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Soil characteristics under different crops in mountain environments in Pamplona, Norte de Santander

Características edáficas bajo diferentes cultivos en ambientes de montaña en Pamplona, Norte de Santander, Colombia

Características do solo sob diferentes culturas em ambientes de montanha em Pamplona, Norte de Santander, Colômbia

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Crop production

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Abstract

Agricultural intensification in mountain regions can alter soil quality and compromise its ecosystem functionality. Accordingly, this study evaluated the influence of land use on the physical, chemical, and biological properties of soils in agricultural and forest systems located in the Monteadentro district, municipality of Pamplona, Norte de Santander. During the 2019 rainy season, five land-use types were analyzed: strawberry, pea, tree tomato, pasture, and natural forest. In 1,000 m² plots, composite soil samples were collected at 0–10 cm depth to determine texture, volumetric water content (VWC), bulk density (BD), pH, electrical conductivity (EC), total organic carbon (TOC), and soil basal respiration (SBR). Both univariate and multivariate statistical analyses were applied (ANOVA, Kruskal–Wallis, correlations, and PCA). The results showed that land use significantly affected soil properties. Forest soils exhibited more favorable conservation conditions, with higher TOC content (2.8 %) and lower BD (0.7 $g.cm^{-3}$), in contrast to agricultural soils, which presented higher BD, lower VWC and TOC, and higher SBR, likely associated with more labile organic substrates and organic matter degradation. Principal Component Analysis identified two main gradients: a physical–textural gradient (clay, VWC, EC, sand) and a biochemical–structural gradient (silt, pH, TOC, SBR), which differentiated land-use systems according to their degree of disturbance. These findings emphasize the need to implement conservation-oriented management strategies and regular soil monitoring in order to preserve soil functionality in mountain ecosystems.

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Resumen

La intensificación agrícola en zonas de montaña puede alterar la calidad del suelo y comprometer su funcionalidad ecosistémica. En tal sentido, este estudio evaluó la influencia del uso del suelo sobre las propiedades físicas, químicas y biológicas en sistemas agrícolas y forestales de montaña en la vereda Monteadentro, municipio de Pamplona, Norte de Santander. Durante el período de lluvias de 2019 se analizaron cinco tipos de utilización: fresa, arveja, tomate de árbol, pasto y bosque natural. En parcelas de 1000 m² se recolectaron muestras compuestas de suelo a 0-10 cm para determinar textura, humedad volumétrica (HV), densidad aparente (Da), pH, conductividad eléctrica (CE), carbono orgánico total (CO) y respiración basal (RB). Se aplicaron análisis estadísticos univariados y multivariados (ANOVA, Kruskal-Wallis, correlaciones y ACP). Los resultados evidenciaron que el tipo de utilización afectó significativamente las propiedades edáficas. Los suelos bajo bosque presentaron condiciones más favorables de conservación, con mayor contenido de CO (2,8 %) y menor Da (0,7 $g.cm^{-3}$), en contraste con los suelos agrícolas, donde se registró mayor Da, menor HV y CO, y mayor RB, posiblemente asociada a sustratos orgánicos más lábiles y degradación de la materia orgánica. El análisis de componentes principales permitió identificar dos gradientes: uno físico-textural (arcilla, HV, CE, arena) y otro bioquímico físico (limo, pH, CO, RB), los cuales diferenciaron los sistemas de uso según su grado de perturbación. Estos resultados sugieren la necesidad de adoptar estrategias de manejo conservacionista y monitoreo regular del suelo para preservar su funcionalidad en ecosistemas de montaña.

Palabras clave: usos del suelo, análisis multivariado, degradación edáfica, indicadores de calidad del suelo.

