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Soil properties under different land uses and slope gradients: Implications for sustainable land management in the Tach Karnuary watershed, Northwestern Ethiopia

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Introduction: Soil degradation resulting from land use changes and topographic variations poses a significant threat to agricultural productivity and environmental sustainability in the Northwestern Ethiopian Highlands. Assessing the influence of land use and slope gradient on soil physicochemical properties is crucial for developing sustainable land management strategies.

Methods: This study investigated the effects of four land-use types (cultivated land, grazing land, forest land, and eucalyptus plantations) and two slope gradients (upper and lower slopes) on selected soil properties in the Tach Karnuary watershed in Northwestern Ethiopia. Twenty-four composite soil samples were collected from 0 to 20 cm soil depth in triplicate across all land use and slope categories. In addition, undisturbed soil samples were obtained using a core sampler to assess the bulk density. Standard laboratory procedures were employed to analyze the physical properties (bulk density, porosity, and texture) and chemical properties (pH, organic matter, total nitrogen, available phosphorus, cation exchange capacity, and exchangeable cations). Data were statistically analyzed using analysis of variance (ANOVA).

Results: The ANOVA results revealed that land-use type significantly ($p < 0.05$) affected most soil physicochemical properties, including texture, bulk density, porosity, pH, available phosphorus, organic matter, total nitrogen, cation exchange capacity, and exchangeable cations. Likewise, the slope gradient had a highly significant ($p < 0.01$) effect on the bulk density, porosity, pH, organic matter, available phosphorus, total nitrogen, cation exchange capacity, and exchangeable cations.

Discussion: Soils on upper slopes exhibited lower fertility and more degraded physical conditions than those on lower slopes, primarily because of erosion and nutrient loss. variations in soil properties were also observed across the different land-use types. These findings underscore the urgent need for slope and land use-specific management interventions to mitigate soil degradation, enhance soil fertility, and promote sustainable land use in the erosion-prone landscapes of the Northwestern Ethiopian Highlands.

KEYWORDS

land use, slope gradients, soil properties, bulk density, soil degradation

1 Introduction

Soil fertility refers to the ability of the soil to provide essential nutrients in the right amounts and balance to support healthy plant growth and sustain agricultural productivity (Javed et al., 2022). It is measured by analyzing the physical, chemical, and biological characteristics of the soil, and is a key factor in determining crop production suitability. Soil properties, including physical, chemical, and biological characteristics, are critical indicators of soil fertility and agricultural productivity (Chen et al., 2020). These properties are heavily influenced by land-use type, slope gradient, and land management practices (Selassie et al., 2015). In Ethiopia, inappropriate land use practices (Lema et al., 2019), combined with steep slopes and unsustainable management, exacerbate soil erosion and degradation, leading to a decline in key soil properties such as texture, structure, organic matter content, and nutrient availability, which are vital for crop production.

Understanding the variations in soil physicochemical properties across different land-use types and slope gradients is essential for identifying the causes of soil fertility decline and land degradation. Such analyses provide insights into how land use and topographic factors affect soil health, helping to inform sustainable land management strategies that can mitigate degradation, restore soil fertility, and support long-term agricultural productivity. Although previous studies have examined the influence of land use and slope gradients on soil properties in various regions of Ethiopia (Assefa et al., 2020; Kassa et al., 2017), there remains a significant research gap regarding the specific interactions between these factors in different agroecological zones, particularly in the Tach Karnuary watershed. Existing literature often focuses on the individual effects of land use and topography, but lacks a comprehensive evaluation of their combined impacts, which are critical for developing targeted soil conservation strategies.

Topography, particularly the slope gradient, plays a significant role in influencing soil physicochemical properties by controlling runoff, drainage, and soil erosion processes (Pitta-Osses et al., 2022). Variations in slope gradients can lead to the redistribution of soil properties and soil organic matter (SOM), thereby impacting overall soil fertility. In combination with land-use practices, such as the widespread conversion of natural forests to agricultural lands and settlements in Ethiopia, these factors have accelerated soil erosion and nutrient loss (Assefa et al., 2020). However, few studies have explicitly addressed the extent to which different slope gradients interact with diverse land use systems to influence soil quality. Addressing this gap is essential for formulating precise and efffective soil conservation measures tailored to the specific landscape characterstics.

