due to its direct influence on coffee's sensory quality (21).

The Central Peruvian Amazon is a key agricultural region characterized by diverse natural resources, extensive forests, the presence of indigenous communities, and the development of emerging crops. It plays a crucial role in the production of staple foods and coffee exports, as well as in the conservation of forested areas. And many crops have been propagated by vegetative propagation from *Plukenetia volubilis*, *coffee arabica*, forest species (22, 23). However, land-use change and the lack of soil conservation practices are contributing to the degradation of soil resources (24). Although several studies have examined SOC in coffee-growing systems of the Peruvian Amazon (13, 25), significant knowledge gaps remain regarding the dynamics of carbon and soil erosion under the influence of climatic, topographic, and edaphic factors, which lead to the structural degradation of soils, thereby limiting coffee production in this part of the country. This study aimed to evaluate the influence of the altitudinal gradient on SOC stocks (t·ha^{-1}) and K index in coffee-growing systems of the Central Peruvian Amazon. The goal was to better understand and interpret the conditions influencing soil structural stability in an increasingly disturbed zone. The findings provide new insights into the edaphic situation of coffee cultivation across different elevations, supporting the identification and implementation of site-specific soil conservation practices suited to the conditions of each altitudinal zone in one of Peru's principal coffee-producing regions (26).

2 Materials and methods

2.1 Study area

The study was conducted in the central Amazon of Peru, specifically in the district of San Martín de Pangoa, Satipo Province, Junín Region, between June and December 2024 (Figure 1). The district covers an area of 5,589.1 km² and is characterized by a bimodal climate, with a dry season from July to September and a rainy season from October to June. The mean annual minimum temperature ranges from 16.7 to 19.8 °C, while the maximum temperature varies between 30.4 and 32.4 °C, with an average annual precipitation of 2,013 mm (27). The research area extends geographically from 11°28′5.61″ S to 11°47′9.08″ S latitude and from 74°35′2.42″ W to 74°11′53.03″ W longitude. The study focused on coffee (*Coffea arabica* L.) cultivation, specifically the Catuaí and Catimor varieties, distributed across three altitudinal zones classified as: altitudinal zone 1 (900–1200 m.a.s.l.), altitudinal zone 2 (1201–1400 m.a.s.l.), and altitudinal zone 3 (1401 to >1600 m.a.s.l.). The main characteristics of the cropping systems are described in Table 1, based on data collected through farmer surveys.

2.2 Climatic conditions were derived from the PISCO (Peruvian Interpolation of SENAMHI Climatological Observations) product developed by SENAMHI

The PISCOp v2.1 product (Sectoral Climate Information Product, stable version) developed by the National Meteorological

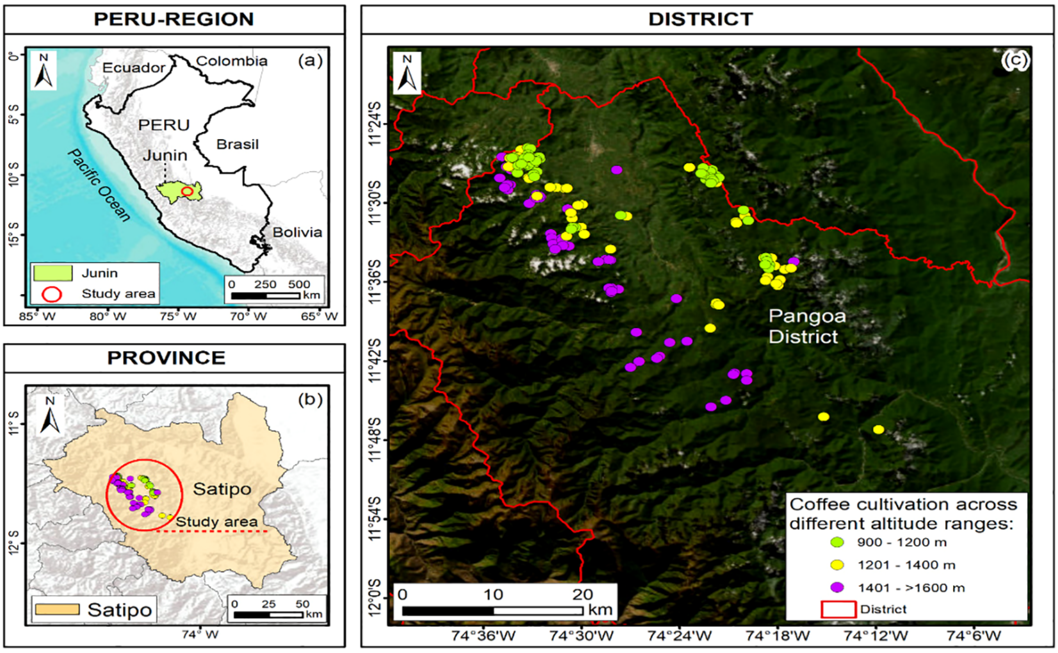

FIGURE 1
Location of the study area in the Central Peruvian Amazon: **(a)** country and region, **(b)** provincial boundaries, and **(c)** district boundaries with sampling points in coffee plantations at different altitudinal ranges.

TABLE 1 **Characteristics of coffee cultivation systems across the three altitudinal zones.**

Altitudinal zone	Coffee system age and prior land use	Logging, burning, and tillage	Fertilization	Shade of the tree	Soil conservation practices
1	Coffee plantations ranged from 3 to 10 years old. The previous land use before coffee cultivation was mainly fallow land (70%) and primary forest (25%). To a lesser extent, areas previously used for coffee, cassava, and plantain cultivation were also identified.	70% of farmers reported having felled and burned the land prior to establishing coffee plantations. Soil preparation practices were mainly based on manual tillage and direct seeding.	Organic fertilization was the most common practice (47%), followed by mixed fertilization (chemical and organic) and exclusively chemical fertilization. Fertilization was generally applied at least once a year.	94% of the coffee-growing systems included shade trees such as *Inga* spp., *Pinus tecunumanii*, *Cedrela odorata*, *Cedrelinga cateniformis*, *Ocotea* sp., *Swietenia macrophylla*, and *Musa* spp.	57% of farmers reported implementing at least one soil conservation practice, such as maintaining vegetative cover, planting against the slope, contour planting, or individual terraces.
2	Coffee plantations ranged from 3 to 9 years old. The previous land use before coffee cultivation consisted mainly of fallow land (50%) and primary forest (40%). A smaller proportion corresponded to areas previously used for coffee, cassava, or plantain cultivation.	50% of the farmers reported having felled and burned the vegetation prior to planting. Soil tillage was carried out manually, and direct seeding was the predominant practice.	Organic fertilization was used by 50% of the farmers, followed by chemical or mixed (organic and chemical) fertilization. Fertilization was carried out at least once a year.	84% of the coffee plantations are managed under shade. The predominant species are *Inga* spp., *Pinus* spp., and *Cedrelinga cateniformis*.	53% of farmers implement at least one soil conservation practice, such as contour planting, planting against the slope, or constructing terraces.
3	Coffee plantations ranged from 3 to 10 years old. The land use prior to coffee cultivation included fallow land (65%), primary forests (24%), and, to a lesser extent, other crops such as ginger.	About 40% of the producers reported having felled and burned the vegetation before planting, while manual tillage and direct seeding were the predominant soil management practices.	Organic fertilization was practiced by 80% of producers, while chemical, mixed (organic and chemical), and no fertilization were each reported in equal proportions among the remaining producers. Fertilization was applied at least once a year.	91% of the coffee systems were managed under shade provided by *Inga* spp., *Pinus tecunumanii*, *Eucalyptus* sp., *Cedrela odorata*, *Cedrelinga cateniformis*, *Ocotea* sp., and *Juglans neotropica*, as well as *Musa* spp.	48% of farmers implement at least one soil conservation practice, such as vegetative cover, planting against the slope contour, planting, or terracing.

and Hydrological Service of Peru (SENAMHI) was used for climatic characterization of the study area (27). This dataset includes monthly precipitation and temperature records for the period 1981–2016, with a spatial resolution of 0.1° (~10 km). As this research required a continuous climate series and validated data for 2024 were not yet available in the stable version of the PISCOp product for the aforementioned years, the dataset was generated through a spatial interpolation process based on meteorological stations distributed nationwide. This interpolation was further adjusted using reanalysis information and satellite data to ensure high temporal and spatial consistency (28). This approach has allowed the PISCOp product to be widely applied in hydrological, agricultural, and environmental studies across different regions of Peru.

This approach allows for the representation of "normal" or reference climatic conditions, consistent with the World Meteorological Organization's (29) definition of climatic normals, while ensuring the consistency and robustness of the time series used. The precipitation and temperature data incorporated into the structural equation modeling (SEM) correspond to monthly climatological values (1981–2016), derived from the mean of each month over the 36-year period. Climate data processing and analysis were carried out using R software version 4.5.0 (30), within the RStudio development environment (31).

2.3 Spatial variability of slope in the study area

Digital elevation models (DEMs) were obtained from Earthdata (32), using the SRTM-Downloader plugin in QGIS (version 3.42.2) to generate the slope map. The DEMs were combined and processed with the GDAL Slope tool, following the (33) classification adapted by Pucha-Cofrep. (34) which defines eight slope classes expressed in both percentages and degrees. Classification was performed using the Raster Calculator, and the resulting map was clipped to the boundaries of the San Martín de Pangoa district. A unique values symbology was then applied for visual differentiation. Finally, slope values corresponding to each sampling point were extracted using the Sample Raster Values tool.

2.4 Sampling design and soil analysis

Three altitudinal zones commonly used for *Arabica coffee* cultivation were identified in the study area. These were defined as 900–1,200 m.a.s.l. (altitudinal zone 1), 1,201–1,400 m.a.s.l. (altitudinal zone 2), and 1,401–>1,600 m.a.s.l. (altitudinal zone 3). Although coffee plantations exist below 900 m.a.s.l., they represent a minor proportion of the total cultivated area, as higher elevations are associated with better plant development and coffee quality. Soil samples were collected from a depth of 0–20 cm across the three altitudinal zones, with 55 samples for zone 1, 56 for zone 2, and 62 for zone 3. Each soil sample represented an area of 1 hectare (ha). This sampling depth was selected because the highest concentration of SOC is typically found in the soil surface layer, with contents decreasing progressively at greater depths (35). According to INRENA (36), the life zones of the sampling area correspond mainly to bp-PM-T, bmh-PM-T, and bp-MB-T.

The soil sampling framework followed a stratified random approach at the farm level. Within each altitudinal zone, representative coffee plots were selected, and a systematic "W" or zigzag transect design was implemented in each plot to ensure spatial coverage. To account for within-plot variability, ten sub-samples were collected along the transect and thoroughly mixed to form a single composite sample per hectare. A total of 173 soil samples were analyzed at the Soil, Water, and Foliar Laboratory of the Pichanaki Agrarian Experimental Station, of the National Institute for Agrarian Innovation (INIA), Peru. The samples were pre-treated at temperatures below 40 °C and sieved to a particle size of< 2 mm in accordance with the International Organization for Standardization (37), prior to physicochemical analysis. The textural class was determined based on the percentages of sand, silt, and clay using the Bouyoucos hydrometer method. Soil pH was measured in a 1:1 soil-to-water suspension (38). OM was quantified using the Walkley and Black method (39), total nitrogen by the Kjeldahl method (40), available phosphorus by the Bray and Kurtz method (39), and available potassium following (41).