Resumo

A intensificação agrícola em áreas de montanha pode alterar a qualidade do solo e comprometer sua funcionalidade ecossistêmica. Nesse sentido, este estudo avaliou a influência do uso do solo sobre as propriedades físicas, químicas e biológicas em sistemas agrícolas e florestais de montanha na vereda Monteadentro, município de Pamplona, Norte de Santander. Durante o período chuvoso de 2019 foram analisados cinco tipos de uso: morango, ervilha, tomate de árvore, pastagem e floresta nativa. Em parcelas de 1.000 m² foram coletadas amostras compostas de solo na profundidade de 0–10 cm para determinar textura, umidade volumétrica (UV), densidade aparente (DA), pH, condutividade elétrica (CE), carbono orgânico total (COT) e respiração basal (RB). Foram aplicadas análises estatísticas univariadas e multivariadas (ANOVA, Kruskal–Wallis, correlações e ACP). Os resultados evidenciaram que o tipo de uso afetou significativamente as propriedades edáficas. Os solos sob floresta apresentaram condições mais favoráveis de conservação, com maior teor de COT (2,8 %) e menor DA (0,7 $g.cm^{-3}$), em contraste com os solos agrícolas, que apresentaram maior DA, menor UV e COT, e maior RB, possivelmente associada a substratos orgânicos mais lábeis e à degradação da matéria orgânica. A Análise de Componentes Principais permitiu identificar dois gradientes: um físico-textural (argila, UV, CE, areia) e outro bioquímico-físico (silte, pH, COT, RB), os quais diferenciaram os sistemas de uso conforme seu grau de perturbação. Esses resultados sugerem a necessidade de adotar estratégias de manejo conservacionista e de monitoramento regular do solo para preservar sua funcionalidade em ecossistemas de montanha.

Palavras-chave: uso do solo, análise multivariada, degradação do solo, indicadores de qualidade do solo.

Introduction

The mountain environments of the Andean regions of Colombia exhibit distinctive edaphoclimatic conditions that favor diversified agricultural systems, which are fundamental to ensuring food security and promoting rural development. At elevations ranging from 2,000 to 3,600 m.a.s.l., small-scale family farming predominates, centered on crops such as strawberry (*Fragaria × ananassa* Duchesne ex Rozier), tree tomato (*Solanum betaceum* Cav.), and pea (*Pisum sativum* L.), in addition to livestock systems sustained by Kikuyu grass (*Cenchrus clandestinus* (Hochst. ex Chiov.) Morrone). In the municipality of Pamplona, Norte de Santander, these systems play a critical role in sustaining rural employment, securing household income, and maintaining the continuity of the local agrarian fabric (Villamizar *et al*., 2024).

However, inadequate practices, such as the intensive use of agrochemicals and the limited adoption of conservation measures, have triggered soil degradation processes. Local studies report high acidity (pH 3.5–5.5), low biological activity, and nutrient deficiencies (P, Mg, S, Zn, and B), particularly in conventional agricultural systems (Visconti-Moreno & Valenzuela-Balcázar, 2019), thereby compromising productive sustainability (Rodríguez *et al*., 2024; Flórez & Ochoa, 2022).

Considering these conditions, it is necessary to compare land-use systems in order to determine their effects on soil structure, fertility, and biological functioning. Multivariate characterization based on physical, chemical, and biological indicators provides a comprehensive framework for assessing soil quality and guiding sustainable management strategies (Cruz *et al*., 2022). In this context, the present study aimed to compare the physical, chemical, and biological properties of soils under strawberry, tree tomato, pea, and pasture cultivation with those of a natural forest in the Monteadentro district (Pamplona), with the objective of generating technical information to support the sustainability of mountain agroecosystems.

Materials and methods

Study area

The research was conducted in the Monteadentro district (Pamplona, Norte de Santander), within the cold thermal belt (2,000–3,000 m.a.s.l.) and the lower montane humid forest life zone. The climate is classified as oceanic (Cfb), with a mean annual temperature of 14.4 °C and an average annual precipitation of 1,863 mm, concentrated mainly in April and October (Climate-Data.org, 2024). The topography is characterized by steep slopes (>20 %), which increase the risk of erosion (Villamizar *et al*., 2024; IGAC, 2012). Inceptisols derived from the Durania Granite predominate, with a sandy loam texture, slightly acidic pH (~6.0), and medium organic carbon content (2.46 %). In agricultural areas, soil acidity increases as a result of the intensive use of highly acidifying nitrogen fertilizers (González-Pedraza *et al*., 2023; Visconti-Moreno & Valenzuela-Balcázar, 2019; IGAC, 2012).

