Research Article

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Effect of silvopastoral systems with integrated forest species from the Peruvian tropics on the soil chemical properties

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Abstract: Vegetation and trees in Amazonian ecosystems influence soil chemistry. Understanding these effects is essential for selecting the right tree species in silvopastoral systems to promote soil conservation. The objective of the study was to evaluate the effect of different silvopastoral systems (SPS) on the soil chemical properties within a livestock system. The research was developed at the Estación Experimental Agraria El Porvenir in San Martín Department, Peru, which is characterized by a humid tropical climate, with an annual temperature of 33°C, humidity levels between 70 and 80%, and precipitation of 1,225 mm. Six SPS [Bolaina (*Guazuma crinita* Mart.), Teak (*Tectona grandis* L.), an arboretum, Pucaquiro (*Sickingia tinctoria* Schult.), Quinilla (*Manilkara bidentata* A. DC.), and a natural forest – NF] and two sampling depths were compared, with two replicas for each. The main effect showed that the Quinilla SPS was higher in pH ($p < 0.05$), while the Quinilla SPS, Pucaquiro SPS, and NF stood out in K^+ and Ca^{2+} ($p < 0.05$). Organic matter (OM) and nitrogen content were higher at the 0–10 cm depth; however, there was an interactive effect on EC, OM, and nitrogen in the Quinilla SPS ($p < 0.05$). A total of 65.31% of the variance is explained by exchangeable cations (47.98%) and OM and nitrogen (17.33%). The planting of *M. bidentata* A. DC. and *S. tinctoria* Schult. trees in SPS could enhance soil nutrient availability similarly to natural forests, although the age of systems may influence these outcomes.

Keywords: sustainable livestock, agroforestry, tropical forest, Quinilla, Pucaquiro, exchangeable cations

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1 Introduction

Pasture is the main and most cost-effective source of feed for cattle and other herbivores. Livestock systems based on sustainable grazing provide diverse ecosystem services that help prevent soil degradation, protect biodiversity, and promote strategies for climate change mitigation and adaptation [1]. In Latin America, extensive cattle grazing is one of the primary drivers of soil changes, as new areas are often deforested to establish pastures [2]. Inappropriate livestock practices generate greater pressure on existing areas and lead to soil degradation. The implementation of silvopastoral systems (SPS) is a sustainable alternative by promoting natural tree regeneration in degraded areas [3].

The SPS involve the integration of trees and shrubs with pastures to increase biomass and improve pasture quality [4]. Compared to traditional or extensive livestock systems, SPS have been linked to various benefits for soil, including improvements in physical, chemical, and biological indicators [5]. Although changes in soil indicators in pastures have received less attention than those in croplands [6], it is recognized that SPS can positively affect various soil characteristics. By incorporating woody, herbaceous, and shrubby plants, SPS can enhance nutrient cycling from deeper soil layers to surface layers, making nutrients more available to pasture [3].

In countries like Peru and Colombia, there are already reports of the use of SPS, demonstrating economic, environmental, and social benefits for sustainable livestock farming [7]. In Peru, studies on soils in San Martín with SPS have reported lower pH values (4.8) and variation in the content of P (2.36 ppm), K (114 ppm), and organic matter (OM) (4.3%). Additionally, these systems reduced soil compaction after 8 months of installation using *Guazuma crinita*, *Calycophylum spruceanum*, and *Simarouba amara*, with *Centrosema virginanum* as forage [8,9]. In Colombia, after 24 months of applying dolomite and phosphate rock, significant increases in pH, P, and Mg content were observed in SPS with *Anadenanthera peregrina*, *Pithecellobium guachapele*, *Acacia mangium*, and *Brachiaria* as forage [10]. However, no effect on soil pH (from 5.50 to 5.60) was found in SPS with *Erytrina berteroana* in Costa Rica, although a reduction in OM was observed (from 1.70 to 1.20%) [11]. There is a wide variety of tree species available for SPS in this region, many of which have a high capacity to generate positive effects on the soil's chemical properties.

However, large-scale SPS implementation faces challenges such as limited knowledge of its benefits, along with technological, climatic, financial, and organizational barriers [12]. The effect on soil quality is one of the most relevant benefits, although this can vary depending on factors such as agroclimatic conditions, initial soil properties, tree and pasture species, and grazing intensity [3]. It is necessary to determine the effect of different types of SPS and select species that offer the greatest benefits to the soil. Therefore, the objective of this study was to evaluate the effect of Bolaina SPS (*Guazuma crinite* Mart.), Teak SPS (*Tectona grandis* L.), an arboretum (various tree species), Pucaquiro SPS (*Sickingia tinctoria* Schult.), Quinilla SPS (*Manilkara bidentata* A. DC.), and a natural forest (NF) on the soil chemical properties in the Peruvian tropics.

2 Materials and methods

2.1 Study location

The study was conducted in the Juan Guerra district, San Martin department, Peru (Figure 1). The area is located at the coordinates 6°35′6″S 76°19′10″W from the north, 6°36′30″ S 76°19′21″W from the south, 6°35′30″S 76°18′24″W from the east, and 6°35′44″S 76°19′48″W from the west, at an elevation of 250 m above sea level. The region is classified as Humid Tropical (Af) according to the Köppen–Geiger climate classification, with an average annual temperature of 33°C, relative humidity ranging from 70 to 80%, and an average yearly rainfall of 1,225 mm (Weather Station "El Porvenir," SENAMHI). The soil in the region is classified as Cambisols (cm) according to the World Reference Base for Soil Resources, with the supplementary qualifier hypereutric (je) due to the high base saturation (greater than 80%).