2.5 Determination of soil organic carbon density, erodibility, clay ratio, and soil structural stability index

SOC was quantified based on the organic carbon content (%) determined by the Walkley and Black method, considering the sampling depth and soil bulk density. The SOC stock ($t{\cdot}ha^{-1}$) was calculated following Equation 1:

$$SOC\ (t\ C \cdot ha^{-1}) = OC \times D \times BD \tag{1}$$

Where OC is the organic carbon content in the soil (%), D is the soil sampling depth (cm), and BD is the bulk density ($g{\cdot}cm^{-3}$).

The soil organic carbon density (DSOC) was calculated using the formula (Equation 2) proposed by (42):

$$DSOC = Hh\,[BDh \times SOCh \times (1 - Ch)]/100 \tag{2}$$

Where DSOC is the soil organic carbon density ($t\ C{\cdot}ha^{-1}$), Hh is the soil layer thickness (cm), BDh is the bulk density of the soil ($g{\cdot}cm^{-3}$), SOCh is the soil organic carbon stock ($t\ C{\cdot}ha^{-1}$), and Ch is the percentage by volume of the >2 mm fraction.

Generally, soils of the Peruvian Amazon are located on high terraces or hilly landscapes (43) and contain between 0.05 and 0.15 of soil fraction without organic carbon (Ch). This indicates that approximately 5–15% of the soil presents a volumetric fraction of coarse fragments (> 2 mm). These coarse fragments do not contain measurable organic carbon, whereas the remaining 85–95% corresponds to the fine soil fraction that contains organic carbon. Therefore, the carbon-containing soil fraction (1 − Ch) ranges from 0.85 to 0.95.

The K index was calculated using the model proposed by Williams et al. (44), as expressed in Equation 3:

$$K = \{0.2 + 0.3exp[-0.0256SAN(1 - SIL/100)]\} \times \left[\frac{SIL}{CLA + SIL}\right]^{0.3} \times \left[1.0 - \frac{0.25SOC}{SOC \ + e^{3.72-2.95SOC}}\right] \times \left[1.0 - \frac{0.75SN_1}{SN_1 + e^{-5.51+22.9SN_1}}\right] \quad (3)$$

Where SAN is the sand content (%), SIL is the silt content (%), CLA is the clay content (%), SOC is the soil organic carbon content (%), and $(SN)_1$ is the modified sand fraction, calculated as 1 − SAN/100.

The clay ratio (CR) is an indicator of soil erosion susceptibility (45), as it relates the proportion of sand and silt to clay content. This index is based on the principle that clay and colloidal humus exert a binding and cementing effect on soil particles, promoting aggregate formation and preventing particle dispersion. The CR was calculated following Equation 4:

$$CR = (\%Sand + \%Silt)/\%Clay \quad (4)$$

The SI is used to assess the risk of soil structural degradation by relating SOC to the mineral fractions. It was calculated according to the method proposed by Pieri (46), expressed by Equation 5, which incorporates the percentages of OM, silt, and clay:

$$SI = \%\ OM/(\%\ Silt + \%\ Clay) \times 100 \quad (5)$$

According to Pieri (46), soils are classified as follows: SI > 9% (stable structure), 7%< SI ≤ 9% (low risk of structural degradation), 5%< SI ≤ 7% (high structural degradation), and SI ≤ 5% (structurally degraded soil).

2.6 Statistical analysis

The data were analyzed using R software (version 4.4.1) within the RStudio environment (2023 edition). Multiple analyses of variance (ANOVA) were performed based on generalized linear models (GLMs) with normal, lognormal, beta, gamma, and Tweedie distributions (using the *glmmTMB* package). The most appropriate distribution for each variable was selected using the corrected Akaike Information Criterion (AICc) from the *MuMin* package. Model assumptions were evaluated with the *DHARMa* package, verifying the normality of residuals, absence of outliers, overdispersion, and homoscedasticity. Multiple comparisons were conducted using the *emmeans* package, applying Tukey's adjustment method (p< 0.05). For bulk density, which did not meet the aforementioned assumptions, a non-parametric test based on ANOVA of aligned ranks was applied using the *ARTool* package. Principal Component Analysis (PCA) was conducted on the standardized physicochemical variables, including those without linear dependence. The optimal number of components was determined using the elbow method and eigenvalues greater than one, implemented through the *factoextra* package. Finally, a path model was estimated using the lavaan package with the robust maximum likelihood (MLR) estimator. The sample size was considered adequate for structural equation modelling (SEM), as Hair et al. (47) recommend a minimum of eight observations per observed variable, while Catena et al. (48) suggest at least 15 observations per variable. Given that the model included 11 observed variables and a sample of 173 observations, both criteria were satisfied. Model fit was evaluated using the Root Mean Square Error of Approximation (RMSEA), the Standardized Root Mean Square Residual (SRMR), the Comparative Fit Index (CFI), and the Tucker–Lewis Index (TLI).

3 Results

3.1 Seasonal and interannual variability of climatic conditions in the study area

The time series showed seasonal and interannual variability in precipitation at the three altitudinal zones, with higher values in zone 3, ranging from approximately 30 to 550 mm·month^{-1} and moving means of 150 to 250 mm·month^{-1}. In contrast, zones 1 and 2 had precipitation values ranging from approximately 20 to 450 mm·month^{-1} and moving means of 100 to 180 mm·month^{-1}. Analysis of the 12-month moving mean smoothed out monthly variability and revealed clear interannual cycles, confirming a positive relationship between altitude and precipitation accumulation (Figure 2A). The non-parametric Kruskal–Wallis analysis showed that there is at least one significant difference in precipitation between the altitude ranges evaluated (H = 8.27; p = 0.016), and Dunn's *post hoc* comparisons with Bonferroni adjustment indicated that altitude zone 3 had significantly higher values compared to zone 1 (p< 0.05), as shown in Figure 2B.

Average temperatures exhibited clear differentiation among the altitudinal zones during the 1981–2016 period. In both the monthly series and the 12-month moving mean (12-MMA-Pp), zones 1 and 2 exhibited similar and consistently higher temperature values, ranging from 19 to 24 °C, with a moving mean of approximately 21–22 °C. In contrast, zone 3 recorded lower temperatures throughout the period, ranging from 17 to 21 °C, with a moving mean near 19 °C (Figure 3A). Despite interannual variability, temperature trends across all three zones remained stable, without evidence of abrupt fluctuations. Statistical analysis confirmed significant differences among the altitudinal zones (Figure 3B). The Kruskal–Wallis test indicated highly significant differences (H = 217.78, p< 0.0001). The Dunn–Bonferroni *post hoc* test revealed that zones 1 and 2 did not differ significantly (p = 0.483), whereas both zones exhibited significantly higher temperatures than zone 3 (p< 0.0001 in both cases).

3.2 Spatial variability of the slope in the study area

The slope analysis of the San Martín de Pangoa district, according to the [41] classification, revealed that only 0.98% of the total area corresponds to flat to very gently sloping terrain (0–1.15°), mainly located in valleys and alluvial plains. In contrast, 84% of the district is characterized by sloping terrain: 2.51% with Slightly inclined slopes (1.15–2.86°), 5.72% with inclined slopes (2.86–

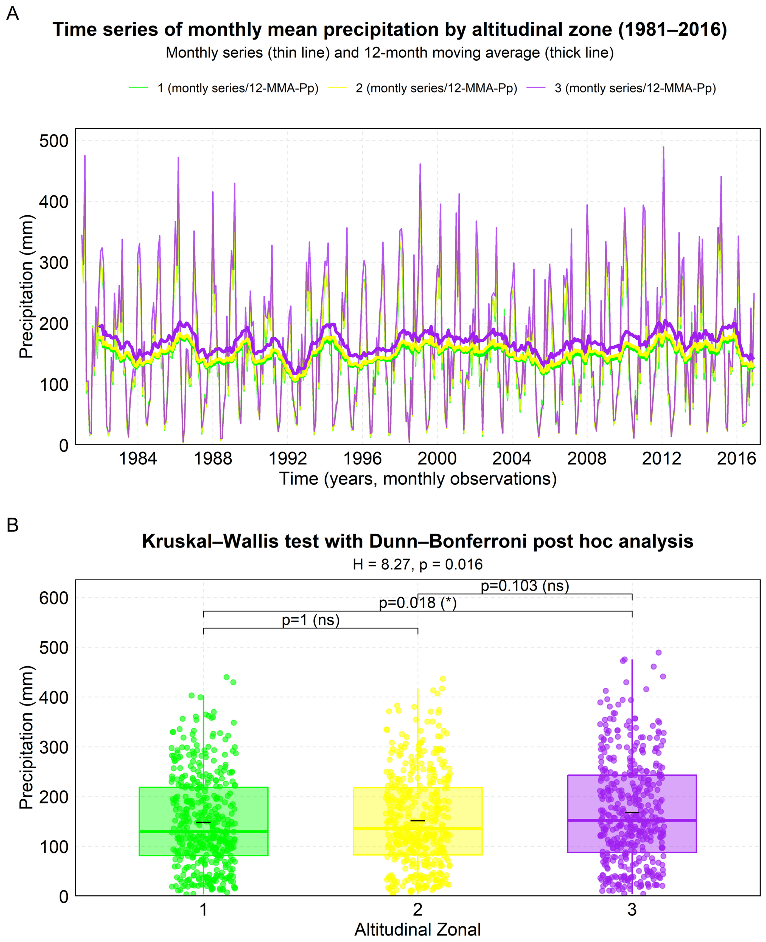

FIGURE 2
(A) Time series of mean monthly precipitation and its 12-month moving mean (12-MMA-Pp) across three altitudinal zones during the period 1981–2016. **(B)** Distribution of precipitation by altitudinal range and results of the non-parametric Kruskal–Wallis analysis with Dunn–Bonferroni *post hoc* comparisons. *p< 0.05; ns, not significant.

5.71°), 6.61% with Strongly inclined slopes (5.71–8.53°), 22.80% with Moderately steep slopes (8.53–16.70°), 35.91% with steep slopes (16.70–30.96°), and 25.46% with Very steep slopes (>30.96°). At the 173 sampling points, slopes corresponding to classes 3 to 8 were identified. Classes 6 and 7 predominated in Zone 1; class 6 remained the most frequent in Zone 2; and class 7 was dominant in Zone 3. Overall, classes 6 and 7 accounted for the majority of the recorded observations (66 and 59 points, respectively), indicating a landscape primarily composed of moderately to very steep slopes and, consequently, a high susceptibility to erosive processes.