Research design

Five land-cover types were evaluated—strawberry (*Fragaria × ananassa* Duchesne ex Rozier), pea (*Pisum sativum* L.), tree tomato (*Solanum betaceum* Cav.), kikuyu grass (*Cenchrus clandestinus* (Hochst. ex Chiov.) Morrone), and natural forest—during the rainy season of May 2019 in the Monteadentro district, municipality of Pamplona (Norte de Santander), located between 2,506 and 2,533 m.a.s.l. The plots, situated in relatively close proximity (500–1,000 m apart), were selected to represent each land-cover system. In each case, a 1,000 m² plot was delineated, with slopes of 17.3 % in pasture, 37 % in strawberry, 22 % in pea, 30 % in tree tomato, and 24 % in forest. These plots were representative of the topographic conditions of the study area, characterized by steep slope gradients (23–59 %) that increase susceptibility to erosion (Villamizar *et al*., 2024; IGAC, 2012).

In addition to slope, the relative position of the plots within the landscape was considered: pasture and pea were located on midslopes; strawberry and tree tomato on upper slopes with greater exposure to erosive processes; and forest on a steeper slope with a protective function within the landform, following the geomorphological classification criteria proposed by IGAC (2012).

From a geomorphological and geological perspective, the municipality of Pamplona is situated in the Espíritu Santo Valley, underlain by Quaternary fluvio-lacustrine deposits that unconformably overlie igneous bedrock (quartz monzonitic gneiss, Ortoneis unit). The valley is tectonically controlled by the Pamplona Fault and the Chitagá Fault System, which delineate geomorphic units characterized by hills and ridges, associated with sedimentary sequences such as Girón, Tibú–Mercedes, and Aguardiente. This lithostructural configuration explains the marked topographic variability and edaphic heterogeneity of the area (Moya-Gutiérrez *et al*., 2020).

Crop management was carried out under a conventional approach, with mechanical tillage and sprinkler irrigation. In strawberry, certified varieties were used together with plastic mulching, chemical and organic fertilization, chemical control of pests and weeds, periodic pruning, and manual harvesting every two days, primarily performed by family labor. In pea and tree tomato, soil preparation was similar; fertilization combined chemical inputs with organic amendments (vermicompost and manure), along with practices such as early staking, manual weed control, constant irrigation, and both chemical and physical phytosanitary management (González-Pedraza *et al*., 2023).

In each plot, five composite soil samples (0–10 cm) were collected and treated as independent experimental units for the analyses. This number of replicates ensured a balance between statistical representativeness and logistical feasibility. Sampling from the surface layer was justified by its concentration of fine roots, high biological activity, and greater sensitivity to agricultural practices, while also maintaining comparability between agricultural systems and natural covers.

Laboratory analyse

Physical (3), chemical (1), and biological (2) properties were evaluated using standardized methodologies widely recognized in the scientific literature (Table 1). Samples were collected with an auger, stored in 2-kg airtight plastic bags, properly labeled, and immediately transported to the Agricultural Soils Laboratory at the University of Pamplona for processing. Undisturbed samples for bulk density determination were collected using cylinders measuring 10 cm in height and 5 cm in diameter.

Statistical analysis

A one-way ANOVA ($p < 0.05$) was performed, with Tukey's HSD post hoc test applied after verifying normality (Shapiro–Wilk test) and homogeneity of variances (Levene's test). The variables VWC, EC, sand, TOC, and SBR were log-transformed. However, TOC did not meet the assumption of normality even after transformation and was therefore analyzed using the Kruskal–Wallis test followed by Dunn's test with Bonferroni correction. Pearson correlation coefficients were calculated among continuous variables, and a Principal Component Analysis (PCA) was performed on standardized data (z-scores), retaining components with eigenvalues > 1 according to Kaiser's criterion. To facilitate interpretation, land-use centroids were represented by the mean of their factorial coordinates (F1 and F2), so that each system was summarized in a single central point, enabling comparison and the identification of edaphic gradients. All statistical analyses were conducted in R (version 4.3.1) (R Core Team, 2023).