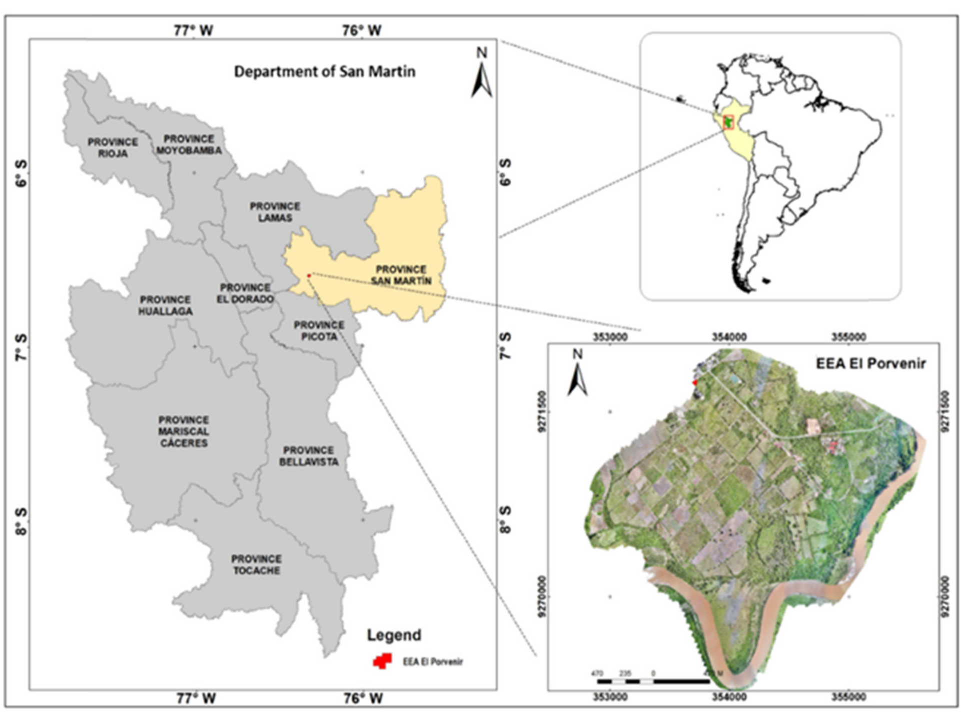

Figure 1: Location of the study area in the Juan Guerra district in San Martin, Peru. Source: This figure was adapted and modified by the authors from https://maps.google.com.

2.2 Silvopastoral systems

Five SPS and a natural forest were evaluated at the Estación Experimental Agraria El Porvenir of the Instituto Nacional de Innovación Agraria. Table 1 provides a description of the characteristics of each SPS.

The floristic composition of the SPS primarily included grasses such as *Brachiaria brizantha* cv. Marandú, *Brachiaria brizantha* cv. Toledo, and *Brachiaria hybrid* cv. Cobra, along with shrub species like Huarango (*Prosopis pallida* Kunth.). The cattle grazing regime within the SPS consisted of 1–2 days per 1 ha plot, with a 30-day rest period during the rainy season and 45 days during the dry season. At the time of soil sampling, all areas were in the rest period. The herd was composed of dry cows and heifers with an average weight of 350 kg, and the stocking density was a maximum of 2 animals per hectare.

2.3 Design and soil analysis

The study was conducted under a factorial arrangement within a completely randomized design with five SPS and a natural forest. Two sampling depths were compared (0–10 cm and 10–20 m). Soil sampling was performed over an average area of 2 ha for each SPS, with samples collected simultaneously at the same time and point, using a zigzag transect and two replications for each depth. The analyses were carried out in the Laboratory of Soils of the Estación Experimental Agraria "El Porvenir," using the methods in Table 2. The pH was determined in a 1:1 soil suspension with deionized water using a pH meter. Electrical conductivity (EC) was determined in a 1:5 soil suspension with deionized water using a conductivity meter. Organic matter was determined by the Walkley–Black method using potassium dichromate and sulfuric acid. Nitrogen was determined by digestion and emission spectrometry. Phosphorus was determined using a sulfuric acid extract and measured by colorimetry. Potassium and exchangeable cations were determined by ammonium acetate extraction and emission spectrometry. The determination of soil texture was performed using the Bouyoucos hydrometer method [13].

The soil analysis data set was uploaded to the Mendeley Database with the DOI: 10.17632/s9g9vk4fzb.1.

2.4 Statistical analysis

The textural class data among SPS were subjected to ANOVA and Tukey's test ($p < 0.05$). A covariance analysis involving SPS and textural class was then performed, with the Bonferroni adjustment applied for mean comparisons.

Table 1: Characteristics of installation and age of silvopastoral systems at the time of soil sampling in the study

Silvopastoral system (SPS)	Species	Distribution	Age at soil sampling
Bolaina SPS	*G. crinita* Mart.	Trees arranged in 3 m × 3 m strips between plants	13 years old
Teak SPS	*T. grandis* L.	Trees in live fences spaced 5 m between plants	13 years old
Arboretum	Estoraque (*Myroxylon balsamum* L.), Caoba (*Swietenia macrophylla* King.), Capirona (*Calycophyllum spruceanum* Benth.), Bolaina (*G. crinita* Mart), Marupa (*Simarouba amara* Aubl.), Quinilla (*Manilkara bidentata* A. DC.), Manchinga (*Brosimum alicastrum* Swartz.), Paliperro (Miconia *barbeyana* Cogn.), Ishpingo (*Amburana cearensis* Allem.), Shihuahuaco (*Dipteryx micrantha* Harms.), Huayruro (*Ormosia Coccinea* Aubl.), Tahuarí (*Tabebuia serratifolia* Vahl.), and Cedro (*Cedrela odorata* L.)	Trees arranged in 3 m × 3 m strips between plants	11 years old
Pucaquiro SPS	*S. tinctoria* Schult.	Trees arranged in 3 m × 3 m strips between plants	28 years old
Quinilla SPS	*M. bidentata* A. DC.	The proportion of trees was 5 units per hectare	80 years old
Natural forest (NF)	Guásimo (*Guazuma ulmifolia* Lam.), Pashaco (*Schizolobium excelsum* Benth.) Yahuar caspi (*Virola calophylla* Spruce.), Shapana (*Terminalia* sp.), Leucaena (*Leucaena leucocephala* Lam.), Capirona (*C. spruceanum* Benth.), Caoba (*S. macrophylla* King.), and unknown shrubs and herbaceous plants	Untreated pattern	Unknown age