3.3 Soil properties across different altitudinal zones

Soil properties can vary significantly along altitudinal gradients, influencing the functioning and productivity of coffee-growing ecosystems. To evaluate these variations, multiple analyses of variance (ANOVA) were conducted to determine how soil properties change with altitude and to identify the most significant effects within each of the altitudinal zones studied.

3.3.1 Physical properties

The physical properties evaluated included bulk density, K index, structural stability index (SI), and CR. Different probability distributions were fitted to assess the influence of the altitudinal zone on these variables, and the model with the lowest corrected Akaike Information Criterion (AICc) value was selected. The results are presented in Table 2. A gamma distribution best described the K index and SI, whereas CR followed a lognormal distribution. Bulk density did not adequately fit any probability distribution; therefore, a non-parametric test was applied. Overall, the models indicated that the altitudinal gradient significantly influenced several physical components of coffee-growing soils.

The comparison of means revealed an increasing pattern in bulk density (Figure 4A), SI (Figure 4C), and CR (Figure 4D), with lower estimated means in altitudinal zone 1 (1.42 g cm^3, 0.05, and 5.21, respectively) and higher means in zone 2 (99.47, 0.07, and 7.50, respectively). In contrast, the K index (Figure 4B) exhibited the opposite pattern, with higher estimated means in zone 1 (24.74) and lower values in zone 3 (7.32), suggesting greater susceptibility to erosion in the lower-altitude areas.

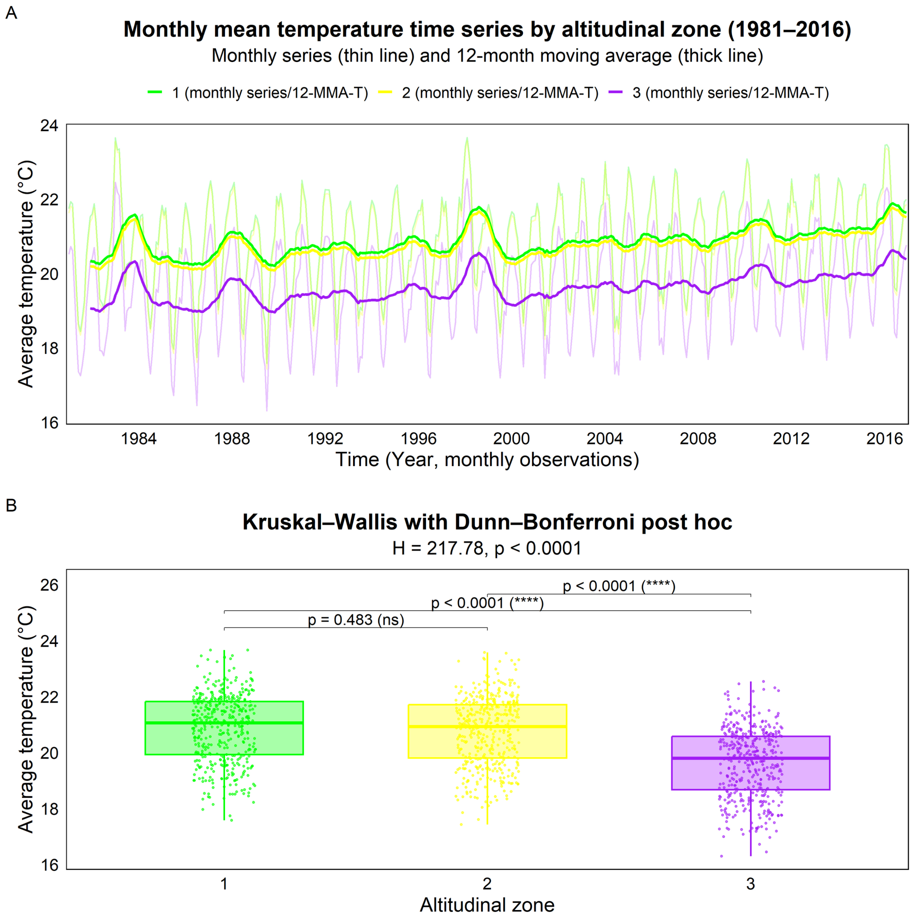

FIGURE 3
(A) Time series of mean monthly temperature and its 12-month moving mean (12-MMA-T) across altitudinal zones 1, 2, and 3 during the period 1981–2016. **(B)** Box plot of average temperature in the three zones with results of the non-parametric Kruskal–Wallis analysis and Dunn–Bonferroni *post hoc* comparisons. ***p< 0.0001; ns, not significant.

3.3.2 Chemical properties

The models fitted for soil chemical properties employed different probability distributions, selecting the best-fitting one according to the AICc. The lognormal distribution was used for pH, the Beta distribution for OM and total nitrogen (N), the Gamma distribution for available phosphorus (PD), and the Tweede distribution for exchangeable potassium (KD), as shown in Table 3. Based on these distributions, the altitudinal zone was found to be significantly associated with the chemical properties OM (p< 0.01), N (p< 0.01), and PD (p< 0.01), indicating that at least one altitudinal zone differs in these parameters. In contrast, pH (p = 0.09) and KD (p = 0.89) showed no significant differences among the three altitudinal zones evaluated.

Comparisons of mean soil chemical properties across the altitudinal gradient (Figure 5) revealed a significant increase in

TABLE 2 ANOVA of soil physical properties: choice of distribution and significance of the altitudinal zone.

Factor	Bulk density ($g \cdot cm^{-3}$)	Soil erodibility (K index)	SI	CR
Factor significance: Statistic (p-values)				
Altitudinal zone	9.06 (< 0.01)	154.37 (<0.01)	143.67 (< 0.01)	30.53 (< 0.01)
Choice of distribution				
Distribution	Non-parametric	Gamma	Gamma	Lognormal
AICc	–	-1089	1160	829

The numerator and denominator degrees of freedom were 2 and 170, respectively. The F statistic was used for the non-parametric test, and Chi^2 in other cases. SI, Soil Structural Stability Index; CR, Clay ratio.

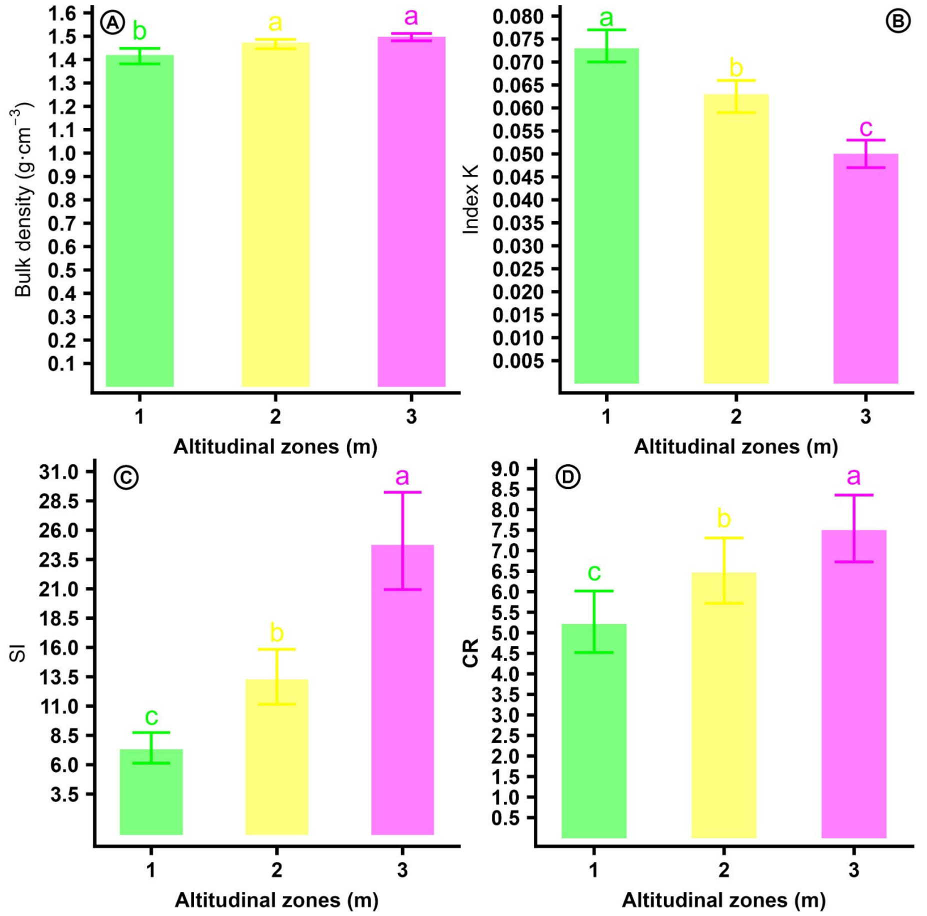

FIGURE 4
Physical soil properties across different altitudinal zones under coffee cultivation. **(A)** Bulk density range, **(B)** soil erodibility (K index), **(C)** Soil structural stability index (SI), **(D)** Clay/(silt + sand) ratio (CR). Vertical bars represent 95% confidence intervals. Altitudinal zones correspond to: 1 = 900–1200 m.a.s.l., 2 = 1201–1400 m.a.s.l., and 3 = 1401–>1600 m.a.s.l. Different letters among altitudinal zones indicate significant differences at a 0.05 significance level, according to Tukey's correction method.

OM (Figure 5B) and total nitrogen (Figure 5C) contents with increasing altitude. The estimated mean values for OM were 3.23% in altitudinal zone 1 and 5.49% in zone 3, while mean values for total nitrogen were 0.16% and 0.27%, respectively. Available phosphorus (Figure 5D) also showed a significant increase, rising from 3.76 mg·kg^{-1} in zone 1 to 5.98 mg·kg^{-1} in zone 3 (the highest zone). In contrast, both pH (Figure 5A) and available potassium (Figure 5E) exhibited similar mean values across the three altitudinal zones, with no statistically significant differences.

TABLE 3 **ANOVA of soil chemical properties: choice of distribution and significance of the altitudinal zone.**

Factor	pH	OM (%)	N (%)	PD (mg·kg^{-1})	KD (mg·kg^{-1})
Factor significance: Statistic (p-values)					
Altitudinal zone	4.64 (0.09)	61.33 (< 0.01)	58.36 (< 0.01)	14.41 (< 0.01)	0.22 (0.89)
Choice of distribution					
Distribution	Lognormal	Beta	Beta	Gamma	Tweede
AICc	314	-389	-389	842	-223

The numerator and denominator degrees of freedom were 2 and 170, respectively. The Chi² statistic was used for the significance test. OM, Organic matter; N, Nitrogen; PD, Available phosphorus; KD, Available potassium.