Table 1. Methods used for the analysis of soil physical, chemical, and biological properties.

Variable	Method	Author / Reference
Volumetric Water Content (VWC)	Bouyoucos hydrometer	Gee & Bauder (1986)
Soil Bulk Density (BD)	Field measurement	Gardner (1986)
pH / Electrical Conductivity (EC)	Uhland core method	Blake & Hartge (1986)
Total Organic Carbon (TOC)	Potentiometric determination in a 1:2 soil-to-water suspension	Mclean (1982)
Soil Basal Respiration (SBR)	Loss on ignition (LOI, 450 °C)	Westman *et al*. (2006)
Volumetric Water Content (VWC)	Static incubation with CO_2 titration	Alef & Nannipieri (1995)

Results and discussion

Descriptive statistics of soil properties

Based on the exploratory analysis of soil variables (Table 2), marked heterogeneity was observed across the different land uses. The properties with the highest relative variability were SBR, TOC, and VWC. Silt also exhibited high dispersion, whereas EC and clay showed moderate variability. In contrast, pH and bulk density were the most stable properties, reflecting more homogeneous conditions within the system.

Physical properties of soils

The comparison of soil textural fractions among the five land-use types revealed significant differences. Clay content was higher in soils under pea and strawberry, whereas forest and tree tomato recorded the lowest values; pasture fell within an intermediate range. With respect to sand, higher proportions were observed in forest and tree tomato, in contrast to strawberry and pea, which exhibited the lowest percentages; pasture showed intermediate values. Silt was more abundant in soils under pasture, followed by strawberry and pea, with the lowest levels found in tree tomato and forest. Although soil texture is a relatively stable property, these results indicate marked granulometric variability associated with the spatial heterogeneity of soils across land uses (Table 3).

The results of particle size distribution revealed variations among land uses that, rather than being attributable to immediate agricultural management, may be associated with topography, land-use history, and geomorphological dynamics.

Table 2. Descriptive statistics of soil physical and chemical properties under different land uses.

	N	Mean	Minimum	Maximum	Variance	SD	CV
VWC	25	23.8	4.5	53.9	126.7	11.3	47.3
EC	25	1.1	0.3	2.0	0.2	0.4	37.1
BD	25	0.9	0.4	1.2	0.0	0.2	20.5
Clay	25	29.9	13.1	47.1	87.5	9.4	31.3
Sand	25	51.4	32.5	76.7	196.0	14.0	27.2
Silt	25	18.6	6.8	37.4	72.8	8.5	45.8
pH	25	5.6	4.2	7.0	0.4	0.7	11.8
TOC	25	1.5	0.7	3.2	0.6	0.8	52.2
SBR	25	39.4	5.0	110.0	723.8	26.9	68.2

VWC: Volumetric water content (%); EC: Electrical conductivity ($dS.m^{-1}$); BD: Soil Bulk density ($g.m^{-3}$); Clay (%); Sand (%); Silt (%); TOC: Total organic carbon (%); SBR: Soil basal respiration (µg $C–CO_2$·100 g.24 h^{-1}). SD: Standard deviation; CV: Coefficient of variation.

Table 3. Comparison of particle size distribution under different land uses.