Table 2: Methodology used for soil properties analysis

Soil properties	Method
pH	EPA 9045D [14]
Electrical conductivity (EC mS m^{-1})	ISO 11265:1994(E) [15]
Organic matter (OM %)	NOM-021-RECNAT-2000 AS-07 [16]
N (%)	ISO 11261:1995(E) [17]
P (ppm)	NOM-021-RECNAT-2000 AS-10 AS-11 [16]
K (ppm)	NOM-021-RECNAT-2000 (modified) [16]
Ca^{2+} $cmol_{(+)}$ kg^{-1}	NOM-021-RECNAT-2000 AS-12 y
Mg^{2+} $cmol_{(+)}$ kg^{-1}	NOM-021-RECNAT-2000 AS-13 [16]
K^+ ($cmol_{(+)}$ kg^{-1})	
Na^+ ($cmol_{(+)}$ kg^{-1})	
Acidity ($cmol_{(+)}$ kg^{-1})	
Cation exchange capacity (CEC ($cmol_{(+)}$ kg^{-1}))	
Textural type	
Sand (%)	NOM-021-RECNAT-2000 AS-09 [16]
Silty (%)	
Clay (%)	

A *t*-test was employed for comparisons at different sampling depths using the agricolae package of Agricultural library in RStudio version 4.2.1. Violin plots were created to visualize the distribution of variables according to sampling depth, using the ggstatsplot library. The interactive effects were analyzed through a covariance analysis with Bonferroni adjustment ($p < 0.05$) in SPSS version 15.0. Additionally, to explain the total variance of the soil chemical properties, a principal component analysis (PCA) was performed using the R libraries factoMineR, factoextra, and ggplot2 to assess variation among the SPS, sampling depth, and soil textures. Soil chemical properties were also correlated using the GGally and Hmisc libraries in R.

3 Results

3.1 Silvopastoral systems

Regarding the main effects of SPS and sampling depth on the soil chemical properties, significant differences were found in the pH values among SPS ($p < 0.01$). The soil pH in the Quinilla SPS was 7.38 ± 0.20, which was higher than those of the other systems. Additionally, the Quinilla SPS exhibited high EC values but the differences were not significant ($p > 0.05$) (Table 3). No significant differences were found in OM, N, P, and K between SPS. Soil cation concentrations according to SPS are shown in Table 3 and Table S1. Differences were also found in Ca^{2+}, K^+ ($p < 0.05$), Mg^{2+}, and CEC ($p > 0.05$), where the Quinilla SPS, Pucaquiro SPS, and NF exhibited higher levels compared to the other SPS. In soil texture, differences in the percentages of sand and silt were noted among the SPS, where the Teak SPS and Bolaina SPS had a higher sand percentage, while the Quinilla SPS had a higher silt percentage ($p < 0.01$) (Table 3).

Table 3: Soil chemical properties (estimated marginal means ± SE) by silvopastoral system

Variable	Silvopastoral systems (SPS)						*p*-value
	Bolaina SPS	Teak SPS	Arboretum	Pucaquiro SPS	NF	Quinilla SPS	
pH	6.44 ± 0.15^{b}	6.48 ± 0.24^{ab}	6.28 ± 0.16^{b}	6.46 ± 0.16^{b}	6.41 ± 0.18^{b}	7.38 ± 0.20^{a}	0.006
EC (mS m^{-1})	3.30 ± 0.87	3.37 ± 1.35	4.60 ± 0.91	4.57 ± 0.90	4.42 ± 1.01	6.62 ± 1.15	0.424
MO (%)	2.56 ± 0.90	2.09 ± 1.39	2.79 ± 0.94	2.56 ± 0.92	2.10 ± 1.04	2.01 ± 1.18	0.989
N (%)	0.10 ± 0.04	0.09 ± 0.06	0.12 ± 0.04	0.10 ± 0.04	0.08 ± 0.05	0.08 ± 0.05	0.992
P (ppm)	5.43 ± 8.96	3.38 ± 13.90	14.59 ± 9.35	41.59 ± 9.35	19.40 ± 10.37	21.65 ± 11.83	0.169
K (ppm)	139.43 ± 45.08	97.85 ± 69.91	177.01 ± 47.0	359.94 ± 46.37	203.53 ± 52.15	345.01 ± 59.51	0.044
Exchangeable cations							
Ca^{2+} ($cmol_{(+)}$ kg^{-1})	5.52 ± 0.74^{b}	6.90 ± 1.15^{ab}	5.62 ± 0.77^{b}	6.86 ± 0.76^{ab}	7.03 ± 0.86^{ab}	10.65 ± 0.98^{a}	0.01
Mg^{2+} ($cmol_{(+)}$ kg^{-1})	1.97 ± 0.42	2.38 ± 0.66	1.89 ± 0.44	2.82 ± 0.44	2.34 ± 0.49	2.66 ± 0.1156	0.654
K^+ ($cmol_{(+)}$ kg^{-1})	0.31 ± 0.12^{b}	0.25 ± 0.19^{b}	0.44 ± 0.13^{ab}	0.95 ± 0.13^{a}	0.53 ± 0.14^{ab}	0.89 ± 0.16^{ab}	0.036
CEC ($cmol_{(+)}$ kg^{-1})	7.88 ± 1.10	9.69 ± 1.71	8.17 ± 1.15	10.76 ± 1.14	10.06 ± 1.28	14.19 ± 1.46	0.051
Textural class	**Sandy clay loam**	**Sandy loam**	**Sandy clay loam**	**Loam**	**Loam**	**Loam**	
Sand (%)	54.50 ± 7.55^{ab}	70.75 ± 5.44^{a}	52.00 ± 6.63^{b}	46.00 ± 11.60^{b}	44.50 ± 6.61^{b}	40.25 ± 6.18^{b}	<0.001
Silt (%)	24.50 ± 5.92^{ab}	17.75 ± 5.91^{b}	22.75 ± 3.30^{ab}	30.00 ± 9.66^{ab}	33.50 ± 5.97^{ab}	39.00 ± 6.00^{a}	0.002
Clay (%)	21.00 ± 2.71	11.50 ± 6.56	25.25 ± 7.27	24.00 ± 14.47	19.25 ± 4.92	20.75 ± 4.35	0.215