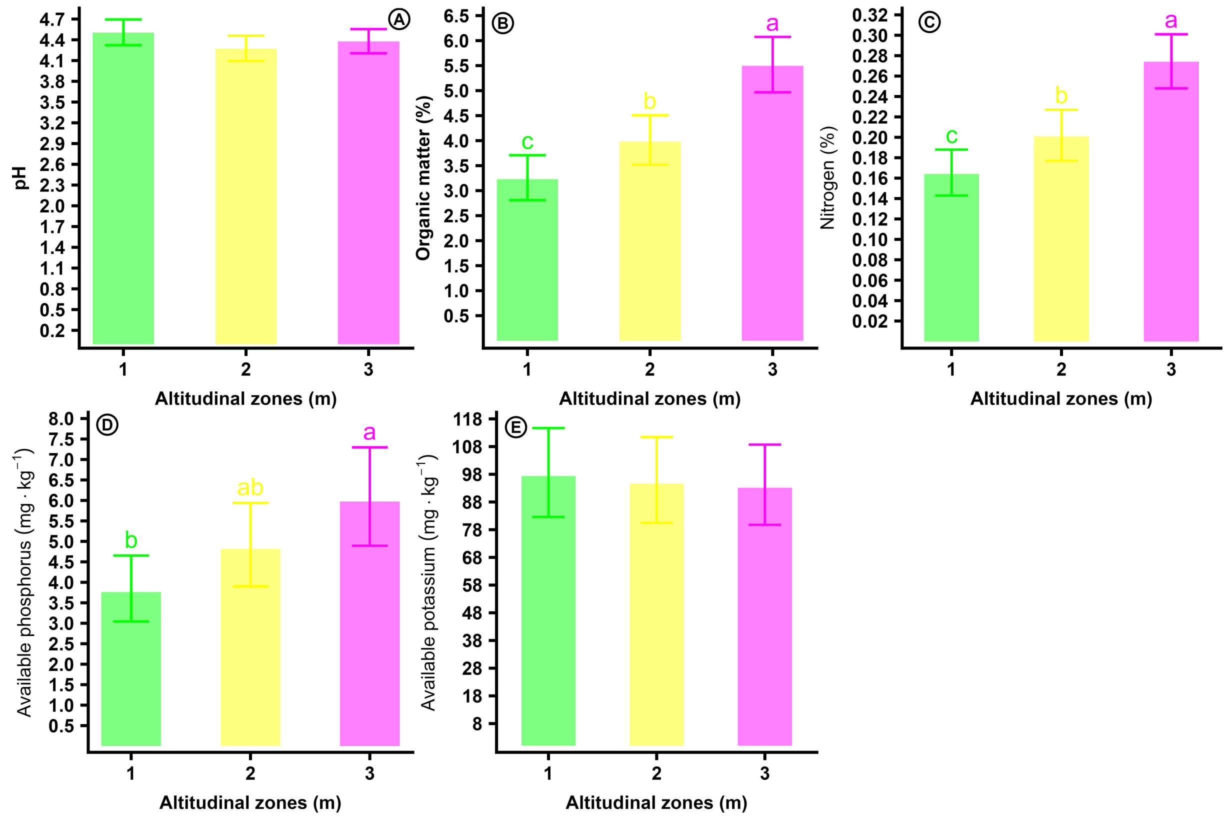

FIGURE 5
Soil chemical properties at different altitudinal zones under coffee cultivation. **(A)** pH, **(B)** Organic matter (%), **(C)** Total nitrogen (%), **(D)** Available phosphorus (P-Bray, mg·kg^{-1}), and **(E)** Available potassium (mg·kg^{-1}). Vertical bars indicate 95% confidence intervals. The altitudinal zones correspond to: 1 = 900–1200 m.a.s.l., 2 = 1201–1400 m.a.s.l., and 3 = 1401–>1600 m.a.s.l. Different letters among altitudinal zones indicate significant differences at the 0.05 significance level, according to Tukey's correction method.

3.3.3 Carbon indicators

The evaluated carbon indicators (SOC and DSOC) were best fitted to a tweede distribution model with the lowest AICc values, as detailed in Table 4. According to this distribution model, the altitudinal zone was significantly associated with both indicators ($p < 0.01$), suggesting that the parameters exhibited different behavior across at least one of the altitudinal zones analyzed.

SOC (Figure 6A) and DSOC (Figure 6B) increased significantly with higher altitude. The estimated mean SOC values were 37.56 t·ha^{-1} in altitudinal zone 1, 46.77 t·ha^{-1} in zone 2, and 63.19 t·ha^{-1} in zone 3. Similarly, DSOC values rose from 0.46 t·ha^{-1} in zone 1 to 0.58 t·ha^{-1} and 0.81 t·ha^{-1} in zones 2 and 3, respectively.

TABLE 4 **ANOVA of carbon indicators: choice of distribution and significance of the altitudinal zone.**

Factor	SOC (t·ha^{-1})	DSOC (t·ha^{-1})
Factor significance: Statistic (p-values)		
Altitudinal zone	58.87 (< 0.01)	65.66 (< 0.01)
Choice of distribution		
Distribution	Tweedie	Tweedie
AICc	1495	851

The numerator and denominator degrees of freedom were 2 and 170, respectively. The Chi² statistic was used for the significance test. SOC, Soil organic carbon stock; DSOC, Density of soil organic carbon stock.

3.4 Principal component analysis of soil properties in coffee-growing systems: influence of altitude

Analyzing soil properties in coffee-growing systems provides valuable insight into their variability and relationship with altitudinal gradients. Principal component analysis (PCA) was applied to evaluate how altitude influences soils' physicochemical characteristics across different zones, thereby identifying relatively higher or lower fertility areas. The PCA revealed two principal components. The first, termed "Physical Properties of the Soil," included bulk density, SOC, the K index, SI, and CR, accounting for 38.7% of the total variance. This component primarily represents the soil's physical characteristics and its susceptibility to erosion. The second component, termed "Chemical Properties of the Soil," comprised soil pH, available potassium, and available phosphorus, explaining 20.9% of the total variance. This component reflects the fundamental chemical conditions that determine soil fertility and the availability of essential nutrients for plant growth.

Overall, the variables that contributed most to soil differentiation were the SI, SOC, and the K index, all associated with the "Physical Properties of the Soil" component. These variables exhibited the highest correlations along this axis,

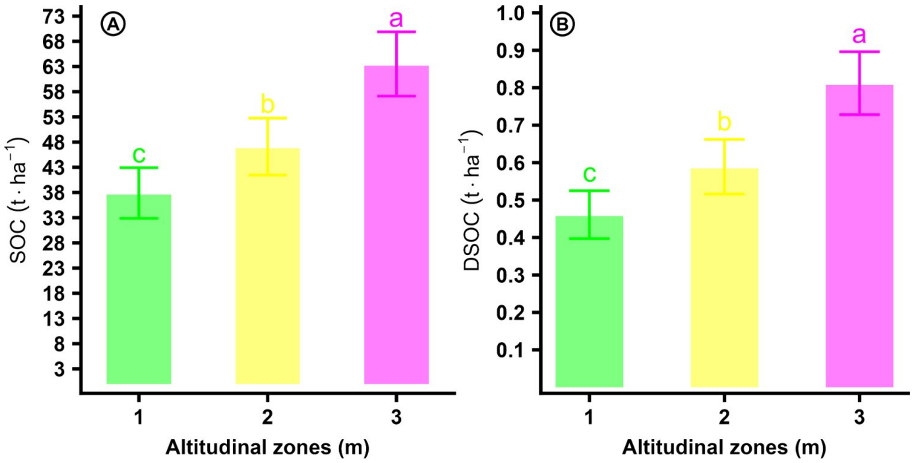

FIGURE 6
Soil carbon at different altitudinal zones under coffee cultivation. **(A)** Soil organic carbon stock (SOC, t·ha^{-1}) and **(B)** Density of soil organic carbon stock (DSOC, t·ha^{-1}). Vertical bars represent 95% confidence intervals. The altitudinal zones correspond to: 1 = 900–1200 m.a.s.l.; 2 = 1201–1400 m.a.s.l.; and 3 = 1401–>1600 m.a.s.l. Different letters among altitudinal zones indicate significant differences at a 0.05 significance level according to Tukey's correction method.

indicating that they were well represented within this dimension. In contrast, within the "Chemical Properties of the Soil" component, the best-represented variables were soil pH and available potassium, suggesting that this axis primarily explained their greater variability.

Figure 7 shows that the highest altitudinal zone (1400–>1600 m.a.s.l.) was associated with higher values of available phosphorus, CR, SOC, bulk density, and SI. In contrast, the lowest altitudinal zone (900–1200 m.a.s.l.) was mainly associated with a greater K index, higher pH, and higher concentrations of available potassium. This pattern reflects a clear differentiation in the expression of soil physicochemical properties along the altitudinal gradient.

3.5 Soil–environment relationship model in coffee-growing systems

Coffee-growing systems in tropical regions are highly susceptible to physical degradation and erosion processes, which threaten soil structural stability and long-term crop sustainability. This vulnerability underscores the need for integrated approaches

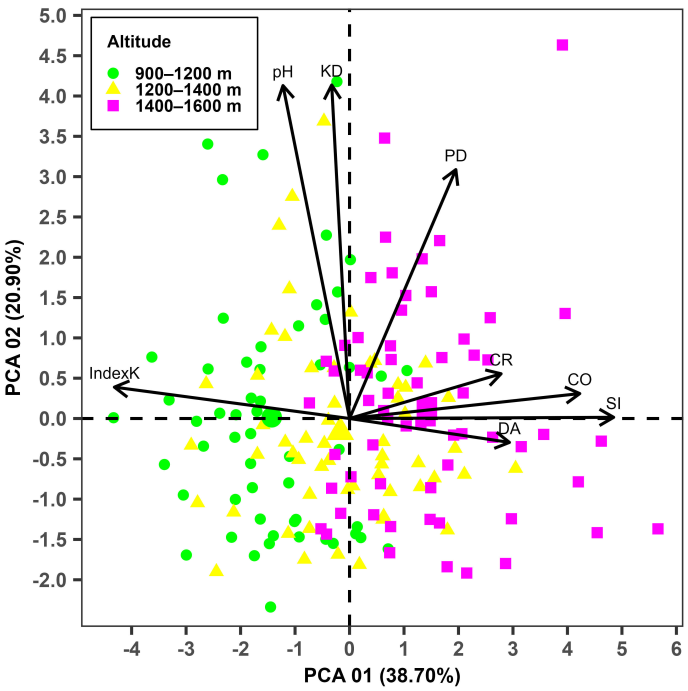

FIGURE 7
Distribution of altitudinal zones and soil variables in the space of the first two principal components. K index, soil erodibility; KD, available potassium; PD, available phosphorus; CR, (silt + sand)/clay ratio; SOC, soil organic carbon; SI, soil structural stability index; DA, bulk density.