Land Uses	Clay	CV	Sand	CV	Silt	CV	Textural Class
Pasture	24.0±9.4c	23.3	47.5±9.2ac	19.4	28.6±6.2a	21.6	Loam
Strawberry	37.1±4.0ab	10.8	40.0±5.0a	12.6	23.0±1.9a	8.3	Clay loam
Pea	41.0±3.7a	9.1	39.3±6.8a	17.3	19.7±6.5ac	33.2	Clay loam
Tree tomato	27.4±6.5bc	23.9	63.3±5.7bc	8.9	9.4±2.8b	30.2	Sandy clay loam
Forest	20.2±5.9ac	29.3	67.2±11.6b	17.3	12.6±6.5bc	52.0	Sandy loam

Note. Mean values ± standard deviation followed by different letters indicate significant differences among land uses at $p < 0.05$ according to Tukey's test. CV: Coefficient of variation.

It is important to note that soil texture is a relatively stable edaphic property, whose variability is primarily driven by erosive processes or the intrinsic spatial heterogeneity of soils. In this regard, it should be emphasized that the plots belong to the same physiographic framework (Espíritu Santo Valley) but were located in contrasting topographic positions (IGAC, 2012), which explains part of the observed variation.

On upper and convex slopes (strawberry, 37 %; tree tomato, 30 %), runoff promotes the selective removal of silt and clay. On midslopes (pea, 22 %), in addition to reduced runoff energy, partial accumulation of materials transported from higher elevations may occur, which also influences particle size distribution. In forest soils (24 %), dense vegetation cover and the natural dynamics of erosion and deposition favor the retention of fine fractions, whereas in pasture (17.3 %), compaction from livestock trampling induces the redistribution of surface particles. Thus, differences in slope position and management practices account for the observed granulometric variations (Villamizar *et al*., 2024; Moya-Gutiérrez *et al*., 2020).

Regarding VWC, soils under pasture exhibited the highest values (38.6 %), followed by strawberry and tree tomato, whereas forest presented the lowest value (13.0 %). These differences may be associated with variations in vegetation cover and soil management. With respect to BD, forest soils exhibited the lowest values (0.7 $g.cm^{-3}$), indicating greater porosity, while cultivated soils (strawberry, pea, and tree tomato) showed higher values, suggesting compaction related to intensive agricultural practices (Table 4).

Although plastic mulching reduces evaporation, it can alter water redistribution and promote subsurface compaction if not accompanied by organic matter incorporation (Gao *et al.*, 2019). In pea, also with a clay loam texture, VWC was even lower, indicating reduced water retention associated with intensive tillage and limited cover; although BD was low, it may be masking subsurface compaction (Ewunetu *et al*., 2025).

In tree tomato (sandy clay loam texture), VWC remained within the expected range (20–30 %), and BD was lower than the typical values (1.3–1.6 $g.cm^{-3}$), reflecting low compaction and good porosity, likely favored by its perennial nature and reduced soil disturbance.

Table 4. Comparison of soil physical parameters under different land uses.

Land Uses	Volumetric water content (%)	CV	Soil bulk density ($g.cm^{-3}$)	CV
Pasture	38.6±14.0a	36.2	0.9±0.1ab	26.5
Strawberry	27.1±4.5a	16.5	1.0±0.1a	8.8
Pea	17.2±4.4a	25.7	1.0±0.1a	9.9
Tree tomato	22.9±2.7a	11.7	0.9±0.1ab	11.3
Forest	13.0±5.4b	41.4	0.7±0.2b	27.0

Note. Mean values ± standard deviation followed by different letters indicate significant differences among crops. CV: Coefficient of variation.

In forest (sandy loam texture), VWC matched the reference range for this texture (10–20 %), while BD was the lowest among all land uses, well below the range for mineral soils (1.4–1.7 g.cm^{-3}). This highlights the positive influence of litterfall and higher organic carbon content on structural stability (Gao *et al*., 2019).

These results are consistent with the findings of Huf dos Reis *et al*. (2024), who demonstrated that volumetric water content at different matric potentials can be predicted using pedotransfer functions (PTFs) that incorporate texture, bulk density, and porosity. Consequently, soils with higher clay content and greater organic matter inputs tend to retain more water, whereas sandy soils exhibit lower values. The combination of the identified textural classes and the specific management of each land cover explains the observed differences in BD, VWC, and porosity, confirming the decisive role of land use and agricultural management in shaping soil physical functionality.