Different superscript letters in the rows in soil chemical properties indicate differences according to a covariance analysis and the Bonferroni adjustment for means comparison. Different superscript letters in the rows in textural class indicate significant differences according to Tukey's test ($p < 0.05$). EC, electrical conductivity; MO, organic matter; CEC, cation exchange capacity.

3.2 Sampling depth

No significant differences were found in pH, EC, P, and K based on soil sampling depth (Figure 2a, b, e, and f). The OM and N contents were significantly higher in the 0–10 cm depth compared to the 10–20 cm depth ($p < 0.001$) (Figure 2c and d). There were no differences in Ca^{2+} (Figure 3a), Mg^{2+} (Figure 3b), K^{+} (Figure 3c), and CEC (Figure 3d) among soil sampling depths. The percentage of sand, silt, and clay did not vary between sampling depths. The surface layer (0–10 cm) exhibited a sandy loamy texture, while the deeper layer (10–20 cm) was classified as loam (Table 4).

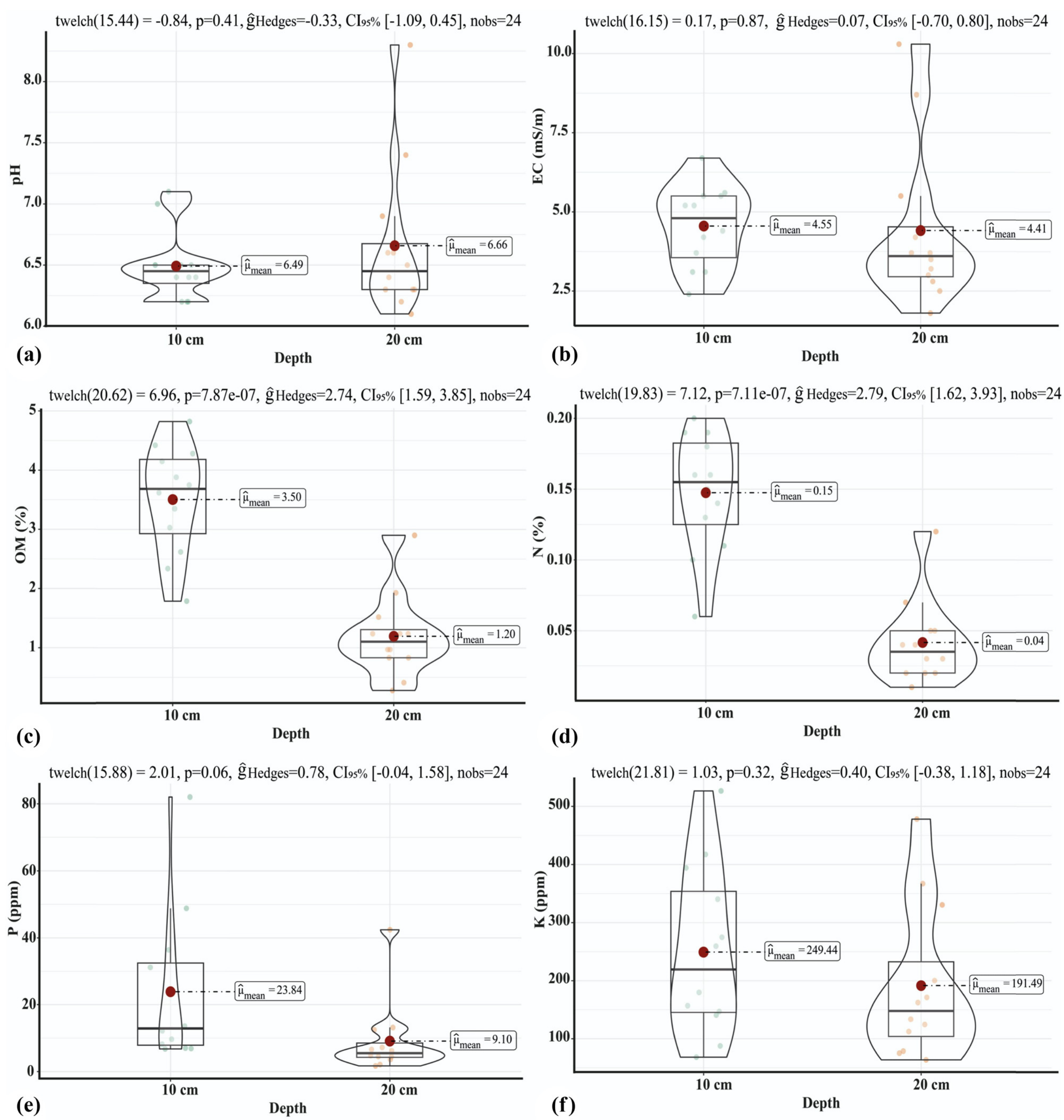

Figure 2: Soil chemical properties based on sampling depth (0–10 cm and 10–20 cm). (a) pH, (b) electrical conductivity (mS m^{-1}), (c) organic matter content (%), (d) nitrogen (%), (e) phosphorus (ppm), and (f) potassium (ppm).