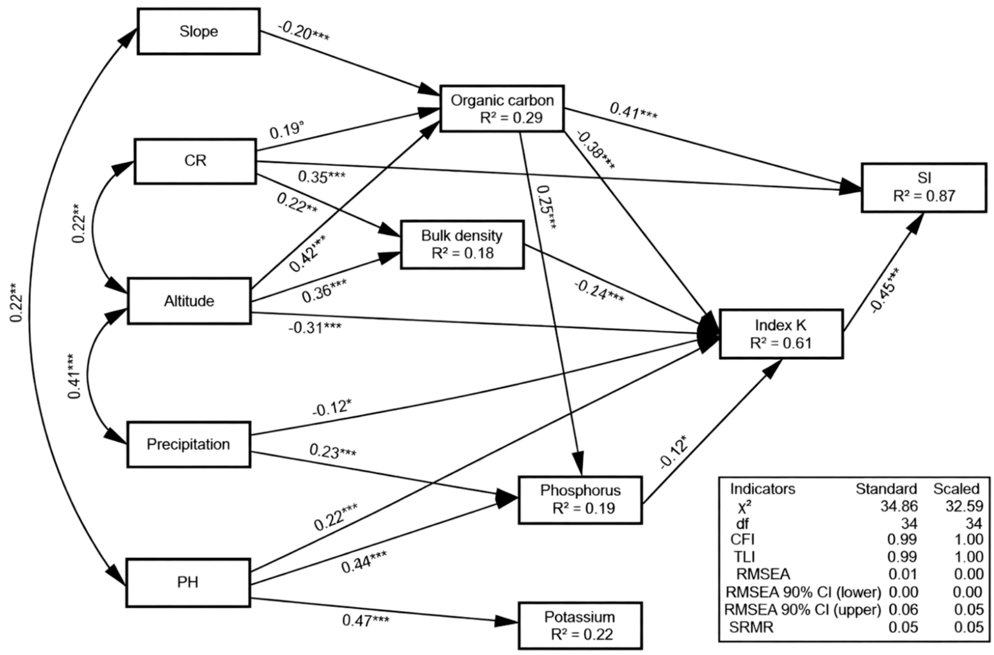

FIGURE 8
Structural soil–environment model in coffee-growing systems. R^2, coefficient of determination; CR, clay/(silt + sand) ratio; SI, soil structural stability index. ° p< 0.1; *p< 0.05; **p< 0.01; ***p< 0.001.

capable of explaining the interactions among edaphic, topographic, and climatic factors. Accordingly, a structural model was developed to articulate these dimensions, and its results are presented in Figure 8. The model fit was evaluated using both standard and robust (scaled) fit indices (Figure 8). The robust chi-square statistic was not significant (χ^2 = 32.59, df = 34, p > 0.05). The absolute fit indices indicated satisfactory model fit, with an RMSEA of 0.00–0.05 (90% CI) and an SRMR of 0.05. Similarly, the incremental fit indices showed satisfactory values (CFI = 1.00; TLI = 1.00), suggesting that the model provides an adequate representation of the observed data.

The results indicated that altitude positively influenced SOC (β = 0.42) and bulk density (β = 0.26), while decreasing the K index (β = –0.31). Similarly, higher precipitation levels positively affected available phosphorus (β = 0.23), enhancing its availability and, to a lesser extent, reducing the K index (β = –0.12). An increase in soil pH primarily favored the availability of potassium (β = 0.47), followed by phosphorus (β = 0.26) and the K index (β = 0.22). Higher CR content had a pronounced effect on soil structural stability (β = 0.35), followed by bulk density (β = 0.28) and organic carbon (β = 0.19). Slope negatively affected organic carbon, reducing its content (β = –0.20). Organic carbon had its strongest effect on SI (β = 0.41), increasing soil resistance, followed by K index (β = –0.38), which reduced its susceptibility, and available phosphorus (β = 0.25), which increased its concentration. The variability in organic carbon was explained by 28.50% due to the combined effects of altitude, CR, and slope. This suggests that SOC plays a mediating role in the interaction among topographic and textural factors with soil properties, thereby modulating both susceptibility to erosion and the availability of phosphorus and structural stability.

Regarding the K index, bulk density exhibited a negative effect (β = –0.14), and its variability was explained by altitude and CR, accounting for 18% of the variation. This suggests that this variable may act as a mediator by integrating the influence of topographic and textural factors on soil susceptibility to erosion. Similarly, available phosphorus exerted a negative influence on the K index (β = –0.12), with its variability explained by 19.10% through the combined effects of SOC, precipitation, and pH. This suggests that phosphorus could function as a mediating variable linking SOC with the K index, primarily through enhanced soil fertility and increased vegetation cover, which collectively reduce the soil's susceptibility to erosion.

The K index exerted a significant negative effect on SI (β = –0.45), reducing the soil's capacity to maintain stable aggregates. Its variability was explained by 61.30% through environmental and edaphic factors, suggesting that the K index can be conceptualized as a mediating variable that not only integrates the influence of these factors and transmits it to soil structural stability but also has the potential to amplify or attenuate their effects depending on the prevailing interactions between soil and environmental conditions. Consequently, SI was explained by 86.70% within the soil–environment relationship model for coffee-growing systems.

4 Discussion

4.1 Climatic conditions across the three altitudinal zones

In the study area, precipitation increased with altitude, reaching 4,000–5,000 mm per year, consistent with values reported for hotspots in the Peruvian cloud forest fringe (49). This pattern corresponded to the topographic gradient: slopes of class 6 (moderately steep) predominated below 1,400 m.a.s.l., while slopes of class 7 (steep) dominated above 1,400 m.a.s.l. Statistical analysis revealed a clear altitudinal control over the precipitation regime. Conversely, temperature decreased from 19–24 °C in low to mid-altitude zones to 17–21 °C in higher areas, corresponding to a negative thermal gradient of 0.5–0.6 °C per 100 m, a pattern recurrent along the eastern Andean slope (50). Overall, the interaction among altitude, slope, and climate defines a contrasting climatic-topographic pattern, with higher rainfall and water energy at higher elevations and warmer, drier conditions at lower altitudes within coffee-growing systems.

4.2 Relationship between climatic conditions and soil physicochemical properties

Variables such as SI and CR increased with altitude, primarily due to higher organic carbon content (51), which enhances soil resistance to water impact by improving aggregate cohesion and resistance (52–54). Likewise, the rise in bulk density may be attributed to the higher CR, which affects the degree of soil compaction (55). In contrast, the K index decreased at higher altitudes due to increased OM (Figure 5B), which acts as a cementing agent that enhances aggregate stability and reduces particle detachment (56, 57). Additionally, factors such as soil texture, structure, OM content, wettability, and hydraulic properties were also found to play significant roles (58, 59).

At higher altitudes, available phosphorus increased by 2.22 $mg{\cdot}kg^{-1}$ compared with the lowest range (Figure 5D). This pattern is likely related to the higher OM content (Figure 5B), which enhances microbial activity and, consequently, phosphorus availability (60). However, the mean P concentrations across altitudinal zones (3.75, 4.81, and 6.88 $mg{\cdot}kg^{-1}$) are considered low or deficient (<15 $mg{\cdot}kg^{-1}$) according to (39). Such deficiency can lead to chlorosis, necrosis, and a reduction in leaf photosynthetic area. SOC and nitrogen (N) followed a similar trend (Figures 5B, C), associated with higher precipitation and lower temperatures at greater altitudes (Figures 2, 3) (61). Comparable findings were reported by Cai et al. (62), who observed increased soil nutrient levels at higher elevations, which, together with soil pH, influence OM composition. Similarly, Xu et a. (63) found that organic carbon and nitrogen showed fluctuating trends with altitude, reaching their highest values at 1500 m a.s.l. in subtropical forest ecosystems. In this study, pH exhibited similar averages across the three altitudinal zones (4.5, 4.24, and 4.38), remaining below the optimal pH range for coffee cultivation (5.0–5.5), thereby limiting nutrient availability (64). Altitude affects the nutrient cycle, vegetation, and ecosystem dynamics, which are key to maintaining biodiversity in mountainous regions and essential for developing sustainability strategies for coffee plantations.

4.3 Relationship among environmental factors, SOC, and DSOC

SOC and DSOC levels reached their highest averages in altitude zone 3, with 63.19 and 9.50 $t{\cdot}ha^{-1}$, respectively. Golchin et al. (10) reported similar trends in mountain forests of Iran, where SOC stocks increased at altitudes of 2000–2500 m.a.s.l. compared to lower elevations (500–1000 m.a.s.l.). In agricultural and fallow grassland systems, (65) also observed that all SOC fractions increased with elevation, ranging from 2200 to 3100 m.a.s.l. in the temperate and arid regions of the Himalayas. In Brazil, agroforestry coffee systems with annual rainfall of 854 mm and an average temperature of 20.4 °C achieved SOC levels comparable to those of native forests (66). Under tropical and subtropical conditions, higher altitudes are typically associated with lower temperatures and greater rainfall, which promote SOC retention (67). This occurs due to the accumulation of OM that decomposes more slowly (68), thereby enhancing SOC storage and influencing soil nutrient dynamics. Moreover, in arid and semi-arid mountain ecosystems, an increase in carbon use efficiency and extracellular microbial enzyme activity has been reported, facilitating OM decomposition (69).

The higher accumulation of OM and nutrients at greater altitudes is driven by a temperature-dependent reduction in microbial metabolism. Lower average temperatures limit the enzymatic activity of decomposers, particularly cellulases and ligninases, thereby decelerating the mineralization rate of organic residues. This creates a kinetic imbalance where the rate of leaf litter input exceeds the rate of microbial decomposition, leading to a progressive buildup of SOC and associated nutrients in the topsoil (14). Moreover, in arid and semi-arid mountain ecosystems, an increase in carbon use efficiency and extracellular microbial enzyme activity has been reported, facilitating OM decomposition.

However, this accumulation mechanism depends on a delicate balance between organic matter input and decay rates, which can be disrupted at extreme environmental limits. It is important to note that this trend may reverse at higher elevations. Thapliyal et al. (70) reported a steady decline in SOC (%) with increasing altitude from 2100 to 2700 m a.s.l. in Quercus floribunda forest areas of the Himalayas. Similarly, negative correlations between SOC and its fractions have been found at elevations ranging from 3325 to 4046 m a.s.l., attributed to the reduction in tree cover, lower temperatures, and limited humus availability resulting from slower decomposition under colder conditions (71). Therefore, altitude alone cannot fully explain the variability in carbon stocks, as other interacting factors, such as management practices, disturbances, vegetation type, and tree species diversity, also play critical roles (72).

4.4 Soil variable interrelationships across altitudinal zones

The PCA reveals a consistent pattern of edaphic differentiation along the altitudinal gradient (Figure 7). Altitude zone 1 was positively associated with pH and available potassium (KD), possibly due to higher weathering rates related to a greater K index. In contrast, higher altitudes were characterized by greater bulk density, SOC, available phosphorus, and CR, indicating denser soils with enhanced nutrient retention and structural stability. The increase in OM and nutrient content at higher altitudes can be attributed to lower microbial decomposition rates (7, 73). Stable organic carbon associated with silt and clay fractions tends to accumulate due to the physical protection of aggregates, which serves as a preservation mechanism for SOC (74). This process promotes the formation of stable aggregates and reduces the K index (52), thereby decreasing vulnerability to water erosion, particularly in mountainous systems (56). Moreover, the interaction between clay minerals and organic compounds emerges as a key mechanism in the physical and chemical stabilization of carbon, explaining the positive relationship observed between CR and SOC in this study.