Soil chemical and biological properties

Significant differences were observed in pH, EC, and TOC, whereas SBR, although variable, did not differ significantly among land uses. Regarding pH, forest soils were significantly less acidic than cultivated soils, particularly strawberry and pasture, likely due to the use of nitrogen fertilizers and the lower buffering capacity of degraded soils. Pea and tree tomato showed intermediate values, with no significant differences compared to the other land uses, indicating greater pH stability in these systems (Table 5).

With respect to EC, interpreted as an indirect indicator of the total concentration of soluble salts in the soil solution rather than as a measure of specific salts, higher values were observed in intensively managed agricultural soils (pasture, strawberry, and tree tomato) compared with pea and forest. This pattern suggests a potential accumulation of salts derived from chemical fertilization and reduced drainage efficiency.

TOC was highest in forest soils, reflecting their ecological stability and continuous organic matter accumulation. Agricultural soils showed intermediate values, with no marked statistical differences among them, likely due to variability among replicates and heterogeneous management practices. Although no significant differences were found in SBR, high variability was observed across land uses, with the highest value in strawberry and the lowest in tree tomato (Table 5).

Soil pH is a key regulator of chemical and biological processes, including nutrient availability and microbial activity. Values below 5.5, such as those observed in soils under strawberry and pasture, can induce Al^{3+} and Mn^{2+} toxicity and decrease the availability of basic cations such as Ca^{2+} and Mg^{2+} (Mitsuta *et al*., 2025).

This pattern is consistent with the findings of Visconti-Moreno & Valenzuela-Balcázar (2019), who reported that the conversion of forest to intensive agricultural systems in Norte de Santander leads to organic carbon loss and reduced aggregate stability, both clear indicators of physical and chemical degradation.

In contrast, forest soils exhibited pH values closer to the optimal range (5.5–7.0), reflecting lower disturbance and greater buffering capacity.

Although soil structure was not directly characterized in this study, the more acidic pH and higher bulk density observed in strawberry and pasture provide indirect evidence of soil deterioration, in contrast to the more stable conditions recorded in forest soils.

Regarding total organic carbon (TOC), the highest content was recorded in forest soils, associated with the continuous accumulation of litterfall and roots, the absence of tillage, permanent cover, and a cool–humid microclimate that slows organic matter decomposition and favors stabilization (Gao *et al*., 2019). In contrast, agricultural systems showed intermediate and variable values, influenced by tillage, trampling, residue removal, and erosion, which accelerate mineralization, oxidation, and leaching of organic compounds. These losses, which may reach 20–45 % following forest-to-crop conversion, reduce soil structural integrity and its capacity for water and nutrient retention (Singh *et al*., 2020).

The absence of clear statistical differences among crops can be attributed to heterogeneity in management practices and the effect of slope topography, which intensifies differential carbon losses and generates high variability among replicates. Recent studies agree that land-use change and agricultural management are key drivers of soil carbon dynamics, emphasizing that its stabilization largely depends on the transformation of residues into microbial necromass and their association with fine mineral fractions (Cotrufo *et al*., 2019).

With respect to SBR, although no statistical differences were detected among land uses, higher values were observed in soils under strawberry, pasture, and pea, likely due to the input of labile compounds such as crop residues (Singh *et al*., 2020). However, elevated SBR does not necessarily indicate improved soil quality, as it may reflect rapid mineralization without long-term carbon stabilization (Shi *et al*., 2025). In forest and tree tomato soils, lower SBR suggests the predominance of complex organic compounds, such as lignin and phenolics, which contribute to long-term carbon sequestration (Almendros & González-Pérez, 2025). This aligns with studies reporting higher respiration rates in grasslands due to changes in substrate quality, temperature, and moisture, as well as residues with low C/N ratios that stimulate microbial activity (Pardo-Plaza *et al*., 2019).