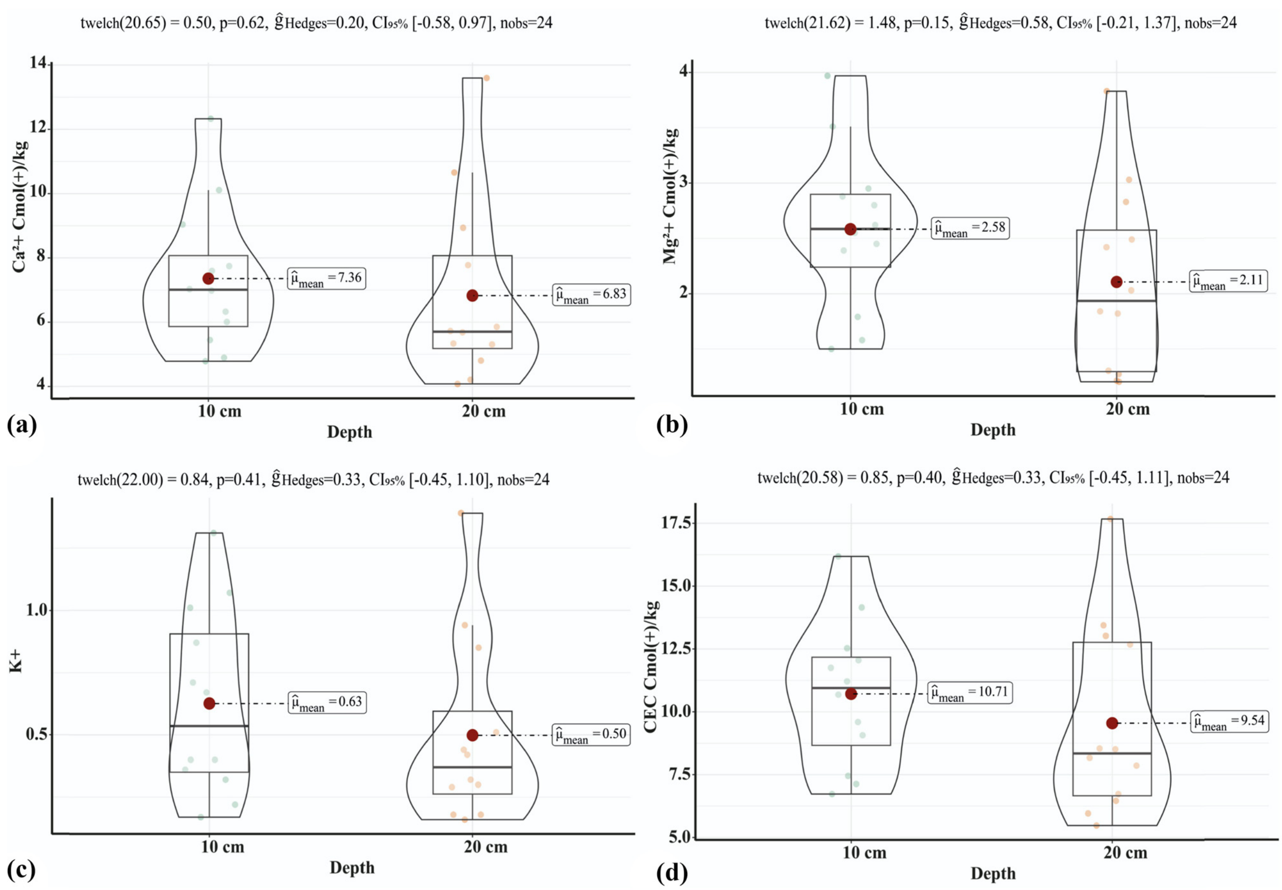

Figure 3: Exchangeable cations based on soil sampling depth (0–10 cm and 10–20 cm). (a) Ca^{2+} ($cmol_{(+)}\,kg^{-1}$), (b) Mg^{2+} ($cmol_{(+)}\,kg^{-1}$), (c) K^{+} ($cmol_{(+)}\,kg^{-1}$), and (d) CEC ($cmol_{(+)}\,kg^{-1}$).

3.3 Silvopastoral system × sampling depth

The analysis of the interactive effects between SPS and sampling depth is shown in Figure 4 and Table S2. EC was highest in the soil of Quinilla SPS sampled at a depth of 20 cm ($p < 0.05$) (Figure 4a). The analysis of covariance showed a significant interaction for OM and N; however, this was not detected by the Bonferroni adjustment for mean comparisons. The lowest OM (Figure 4b) and nitrogen content (Figure 4c) were observed in the soils of Quinilla SPS and NF at 0–10 cm, but no differences were found between SPS at 10–20 cm.

3.4 Multivariate analysis

Two components together explained 65.31% of the variance. Component 1 explained 47.98% of the variance (variables contributing were: K 12.84%, Ca^{2+} 10.88%, K^{+} 12.58%, and CEC 13.17%), and Component 2 explained 17.33% of the

Table 4: Soil texture (mean ± standard deviation) by sampling depth

Sampling depth	Sand (%)	Silt (%)	Clay (%)	Textural class
0–10 cm	52.58 ± 10.41	27.58 ± 10.40	19.83 ± 6.93	Sandy loam
10–20 cm	50.08 ± 13.99	28.25 ± 8.24	20.75 ± 9.55	Loamy
p-value	0.391	0.831	0.639	

The comparison of means was conducted using a *t*-test ($p < 0.05$).