4.5 Path model analysis of edaphic, topographic, and climatic factors associated with soil organic carbon, erosion, and structural stability index

The SEM (Figure 8) indicates that CR, altitude, and slope explain 28.50% of the variability in SOC. This is because there are other influencing factors, such as slope orientation, microbial decomposition dynamics, and soil acidity or alkalinity, that may also play a role (75, 76). The low influence of CR (β = 0.19*) on SOC may be attributed to the acidic conditions of the soil (average pH = 5.5) and the high CR values (mean of 6.5). Rodríguez et al. (77) reported a stronger positive correlation (R^2 = 0.7) in alluvial soils, likely due to their lower acidity and greater fertility, suggesting that SOC is strongly modulated by local edaphic conditions. Regarding the effect of altitude (β = 0.42***), (78) found a similar relationship between elevation and SOC (R^2 = 0.84), indicating that the altitudinal gradient enhances SOC accumulation in coffee-growing systems. Conversely, the negative effect of slope (β = −0.20***) can be explained by the limited accumulation of OM in surface layers. Buraka et al. (78) observed that soils on less steep slopes had 1.8 and 2.6 times higher SOC content than those on moderate and steep slopes, respectively, confirming that SOC depletion intensifies with increasing water erosion on steep terrain.

The K index (R^2 = 0.61) was influenced by six variables: SOC (β = −0.38***), bulk density (β = −0.14***), available phosphorus (β = −0.12*), pH (β = 0.22***), altitude (β = −0.31***), and precipitation (β = −0.12*). The enrichment of SOC reduces the K index, whereas lower SOC levels increase susceptibility to erosion (79, 80). Organic carbon acts as a key aggregate stabilizing agent and improves soil structure (81). Regarding pH and its influence on the K index, Matsumoto et al. (82) reported that as soil pH increased from 2.0 to 6.0, runoff erosion decreased from 2.51 cm·year^{-1} to 1.76 cm·year^{-1}. However, erosion rates increased again (4.37 cm·year^{-1}) when pH rose to 10.0, due to the reduction in electrical repulsion among negatively charged soil particles. The influence of altitude and precipitation on the K index is primarily associated with the mechanical impact of raindrops and surface runoff, which detach and transport soil particles (83, 84). Moreover, characteristics of rainfall patterns, such as duration, intensity, and temporal distribution, directly determine the degree of soil erosion (85).

Variables such as SOC (β = 0.41***), CR (β = 0.35***), and the K index (β = −0.45***) were identified as key determinants of SI (R^2 = 0.87). The increase in SOC significantly reduces the K index by acting as a cementing agent that enhances aggregate mechanical resistance (86). This effect arises from mineral–organic interactions, particularly with clays that play a critical role in the physical and chemical stabilization of carbon, resulting in greater structural stability. Regarding the contribution of CR, Wu et al. (52) reported that clay content was strongly associated with higher erosion resistance and improved soil structure in agro-pastoral ecotone soils. Conversely, the inverse relationship between the K index and SI (56) confirms that enhancing soil physicochemical properties directly strengthens structural stability.

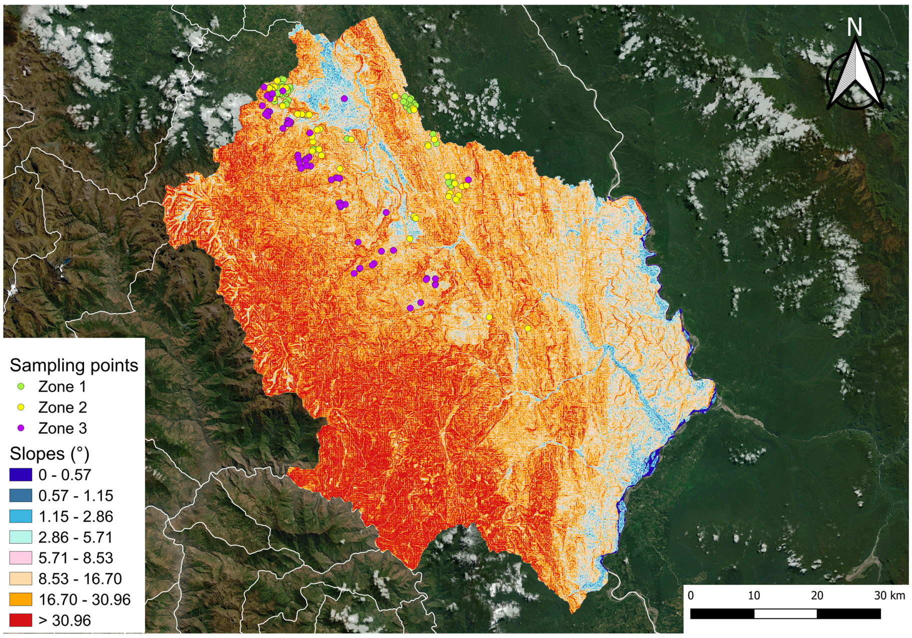

FIGURE 9
Slope map of the study area, expressed in degrees (°) and classified into eight categories: Plane (0–0.57°), Very slightly inclined (0.57–1.15°), Slightly inclined (1.15–2.86°), Inclined (2.86–5.71°), Strongly inclined (5.71–8.63°), Moderately steep (8.63–16.70°), Steep (16.70–30.96°), and Very steep (>30.96°). Sampling points are distributed across three altitudinal zones.

4.6 Implications of altitudinal coffee management in carbon sustainability and erosion resistance

The altitudinal gradient creates contrasts in climatic characteristics and soil physicochemical properties, which in turn influence SOC content and K Index levels. This effect is amplified by the predominance of class 6 and 7 slopes, which control SOC loss or retention, an imbalance that impacts plant nutrition and overall crop sustainability (85). Survey data (Table 1) indicate that, regardless of altitude, at least 50% of coffee growers do not apply soil conservation practices. This issue is further exacerbated by felling and burning vegetation cover for crop establishment, prevalent practices in altitude zone 1. The combination of limited technical knowledge in soil conservation and the high proportion of steep terrain (Figure 9) has contributed to soil degradation in San Martín de Pangoa, one of the districts with the largest coffee-growing areas (26). Different management strategies are needed for each altitudinal zone. In low and mid-altitude zones, where the K index is high and structural stability is limited, the implementation of terraces is recommended to promote the physical protection of labile SOC fractions (69). Similarly, agroforestry systems, especially those incorporating native trees such as *Inga* spp., can improve soil stability and carbon sequestration (25). In higher altitudes, where soils tend to be more stable and clay-rich, management should aim to preserve these favorable conditions through sustainable vegetation cover management and minimal mechanical disturbance, thus promoting stabilization and SOC increase. Moreover, given the steep slopes in these altitudinal zones (Figure 9), proper terrace management remains essential to maintain structural stability and reduce the K index (87).

5 Conclusions

SOC varied across the three altitudinal zones, reaching its highest average in zone 3 (63.19 $t\cdot ha^{-1}$). The lower temperatures and higher precipitation at this elevation favor the accumulation of OM and the availability of P and N, which in turn enhance soil structural stability and reduce the K index. SOC mediates the interaction among environmental, textural, and topographical factors, regulating erosion and vice versa. This relationship is reflected in the higher K index values observed in altitudinal zone 1. Organic carbon, the K index, and the CR together explained the variability of the SI (R^2 = 0.87), with altitudinal zone 3 again standing out. Based on these findings, differentiated management practices are required: in low- and mid-altitude areas, increasing SOC and improving soil structure through terraces and agroforestry systems is recommended, while in high-altitude areas, conserving favorable soil conditions through sustainable vegetation cover management is essential. This study provides valuable insights into soil dynamics across altitudinal gradients and supports the development of conservation and sustainable management strategies for coffee-growing systems in the Central Peruvian Amazon.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

LR: Supervision, Visualization, Writing – original draft, Validation. NH: Conceptualization, Formal analysis, Methodology, Visualization, Writing – review & editing. RC: Validation, Visualization, Writing – original draft, Conceptualization, Data curation. UA: Conceptualization, Validation, Writing – original draft, Methodology, Investigation, Resources. RA: Conceptualization, Resources, Data curation, Formal analysis, Writing – review & editing. RS: Conceptualization, Methodology, Writing – original draft, Visualization, Funding acquisition, Project administration. GV: Conceptualization, Methodology, Supervision, Visualization, Writing – original draft.

Funding

The author(s) declared financial support was received for this work and/or its publication. The research was funded by the Instituto Nacional de Innovación Agraria, within the framework of the project: Mejoramiento de los servicios de investigación y transferencia tecnológica en el manejo y recuperación de suelos agrícolas degradados y aguas para riego en la pequeña y mediana agricultura en los departamentos de Lima, Áncash, San Martín, Cajamarca, Lambayeque, Junín, Ayacucho, Arequipa, Puno y Ucayali" CUI 2487112.

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 not used in the creation of this 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

References

1. Ray RL, Griffin RW, Fares A, Elhassan A, Awal R, Woldesenbet S, et al. Soil CO2 emission in response to organic amendments, temperature, and rainfall. *Sci Rep*. (2020) 10:1–14. doi: 10.1038/S41598-020-62267-6

2. Batjes NH. Total carbon and nitrogen in the soils of the world. *Eur J Soil Sci*. (2014) 65:10–21. doi: 10.1111/EJSS.12114_2

3. Bradford MA, Wieder WR, Bonan GB, Fierer N, Raymond PA, Crowther TW. Managing uncertainty in soil carbon feedbacks to climate change. *Nat Clim Chang*. (2016) 6:751–8. doi: 10.1038/NCLIMATE3071

4. Bünemann EK, Bongiorno G, Bai Z, Creamer RE, De Deyn G, de Goede R, et al. Soil quality – a critical review. *Soil Biol Biochem*. (2018) 120:105–25. doi: 10.1016/J.SOILBIO.2018.01.030

5. Lal R. Soil carbon sequestration impacts on global climate change and food security. *Sci (1979)*. (2004) 304:1623–7. doi: 10.1126/SCIENCE.1097396

6. Orgiazzi A, Ballabio C, Panagos P, Jones A, Fernández-Ugalde O. LUCAS Soil, the largest expandable soil dataset for Europe: a review. *Eur J Soil Sci*. (2018) 69:140–53. doi: 10.1111/EJSS.12499

7. Massaccesi L, De Feudis M, Leccese A, Agnelli A. Altitude and vegetation affect soil organic carbon, basal respiration and microbial biomass in Apennine forest soils. *Forests*. (2020) 11:710. doi: 10.3390/f11060710