Pearson correlation matrix for soil properties

The Pearson correlation matrix was evaluated to explore linear relationships among soil physicochemical variables and to justify the application of Principal Component Analysis (PCA). The results revealed significant associations among key variables, indicating patterns of joint variation that support the multivariate approach.

Table 5. Comparison of soil chemical and biological parameters under different land uses.

Land Uses	pH	CV	Electrical conductivity (dS.m^{-1})	CV	Total organic carbon (%)	CV	Soil basal respiration (µg C-CO_2 100 g.24 h^{-1}).	CV
Pasture	5.2±0.3b	5.7	1.6±0.4a	24.6	1.3±0.4ab	29.1	48.1±32.3a	67.1
Strawberry	5.0±0.6b	11.8	1.3±0.2a	13.0	0.9±0.1b	7.4	56.0±25.3a	45.3
Pea	5.8±0.4ab	7.8	0.9±0.2b	23.7	1.1±0.3ab	24.0	48.3±35.2a	72.8
Tree tomato	5.8±0.5ab	8.1	1.2±0.1a	10.3	1.5±0.7ab	48.6	19.4±6.8a	35.3
Forest	6.4±0.5a	8.0	0.6±0.2b	27.2	2.8±0.4a	14.6	25.4±9.6a	37.8

Note. Mean values ± standard deviation followed by different letters indicate significant differences among crops. CV: Coefficient of variation.

The very strong positive correlation between VWC and EC ($r = 0.97$; $p < 0.05$) indicates that soils with higher water content also exhibit higher concentrations of soluble salts. In strawberry, pea, and tree tomato systems, where amendments such as poultry manure and lime were applied, the increase in ions in solution may explain the rise in EC under conditions of greater water retention. In contrast, in pasture systems nutrients were mainly derived from grazing, whereas in forest soils no external inputs were recorded. This result is consistent with the findings of Ylagan *et al*. (2023), who reported that apparent electrical conductivity is strongly influenced by soil moisture and nutrient accumulation.

Other relevant, although not statistically significant, relationships included the negative correlation between BD and TOC, suggesting that soils with higher organic matter content tend to exhibit more porous structures. A positive association was also observed between sand and TOC, possibly related to profile aeration and residue decomposition. In contrast, SBR showed weak correlations with the other variables, which may be attributed to its high sensitivity to specific microenvironmental conditions.

Overall, the correlation patterns indicate the presence of latent multivariate structures integrating soil physical, chemical, and biological attributes. This provides strong support for the application of PCA as an appropriate dimensionality-reduction technique, facilitating the ordination of soil variables and the identification of shared edaphic gradients across land-use systems.

Principal component analysis (PCA) of soil properties

The correlation matrix was analyzed using PCA, which identified three components with eigenvalues greater than 1, together explaining 63.30 % of the total variance. The first two components (PC1 and PC2), which jointly explained 50.96 %, were retained for graphical interpretation, according to Kaiser's criterion and the scree plot (Table 6).

Table 6. Eigenvalues, percentage of explained variance, and cumulative variance for each principal component.

Component	Eigenvalue	% of Variance Explained	Cumulative Variance (%)
1	3.3255	36.95	36.95
2	1.2611	14.01	50.96
3	1.1109	12.34	63.30

PC1 (36.95 %) represented a textural–hydric gradient, characterized by strong positive loadings for clay content, volumetric water content (VWC), and electrical conductivity (EC), and a negative loading for sand. PC2 (14.01 %) captured a fertility–chemical stability axis, primarily defined by silt, pH, and total organic carbon (TOC), with soil basal respiration (SBR) also showing a positive contribution. In contrast, bulk density (BD) was oriented in the opposite direction to these variables, suggesting divergences in soil structural conditions and biological quality (Table 7).

The biplot (Figure 1) corroborated these patterns, highlighting the opposition between sand and the fine fractions (clay and silt), as well as the positive association of volumetric water content (VWC) with electrical conductivity (EC), in contrast to the inverse projection of bulk density (BD). The clustering of silt, pH, and total organic carbon (TOC) reflected soils with higher fertility and greater stabilization of organic matter, while soil basal respiration (SBR) also aligned positively with this axis.