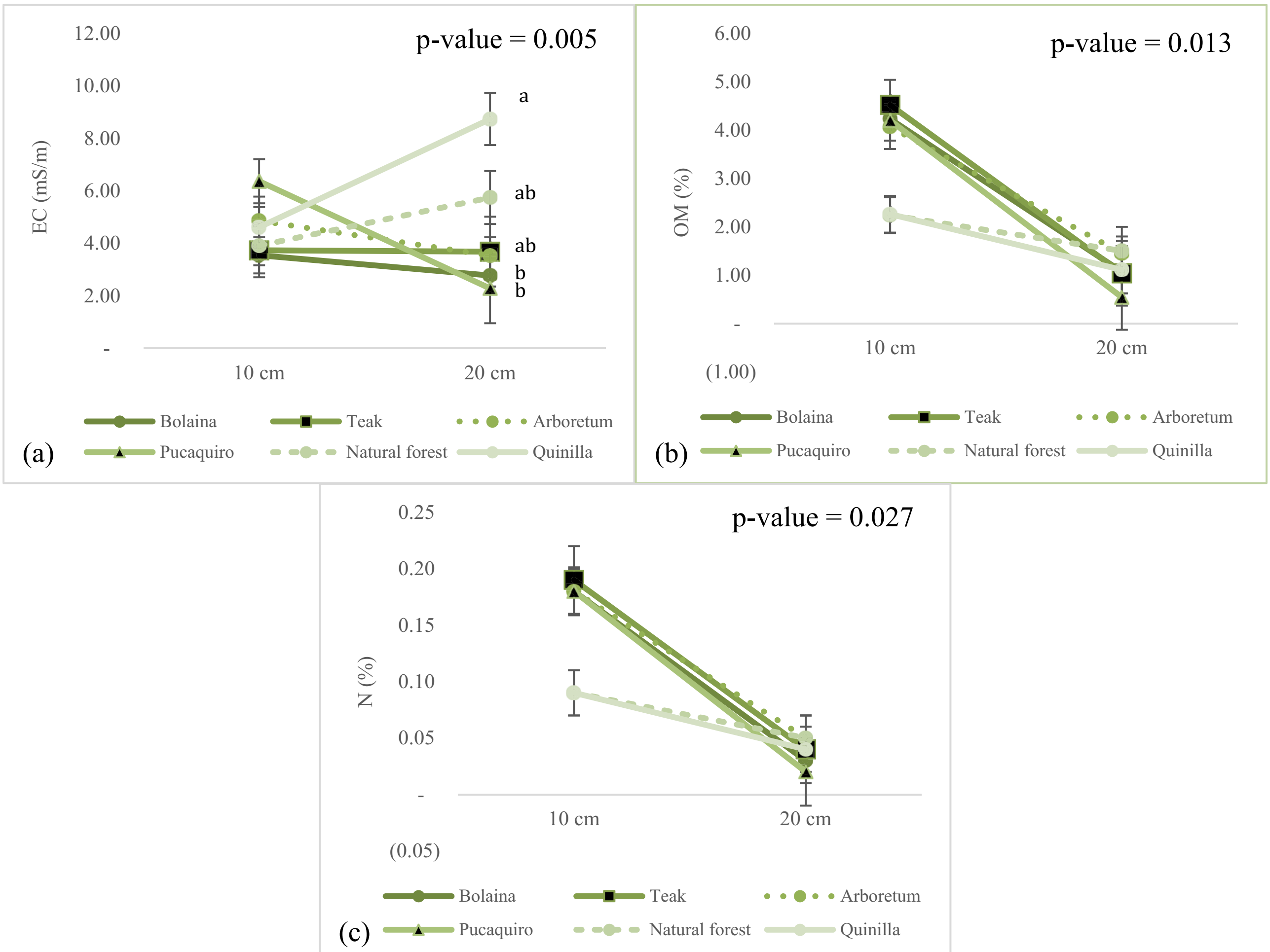

Figure 4: Interactive effect of six silvopastoral systems (SPS) and two soil sampling depths on electrical conductivity (a), organic matter (b), and nitrogen (c). Different letters on each curve indicate significant differences by Bonferroni adjustment ($p < 0.05$).

variance (variables contributing were OM 36.53% and N 36.21%) (Tables S3 and S4). The Quinilla SPS explained a higher contribution and displayed a different composition compared to the Teak SPS, especially regarding sand percentage (Figure 5a). The OM and N content contributed 20% of the observed variability, with higher concentrations found at sampling depths of 0–10 cm (Figure 5b). According to soil texture, P, Mg^{2+}, and sand percentage contributed less to the observed variability (Figure 5c).

According to correlation-based PCA, soil pH was correlated with EC (0.67***), Ca^{2+} (0.79***), and CEC (0.73***). Additionally, EC showed a correlation with K^{+} (0.58**) and CEC (0.52**). The OM content had a strong positive correlation solely with N (0.996***), while P was correlated with both Ca^{2+} (0.53**) and K^{+} (0.80***). Furthermore, Ca^{2+} was correlated with Mg^{2+} (0.63***), K^{+} (0.56**), and CEC (0.97***). Mg^{2+} also displayed a strong correlation with K^{+} (0.67***) and CEC (0.79***). K^{+} was correlated with CEC (0.70***). In addition, CEC showed a negative correlation with sand percentage (−0.60**) and a positive correlation with silt percentage (0.66***) (Figure S1). The exchangeable cations had high correlations with each other and with K^{+}. Notably, while pH and EC values were correlated with most variables, OM and N contents were only correlated with each other.