8. Liu Y, Chi Q, Cheng H, Ding H, Wen T, Zhao J, et al. Comparative microbial nitrogen functional gene abundances in the topsoil vs. subsoil of three grassland habitats in Northern China. *Front Plant Sci*. (2022) 12:792002. doi: 10.3389/FPLS.2021.792002

9. Beltrán-Dávalos AA, Ayala Izurieta JE, Echeverría M, Jara Santillán CA, Verrelst J, Delegido J, et al. Driving variables to explain soil organic carbon dynamics: páramo highlands of the Ecuadorian Real mountain range. *J Soils Sediments*. (2025) 25:1578–97. doi: 10.1007/s11368-025-04017-7

10. Golchin A, Misaghi M. Investigating the effects of climate change and anthropogenic activities on SOC storage and cumulative CO2 emissions in forest soils across altitudinal gradients using the century model. *Sci Total Environ*. (2024) 943:173758. doi: 10.1016/J.SCITOTENV.2024.173758

11. Mishra U, Hugelius G, Shelef E, Yang Y, Strauss J, Lupachev A, et al. Spatial heterogeneity and environmental predictors of permafrost region soil organic carbon stocks. *Sci Adv*. (2021) 7:5236–60. doi: 10.1126/SCIADV.AAZ5236

12. Li C, Xiao C, Li M, Xu L, He N. A global synthesis of patterns in soil organic matter and temperature sensitivity along the altitudinal gradient. *Front Environ Sci*. (2022) 10:959292. doi: 10.3389/fenvs.2022.959292

13. Vallejos-Torres G, Gaona-Jimenez N, Lozano A, Paredes CI, Lozano CM, Alva-Arévalo A, et al. Soil organic carbon balance across contrasting plant cover ecosystems in the Peruvian Amazon. *Chil J Agric Res*. (2023) 83:553–64. doi: 10.4067/S0718-58392023000500553

14. Berrier DJ, Rawls MS, McCallister SL, Franklin RB. Influence of substrate quality and moisture availability on microbial communities and litter decomposition. *Open Journal of Ecology*. 4:421–433. (2014). doi: 10.4236/oje.2014.48037

15. Körner C. The use of "altitude" in ecological research. *Trends Ecol Evol*. (2007) 22:569–74. doi: 10.1016/j.tree.2007.09.006

16. Sun Y, Chen X, Zhong A, Guo S, Zhang H. Variations in microbial residue and its contribution to SOC between organic and mineral soil layers along an altitude gradient in the wuyi mountains. *Forests*. (2023) 14:1678. doi: 10.3390/F14081678

17. IPCC and IP on CC. *Climate change 2021 – the physical science basis: working group I contribution to the sixth assessment report of the intergovernmental panel on climate change*. Reino Unido: Cambridge University Press (2023). doi: 10.1017/9781009157896

18. Ministerio del Ambiente - MINAM, BOSQUES en tus manos and GEO BOSQUES. Geobosques (2024). Available online at: https://geobosques.minam.gob.pe/geobosque/view/perdida.php. (Accessed September 2, 2025).

19. United States Department of Agriculture - USDA. *United states department of agriculture foreign agricultural service Mexico's production recovering from coffee leaf rust* (2023). Available online at: https://esmis.nal.usda.gov/sites/default/release-files/m900nt40f/73667k581/qz20v7955/coffee.pdf. (Accessed September 2, 2025).

20. Díaz Vargas C, Carmen Willems M. *Línea de Base del Sector Café en el Peru Programa De Las Naciones Unidas Para El Desarrollo* (2018). Available online at: https://www.undp.org/es/latin-america/publicaciones/linea-de-base-del-sector-cafe-en-el-peru. (Accessed September 2, 2025).

21. Márquez-Romero FR, Huamán S, Carrión Sánchez HM, Peña Valdeiglesias J, Cabrera Márquez S. Caracterización de la calidad física y sensorial de café de Cirialo – La Convención Cusco-Peru. *TAYACAJA*. (2020) 3:40–52. doi: 10.46908/RICT.V3I2.106

22. Solis R, Gomales N, Pezo M, Arévalo L, Vallejos-Torres G. Rooting of sacha inchi (Plukenetia volubilis) juvenile cuttings in microtunnels. *Acta Agronómica*. (2019) 68:35–40. doi: 10.15446/acag.v68n1.72101

23. Vallejos-Torres G, Ríos-Ramírez O, Saavedra H, Gaona-Jimenez N, Mesén-Sequeira F, Marín C. Vegetative propagation of Manilkara bidentata (A.DC.) A.Chev. using mini-tunnels in the Peruvian Amazon region. *For Syst*. (2021) 30: eRC01. doi: 10.5424/fs/2021302-17971

24. Zeng C, Li T, He B, Feng M, Liang K, Xu Q, et al. Vegetation succession increases soil organic carbon density and decreases soil erodibility: Evidence from a karst trough valley experiencing farmland abandonment. *Catena (Amst)*. (2024) 246:108359. doi: 10.1016/J.CATENA.2024.108359

25. Salgado Veramendi N, Romero-Chavez LE, Huerto Pajuelo ES, Ibarra Porras CC, Cunyas-Camayo JM, Aldava Pardave U, et al. Carbon storage in coffee agroforestry systems: role of native and introduced shade trees in the central Peruvian amazon. *Agric (Switzerland)*. (2025) 15:1415. doi: 10.3390/agriculture15131415

26. Ministerio de Desarrollo Agrario y Riego - MIDAGRI. Observatorio PPA (2024). Available online at: https://observatorio-ppa.midagri.gob.pe/. (Accessed September 8, 2025).

27. Servicio Nacional de Meteorología e Hidrología del Peru - SENAMHI. *SENAMHI HSR PISCO prec* (2019). Available online at: https://iridl.ldeo.columbia.edu/SOURCES/.SENAMHI/.HSR/.PISCO/.Prec/. (Accessed September 8, 2025).

28. Aybar C, Fernández C, Huerta A, Lavado W, Vega F, Felipe-Obando O. Construction of a high-resolution gridded rainfall dataset for Peru from 1981 to the present day. *Hydrol Sci J*. (2019) 65:770–85. doi: 10.1080/02626667.2019.1649411

29. World Meteorological Organization - WMO. *WMO guidelines on the calculation of climate normals* (2017). Available online at: https://library.wmo.int/viewer/55797/download?file=1203_en.pdf&navigator=1&type=pdf. (Accessed September 8, 2025).

30. R Core Team. *R: A language and environment for statistical computing* (2025). Available online at: https://www.r-project.org/. (Accessed September 2, 2025).

31. R Studio Team. *RStudio: Integrated development environment for R* (2023). Available online at: https://posit.co/. (Accessed September 2, 2025).

32. NASA Earthdata. *NASA Shuttle Radar Topography Mission Global 1 arc second V003*. Pasadena: NASA Earthdata (2013). doi: 10.5067/MEASURES/SRTM/SRTMGL1.003.

33. Food and Agriculture Organization of the United Nations - FAO. *Guía para la descripción de suelos*. Food and Agriculture Organization of the United Nations - FAO. Guía para la descripción de suelos. (Rome: FAO) (2009).

34. Pucha-Cofrep F, Fries A, Cánovas-García F, Oñate-Valdivieso F, González-Jaramillo V, Pucha-Cofrep D. *Fundamentos de SIG Aplicaciones con ArcGIS* (2017). Available online at: www.acolita.com. (Accessed September 11, 2025).

35. Hao XX, Han XZ, Li LJ, Zou WX, Lu XC, Qiao YF. Profile distribution and storage of soil organic carbon in a black soil as affected by land use types. *Ying Yong Sheng Tai Xue Bao*. (2015) 26:965–972.

36. Instituto Nacional de Recursos Naturales - INRENA. *Mapa ecológico del Peru INRENA*. (Lima, Perú: INRENA, Ministerio de Agricultura) (1995). Available online at: https://app.ingemmet.gob.pe/biblioteca/pdf/Lib-215.pdf. (Accessed September 15, 2025).

37. ISO. Soil quality Pretreatment of samples for physico-chemical analysis (2006). Available online at: https://www.iso.org/standard/37718.html. (Accessed September 11, 2025).

38. United States Environmental Protection Agency - U.S. EPA. *Method 9045D Soil and waste pH* (2004). Available online at: https://www.epa.gov/sites/default/files/2015-12/documents/9045d.pdf. (Accessed September 11, 2025).

39. Secretaría de Medio Ambiente y Recursos Naturales - RECNAT. *Norma Oficial Mexicana NOM-021-RECNAT-2000, Que establece las especificaciones de fertilidad, salinidad y clasificación de suelos. Estudios, muestreo y análisis* (2002). Available online at: https://www.ordenjuridico.gob.mx/Documentos/Federal/wo69255.pdf. (Accessed September 11, 2025).

40. ISO. Soil quality Determination of total nitrogen - Modified Kjeldahl method (1995). Available online at: https://www.iso.org/standard/19239.html. (Accessed September 11, 2025).

41. Bazán Tapia R. *Manual de procedimientos de los análisis de suelos y agua con fines de riego* (2017). Available online at: https://repositorio.inia.gob.pe/server/api/core/bitstreams/55bde890-0de8-4f7b-8d15-8b39ea07cd26/content. (Accessed September 11, 2025).

42. Orton TG, Pringle MJ, Page KL, Dalal RC, Bishop TFA. Spatial prediction of soil organic carbon stock using a linear model of coregionalisation. *Geoderma*. (2014) 230–231:119–30. doi: 10.1016/J.GEODERMA.2014.04.016

43. Escobedo R. *Fisiografía del departamento de San Martín: Estudios temáticos para zonificación ecológica y económica (Documento temático)*. (Iquitos, Perú: Instituto de Investigaciones de la Amazonía Peruana – IIAP) (2007). Available online at: https://terra.iiap.gob.pe/assets/files/macro/zee-san-martin/04_Fisiografia_2007.pdf. (Accessed October 11, 2025).

44. Williams JR, Jones CA, Dyke PT. A modeling approach to determining the relationship between erosion and soil productivity. *Trans ASAE*. (1984) 27:129–44. doi: 10.13031/2013.32748

45. Bouyoucos GJ. The clay ratio as a criterion of susceptibility of soils to erosion1. *Agron J*. (1935) 27:738–41. doi: 10.2134/AGRONJ1935.00021962002700090007X

46. Pieri CJMG. *Fertility of soils*. Berlin, Heidelberg: Springer Berlin Heidelberg (1992). doi: 10.1007/978-3-642-84320-4

47. Hair J, Joseph, Black W, Babin B, Anderson R. *Multivariate Data Analysis: Pearson new international edition. 7a ed*. New Jersey: Essex: Pearson (2014).

48. Catena A, Ramos M, Trujillo H. *Análisis multivariado: un manual para investigadores*. España: Biblioteca Nueva, S.L (2003).