Table 7. Factor loadings of the variables on the first two principal components.

Variable	PC1	PC2
Volumetric water content	0.8387	-0.2816
Soil bulk density	-0.3940	-0.2263
Clay	0.8496	0.1507
Sand	-0.9300	-0.1432
Silt	0.1905	0.9494
pH	0.1943	0.9202
Total organic carbon (%)	0.1696	0.9136
Electrical conductivity (dS.m^{-1})	0.7868	-0.1945
Soil basal respiration (µg C–CO_2·100 g.24 h^{-1})	0.1159	0.7834

The distribution of centroids further distinguished land uses: forest and tree tomato systems were positioned in the quadrant linked to improved fertility and structural stability; pasture occupied an intermediate position, associated with moderate water retention and compaction; whereas strawberry and pea systems were projected in the opposite direction, indicating structural constraints and reduced water retention capacity under intensive management.

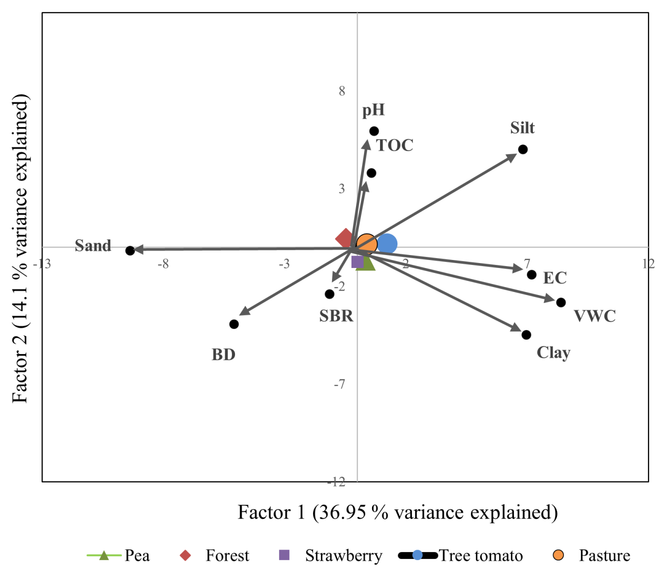

Figure 1. Projection of the variables on the factorial plane defined by the first two principal components (PCA). VWC: Volumetric water content; EC: Electrical conductivity; BD: Soil Bulk density; TOC: Total organic carbon; SBR: Soil basal respiration.

The PCA emphasized the pivotal role of soil texture as a semi-permanent attribute regulating water dynamics and nutrient availability. Intensive production systems, characterized by the combined application of irrigation and fertilization, tended to foster salt accumulation and compaction, whereas forest soils maintained more stable conditions through leaching processes. Soils enriched in fine fractions demonstrated a greater capacity for carbon retention and pH buffering, thereby enhancing microbial activity and structural stability. In contrast, intensively managed agricultural systems exhibited compaction and reduced aeration, which diminished biological efficiency and underscored their susceptibility to degradation.

Conclusions

The study demonstrated that volumetric water content, electrical conductivity, pH, total organic carbon, and basal respiration are sensitive indicators of agricultural management, effectively reflecting the impacts of land use. Strawberry, pea, and tree tomato systems exhibited signs of acidification, carbon depletion, and salt accumulation, whereas pasture systems were characterized by compaction and biological limitations. In contrast, natural forest maintained more favorable conditions, serving as a benchmark for soil stability and quality.

These findings provide clear evidence that intensive land use in mountain environments exacerbates the risk of soil degradation, underscoring the importance of adopting conservation-oriented strategies. Recommended practices include the correction of soil acidity through amendments, the incorporation of stabilized organic matter, the diversification of plant cover with legumes and agroforestry systems, and the rationalization of chemical fertilization, all aimed at enhancing the resilience and sustainability of agroecosystems.

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