4 Discussion

This research evaluated the use of SPS with native tree species from the Peruvian tropics and their effect on the soil's chemical properties. Quinilla SPS soils showed the highest pH value. *M. bidentata* A. DC., a member of the Sapotaceae family, is highly valued in the South American tropics for its timber and pharmacological

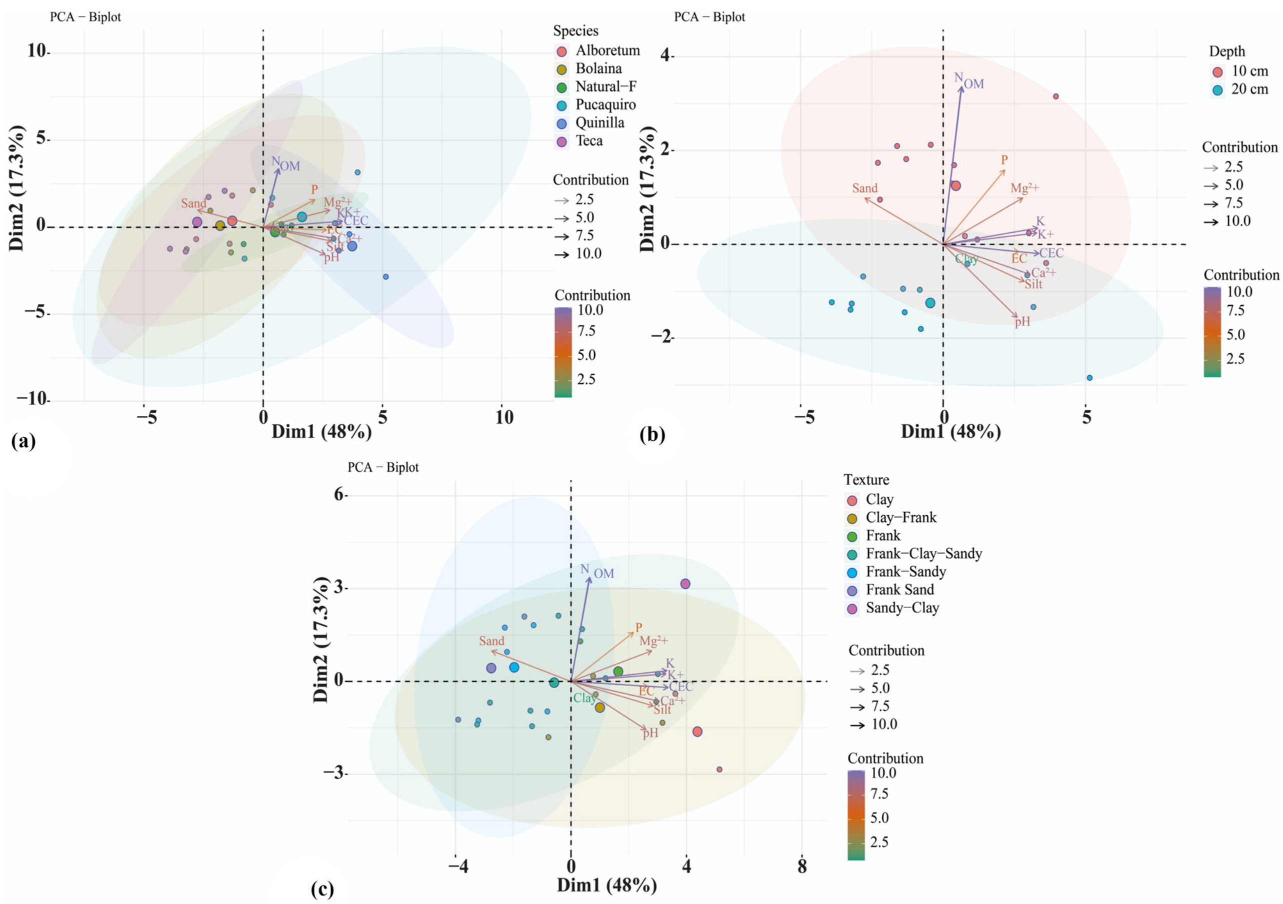

Figure 5: Principal component analysis (PCA) based on the correlation of soil parameters according to (a) SPS, (b) sampling depth, and (c) soil texture. The numbers in parentheses indicate the total variance explained by each axis.

properties, yet little is known about its interaction with soil pH. Since pH is measured on a logarithmic scale, a 1-unit change represents a tenfold increase in acidity, meaning even small shifts in soil pH can have significant consequences. Soils with an average pH of 6.1–6.5 are classified as slightly acidic, which allows for optimal nutrient availability, while soils with an average pH of 7.4–7.8 are moderately alkaline, indicating the presence of calcium carbonates [18]. The decrease in pH in the upper soil layers of Amazonian forests could be attributed to the exudation of organic acids by plants, acting as phytochelants to form less toxic complexes in soils with heavy metals [19]. This process may have occurred in Bolaina SPS, Teak SPS, arboretum, Pucaquiro SPS, and NF. Imoro et al. [20] already reported the influence of *T. grandis* L. on reducing soil pH (from 7.53 to 7.04), while Ikhajiagbe et al. [21] observed a reduction in pH within a 1.5 m radius of *T. grandis* L. trees (from 5.4 outside the radius to 4.4 inside the radius). Similarly, Romero-Delgado et al. [22] recorded lower soil pH values (from 8.21 to 7.83) under the tree canopy in an SPS with *Acacia macracantha*; Camero-Rey and Rodríguez-Díaz [11] found no significant effect of soil pH in an SPS with *Erytrina berteroana* (from 5.50 to 5.60); however, Páez-Martínez et al. [10] observed an increase in pH (from 4.6 to 5.2) after 24 months of SPS installation with *Anadenanthera peregrina*, *Pithecellobium guachapele*, and *Acacia mangium*, using *Brachiaria* as forage and applying dolomite and phosphate rock in Colombia.