49. Huamán-Carrión ML, Espinoza-Montes F, Barrial-Lujan AI, Ponce-Atencio Y. Influencia de la altitud y características del suelo en la capacidad de almacenamiento de carbono orgánico de pastos naturales altoandinos. *Scientia Agropecuaria*. (2021) 12:83–90. doi: 10.17268/sci.agropecu.2021.010

50. Navarro-Serrano F, López-Moreno JI, Domínguez-Castro F, Alonso-González E, Azorin-Molina C, El-Kenawy A, et al. Maximum and minimum air temperature lapse rates in the Andean region of Ecuador and Peru. *Int J Climatol*. (2020) 40:6150–68. doi: 10.1002/JOC.6574

51. Lince-Salazar LA, Castro AF, Castaño WA. Estabilidad de agregados de suelos de la zona cafetera colombiana. *Revista Cenicafe*. (2020) 71:73–91. doi: 10.38141/10778/71206

52. Wu Y, Jia G, Yu X, Rao H, Peng X, Wang Y, et al. Response of soil nutrients and erodibility to slope aspect in the northern agro-pastoral ecotone, China. *SOIL*. (2024) 10:61–75. doi: 10.5194/SOIL-10-61-2024

53. Wu Z, Zhou Y, Wang M. Spatial differentiation and influencing factors of effective phosphorus in cultivated soil in the water source area of the mid-route of South-to-North water transfer project. *Front Microbiol*. (2024) 15:1463291/BIBTEX. doi: 10.3389/fmicb.2024.1463291

54. Xu Z, Tsang DCW. Mineral-mediated stability of organic carbon in soil and relevant interaction mechanisms. *Eco-Environment Health*. (2024) 3:59–76. doi: 10.1016/J.EEHL.2023.12.003

55. Wang G, Zhang Z, Henderson M, Chen M, Dou Z, Zhou W, et al. Effects of terracing on soil aggregate stability and erodibility in sloped farmland in black soil (Mollisols) region of China. *Agriculture*. (2024) 14:1534. doi: 10.3390/AGRICULTURE14091534

56. Li M, Wang K, Ma X, Fan M, Song Y. Effects of land use change on soil aggregate stability and erodibility in the Karst region of Southwest China. *Agronomy*. (2024) 14:1534. doi: 10.3390/AGRONOMY14071534

57. Kiup E, Swan T, Field D. Soil management practices in coffee farming systems in the Asia-Pacific region and their relevance to Papua New Guinea: a systematic review. *Soil Use Manag*. (2025) 41:e70068. doi: 10.1111/SUM.70068

58. Blanco-Canqui H, Lal R. *Principles of soil conservation and management*. United States: Springer Netherlands. (2008). doi: 10.1007/978-1-4020-8709-7

59. Merritt WS, Letcher RA, Jakeman AJ. A review of erosion and sediment transport models. *Environ Modell Software*. (2003) 18:761–99. doi: 10.1016/S1364-8152(03)00078-1

60. Wu T, Liu S, Lie Z, Zheng M, Duan H, Chu G, et al. Divergent effects of a 6-year warming experiment on the nutrient productivities of subtropical tree species. *For Ecol Manage*. (2020) 461:117952. doi: 10.1016/J.FORECO.2020.117952

61. Meng X, Zhang X, Li Y, Jiao Y, Fan L, Jiang Y, et al. Nitrogen fertilizer builds soil organic carbon under straw return mainly via microbial necromass formation. *Soil Biol Biochem*. (2024) 188:109223. doi: 10.1016/J.SOILBIO.2023.109223

62. Cai Y, Xiao J, Liao X, Dong Y, Pan B, Zhang L, et al. Dryland-to-paddy conversions lead to short-term decreases in soil organic carbon and carbon pool management index in Karst soil of Guizhou Province, China. *Agriculture*. (2025) 15:396. doi: 10.3390/AGRICULTURE15040396

63. Xu Z, Xie X, Shao Q, Pu L, Meadows M, Jia Z, et al. Differential response of soil characteristics and extracellular enzyme activities along an altitude gradient in a subtropical forest ecosystem, eastern China. *Catena (Amst)*. (2025) 256:109132. doi: 10.1016/J.CATENA.2025.109132

64. Teron G, Bordoloi R, Paul A, Singha LB, Tripathi OP. Effect of altitude on soil physico-chemical properties and microbial biomass carbon in the Eaglenest Wildlife Sanctuary of Arunachal Pradesh. *Geol Ecol Landscapes*. 10:1–19. (2024). doi: 10.1080/24749508.2024.2430040

65. Kumar J, Bhardwaj DR, Thakur CL, Sharma P, Sharma P. Soil organic carbon dynamics under different land use systems in dry temperate ecosystem of north-western Himalayas. *Catena (Amst)*. (2024) 240:108022. doi: 10.1007/s11270-021-05294-x

66. Reis dos Santos Bastos T, Anjos Bittencourt Barreto-Garcia P, de Carvalho Mendes I, Henrique Marques Monroe P, Ferreira de Carvalho F. Response of soil microbial biomass and enzyme activity in coffee-based agroforestry systems in a high-altitude tropical climate region of Brazil. *Catena (Amst)*. (2023) 230:107270. doi: 10.1016/J.CATENA.2023.107270

67. Dieleman WIJ, Venter M, Ramachandra A, Krockenberger AK, Bird MI. Soil carbon stocks vary predictably with altitude in tropical forests: implications for soil carbon storage. *Geoderma*. (2013) 204–205:59–67. doi: 10.1016/J.GEODERMA.2013.04.005

68. Zhang Y, Heal KV, Shi M, Chen W, Zhou C. Decreasing molecular diversity of soil dissolved organic matter related to microbial community along an alpine elevation gradient. *Sci Total Environ*. (2021) 818:151823. doi: 10.1016/J.SCITOTENV.2021.151823

69. He Z, He S, Zheng Z, Yi H, Luo Z. Transforming slope cropland into terraced cropland to enhance the retention of labile SOC fractions by aggregates in southwestern China. *Catena (Amst)*. (2025) 259:109374. doi: 10.1016/J.CATENA.2025.109374

70. Thapliyal S, Sati SP, Singh B, Rawat D, Khanduri VP, Riyal MK, et al. Effect of altitudes and aspects on carbon sequestration potential of Quercus floribunda forests of Garhwal Himalayas. *Trees Forests People*. (2024) 18:100690. doi: 10.1016/J.TFP.2024.100690

71. Kumar S, Bijalwan A, Singh B, Rawat D, Yewale AG, Riyal MK, et al. Comparison of carbon sequestration potential of Quercus leucotrichophora–based agroforestry systems and natural forest in Central Himalaya, India. *Water Air Soil pollut*. (2021) 232:1–16. doi: 10.1007/S11270-021-05294-X/METRICS

72. Anand J, Rawat JS, Rawat V, Singh B, Khanduri VP, Riyal MK, et al. Climatic and altitudinal variation in physicochemical properties of Citrus sinensis in India. *Land*. (2022) 11:2033. doi: 10.3390/LAND11112033

73. Bangroo SA, Najar GR, Rasool A. Effect of altitude and aspect on soil organic carbon and nitrogen stocks in the Himalayan Mawer Forest Range. *Catena (Amst)*. (2017) 158:63–8. doi: 10.1016/J.CATENA.2017.06.017

74. Cao X, Xu Y, Wang F, Zhang Z, Xu X. Changes of soil organic carbon and aggregate stability along elevation gradient in Cunninghamia lanceolata plantations. *Sci Rep*. (2024) 14:1–13. doi: 10.1038/S41598-024-81847-4

75. Ferro V, Nicosia A. Comment on "Rill erosion processes on steep colluvial deposit slope under heavy rainfall in flume experiments with artificial rain by F. Jiang et al. *Catena (Amst)*. (2020) 185:103793. doi: 10.1016/J.CATENA.2018.10.022

76. Yao Y, Dai Q, Gao R, Yi X, Wang Y, Hu Z. Characteristics and factors influencing soil organic carbon composition by vegetation type in spoil heaps. *Front Plant Sci*. (2023) 14:1240217/BIBTEX. doi: 10.3389/fpls.2023.1240217

77. Rodríguez Delgado I, Pérez Iglesias HI, García Batista RM. Variaciones del contenido de materia orgánica en el suelo y su relación con algunas propiedades Físicas y Químicas (2023). Available online at: https://aes.ucf.edu.cu/index.php/aes/article/view/632/600. (Accessed October 2, 2025).

78. Buraka T, Elias E, Lelago A. Soil organic carbon and its' stock potential in different land-use types along slope position in Coka watershed, Southern Ethiopia. *Heliyon*. (2022) 8:e10261. doi: 10.1016/j.heliyon.2022.e10261

79. Chen L, Li Y, Zhang Z. Impact of land use type and slope position on the erodibility of karst hillslopes in Southwest China. *Catena (Amst)*. (2023) 233:107498. doi: 10.1016/J.CATENA.2023.107498

80. Hofbauer M, Kincl D, Vopravil J, Kabelka D, Vráblík P. Preferential erosion of soil organic carbon and fine-grained soil particles—an analysis of 82 rainfall simulations. *Agronomy*. (2023) 13:217. doi: 10.3390/agronomy13010217

81. Zhao Z, Dong P, Fu B, Wu D, Zhao Z. Soil organic carbon distribution and factors affecting carbon accumulation in natural and plantation forests in tropical China. *Ecol Indic*. (2023) 148:110127. doi: 10.1016/J.ECOLIND.2023.110127

82. Matsumoto S, Ogata S, Shimada H, Sasaoka T, Hamanaka A, Kusuma GJ. Effects of pH-induced changes in soil physical characteristics on the development of soil water erosion. *Geosciences*. (2018) 8:134. doi: 10.3390/GEOSCIENCES8040134

83. Stumpf F, Goebes P, Schmidt K, Schindewolf M, Schönbrodt-Stitt S, Wadoux A, et al. Sediment reallocations due to erosive rainfall events in the three gorges reservoir area, central China. *Land Degrad Dev*. (2017) 28:1212–27. doi: 10.1002/LDR.2503

84. Perović V, Čakmak D, Pavlović D, Matić M, Kostić O, Mitrović M, et al. From prediction to ecological insight: exploring soil erodibility through integrated spatial modelling. *Landsc Ecol*. (2025) 40:1–21. doi: 10.1007/s10980-025-02172-3

85. Liu E, Zhou J, Yang X, Jin T, Zhao B, Li L, et al. Long-term organic fertilizer-induced carbonate neoformation increases carbon sequestration in soil. *Environ Chem Lett*. (2023) 21:663–71. doi: 10.1007/S10311-023-01568-4

86. Cui J, Guo L, Xiong S, Yang S, Wang Y, Zhang S, et al. Soil organic carbon induces a decrease in erodibility of black soil with loess parent materials in northeast China. *Quat Res*. (2023) 120:83–92. doi: 10.1017/QUA.2023.58

87. Cerretelli S, Castellanos E, González-Mollinedo S, Lopez E, Ospina A, Haggar J. A scenario modelling approach to assess management impacts on soil erosion in coffee systems in Central America. *Catena (Amst)*. (2023) 228:107182. doi: 10.1016/J.CATENA.2023.107182