The Tach Karnuary watershed is experiencing soil degradation despite being a known productive area for cereal production, and has a high concentration of expanding eucalyptus plantations nationwide. While previous studies have highlighted the general impact of land-use changes on soil properties, there is a lack of specific research examining how variations in land-use and slope gradients interact to affect the soil physicochemical characteristics of in this region. The magnitude of the differences in soil properties with respect to land use types and slope gradients has not been thoroughly investigated in this area, leading to uncertainties in the development of site-specific soil conservation strategies. Given the urgent need for conservation measures, a fundamental understanding of these interactions is crucial to implement effective soil resource management plans. This study aims to bridge this knowledge gap by providing empirical evidence on the interplay between land use types and slope gradients and their collective impact on soil fertility.

This study hypothesizes that different land-use types and slope gradients significantly influence soil physicochemical properties, and their interactions will lead to compound effects that impact soil fertility and its potential for climate-smart management. Soil degradation poses a significant threat to agricultural productivity in the Tach Karnuary Watershed, underscoring the need for effective soil conservation strategies. Therefore, this study aimed to investigated the effects of various land-use types, including cultivated land (CL), eucalyptus plantation (PL), grazing land (GL), and forest land (NF), and slope gradients, categorized as gentle (0%–8%) and steep (9%–15%), on the physicochemical properties of soil. Specifically, the objectives were to assess the impact of these factors individually and examine their interactions. By addressing these objectives, this study sought to fill the critical knowledge gaps necessary for designing and implementing soil conservation and management strategies. Such efforts are essential for mitigating soil degradation and promoting agricultural sustainability in Ethiopia.

2 Materials and methods

2.1 Study area

Tach Karnuary, the area of study, is situated in northwestern Ethiopia's Blue Nile basin. It is located close to Dangila District in Awi zone, and about 483 km from Addis Ababa. The geographic coordinates of Tach Karnuary are 36° 54′ 46.82″ to 36° 54′ 01.3″ E longitudes and 11° 15′ 45.10″ N latitudes (Figure 1). The altitude varies from 1997 to 2101 m above sea level (Bazezew, 2015). The region has a unimodal rainfall pattern with the highest rates in July and August and an average annual rainfall of 1707.7 mm. During the main rainy season (Kiremt), which runs from May to October, 80%–90% of the rainfall occurs. Bega, or November to March, is the local term for the dry months (Jima et al., 2019). Accordingly, the watershed falls into the category of a Woyna Dega agro-ecological zone that is moist (sub-humid). Likewise, the minimum and maximum temperatures are 10.08°C and 25.49°C, respectively.