In this study, no significant effect on OM and N was observed when using SPS as the independent variable and textural class as the covariate. In contrast, Camero-Rey and Rodríguez-Díaz [11] reported an increase in OM content (from 1.20 to 1.70%) in an SPS with *E. berteroana*, while Romero-Delgado et al. [22] found no variation in OM but detected changes in phosphorus and potassium levels under the canopy in an SPS with *A. macracantha.* Ikhajiagbe et al. [21] recorded higher concentrations of total nitrogen and soluble phosphorus within a 1.5 m radius of 8-year-old *T. grandis* L. trees compared to outside the radius. Similarly, Imoro et al. [20] found slightly higher nitrogen levels associated with *T. grandis* L., whereas Páez-Martínez et al. [10] observed no significant effect on organic carbon or nitrogen in an SPS with *A. peregrina*, *P. guachapele*, and *A. mangium*. Forest ecosystems influence soil nutrient dynamics through the decomposition of accumulated leaf litter at the base of trees [21,23]. The deciduous behavior of some plants may explain variations in OM and nitrogen content, which in turn affect nutrient cycling, soil fertility, health, sustainability, and resilience for agriculture use [24]. Additionally, deep-rooted trees can extract nutrients from deep soil layers, transporting them to the surface and improving soil chemical properties. Delgado-Baquerizo et al. [25] argue that enhancing soil properties impacts microbial community structure, which modulates nutrient availability for plants.

Regarding cations concentration, the soils of Pucaquiro SPS (*S. tinctonia* Schult.), Quinilla SPS (*M. bidentata* A. DC.), and NF stood out in K^+ and Ca^{2+}, which was reflected in the CEC, even though OM and clay percentages were not the highest. However, in this study, the age of the trees may have influenced the high K^+ and Ca^{2+} concentrations in the soil of these species, where the deeper roots of older trees in Quinilla SPS, Pucaquiro SPS, and NF could mobilize more minerals from deeper soil layers. This, in turn, likely increased the amount of leaf litter and fallen fruits on the surface, altering the mineral concentrations in the surface soil layer, although OM, N, and P did not vary significantly. Páez-Martínez et al. [10] observed no changes in base saturation or microelement content in an SPS with *A. peregrina*, *P. guachapele*, and *A. mangium*, likely due to the short evaluation period (24 months). Since most cations are attached to soil particles, CEC provides a nutrient reserve to replenish nutrients absorbed by the grasses and trees in the system. The relevance of CEC lies in its ability to determine the percentage of base saturation in the soil, nutrient exchange, and therefore its fertility [26], and the higher CEC in surface layers is justified by the greater presence of organic matter and greater biological activity.

Soil textural class plays a crucial role in determining the effect of land use on agroecosystem soil quality indicators [27]. In this study, soil texture were different among the SPS. The soils of Pucaquiro SPS, Quinilla SPS, and NF were the oldest and showed variations compared to the younger SPS. However, these findings should be interpreted with caution, and further research on this subject is recommended. Although soil texture is an intrinsic property, certain factors can indirectly influence the distribution of soil particles, the formation of aggregates, and the weathering of parent material factors such as organic matter accumulation, root system expansion, plant exudates, and changes in the soil microclimate, acting over a time scale of several decades [28,29]. The biological, physical, and chemical properties of the soil are largely influenced by climatic variability, soil type, and land-use intensity [30]. In the surface layers, leaf litter is incorporated, while in deeper layers, root turnover contributes to the stabilization of soil aggregates by binding particles together [31].

According to soil sampling depth, the pH ranged from 6.15 to 7.45, indicating optimal conditions for nutrient absorption [13]. In this study, the sources of organic matter in the SPS included the decomposition of roots, crop residues, livestock manure, mulch, leaf litter, and soil organisms, with contributions primarily within the top 10 cm of soil. In the surface layers of *Brachiaria* grasslands, the accumulation and conservation of organic matter are linked to the physical stabilization of carbon and phosphorus availability [32]. Similarly, in Colombia, Gómez-Balanta and Ramírez-Nader [33] found higher nitrogen content in NF within the first 10 cm of soil depth (from 0.9 to 1%), but this content decreased at 20 cm of depth. Regarding CEC, no significant differences were found between the two sampling depths in this study, although Gómez-Balanta and Ramírez-Nader [33] reported higher CEC levels in soils at 0–10 cm than at 10–20 cm in NF (from 33.03 to 46.55 $cmol_{(+)}\,kg^{-1}$) and established pasture soils (from 43.5 to 48.8 $cmol_{(+)}\,kg^{-1}$).

Regarding the interactive effect on EC, *M. bidentata* A. DC. (Quinilla SPS) may influence deeper soil layers due to its higher mineral recycling rate, with minerals being reincorporated into surface layers through organic matter decomposition and leaching. However, the age of this SPS (80 years) could also play a role in this interaction, which might not be observed in younger systems. Interestingly, Quinilla SPS and NF did not show significant reductions in OM and nitrogen content at 20 cm depth, unlike the other SPS. The process of soil regeneration and modification may be linked to the age and nutrient-recycling capacity of tree species, as well as their resilience to severe climatic events.

The variation explained by the PCA coincides with the findings from agroforestry systems involving *Theobroma cacao* and *G. crinita* Mart. in the Amazonian region. In these systems, Component 1 included: CEC (3.35–9.55 $cmol_{(+)}\,kg^{-1}$), Ca^{2+} (2.73–7.75 $cmol_{(+)}\,kg^{-1}$), and Mg^{2+} (0.37–1.36 $cmol_{(+)}\,kg^{-1}$). Component 2 was associated with sand (27–38%) and clay (21–25.4%), while Component 3 involved OM (1.16–1.87%) and nitrogen content (0.06–0.09%) [34]. Therefore, sustainable tree-based systems in the Amazon could significantly influence soil cation concentrations and cation exchange capacity.

5 Conclusions

The planting of *M. bidentate* A. DC. and *S. tinctoria* Schult. in grazing systems integrated with silvopastoral systems can enhance the availability of exchangeable cations (K^+, Ca^{2+}, and CEC), reaching similar concentrations to those observed in NF, although these outcomes may depend on tree age and SPS maturity.

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