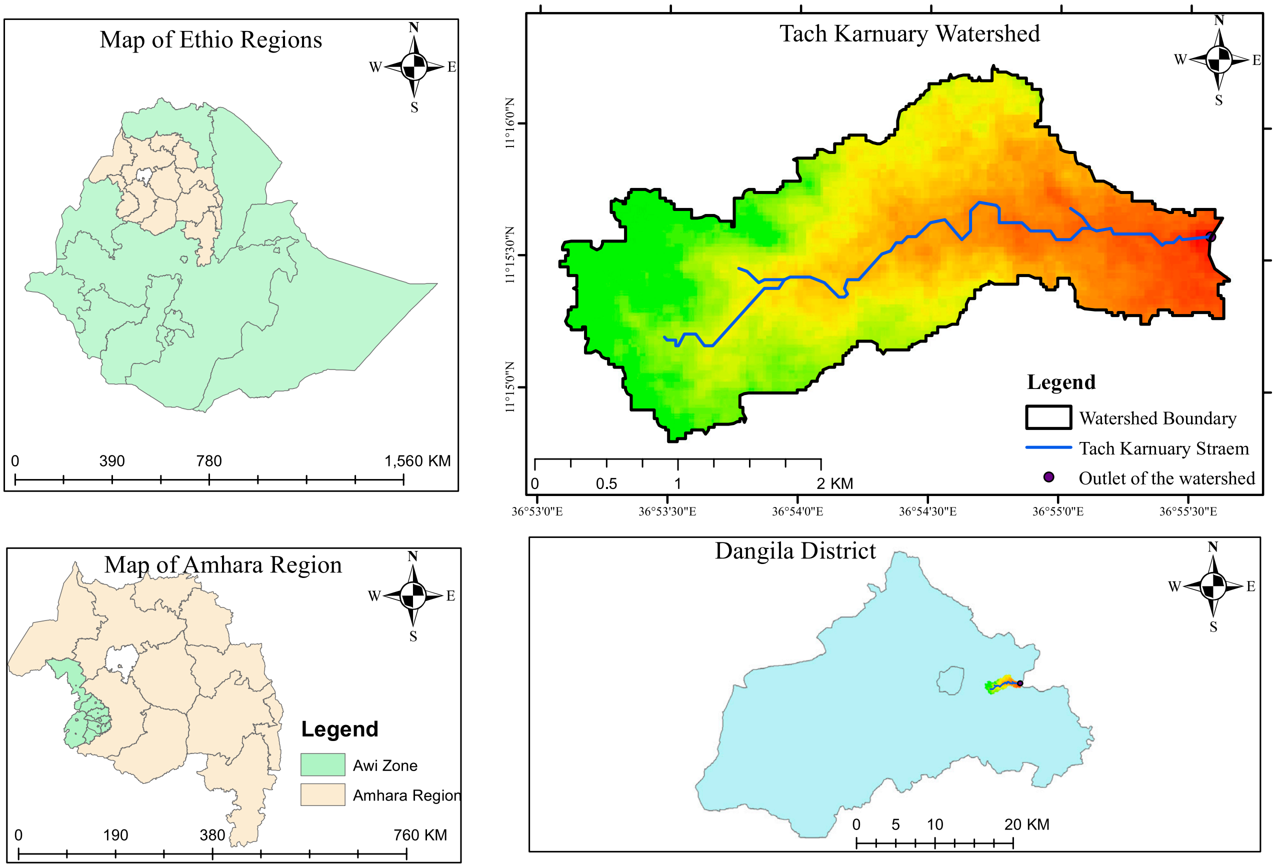

FIGURE 1
The location map of the study area.

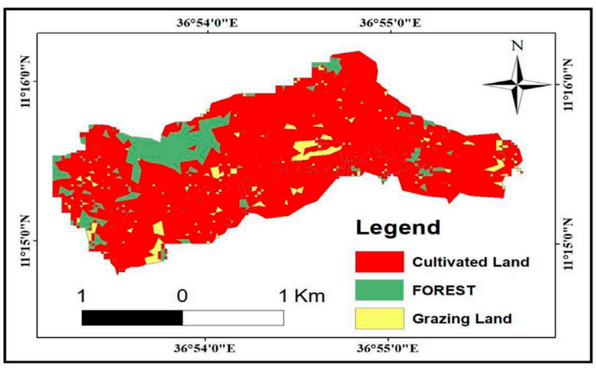

FIGURE 2
Land use/land cover.

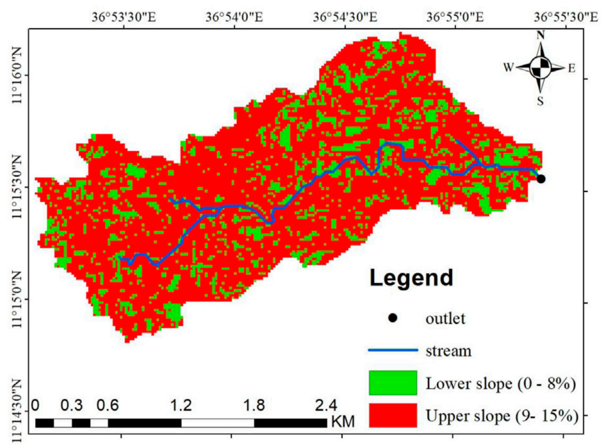

FIGURE 3
Slope class.

2.2 Land use

Within the watershed area, the different types of land use were as follows: 66.78% cultivated land, 12.98% grazing land, 17.57% natural forest, 2.63% eucalyptus plantation, and 0.11% other land uses, including Acacia species, wetlands, settlements, and infrastructure (Figure 2). According to Abey et al. (2023), the dominant soil in the Tach Karnuary watershed is Nitisols, which is a deep, well-drained, and red tropical soil.

These were then classified according to slope, with lower (0%–8%) and upper (9%–15%) slopes due to differences in drainage conditions (Figure 3). Because soils are essential components of landscape positions, local hydrologic and geomorphic processes can have varying effects on them (Güntner and Bronstert, 2004).

2.3 Soil sampling and analysis

A randomized complete block design (RCBD) was employed in this study, which combined four different land-use types (cultivated land, eucalyptus plantation, grazing land, and natural forest) with two slope gradients (gentle: 0%–8%, steep: 9%–15%) as environmental treatments. Each treatment was replicated three times. Soil samples were collected from each land-use type and slope gradient combination in the Tach Karnuary watershed. Both undisturbed and disturbed soil samples were collected to assess the soil properties. In total, twenty-four composite soil samples (four land-use types × two slope gradient categories × three replicates) were collected from a depth of 0–20 cm. Eight representative samples were taken from each land use type for composite sampling.

Additionally, separate core samplers were used to gather undisturbed soil samples from both the lower and upper slopes of each land-use type to calculate the soil bulk density (Ribolzi et al., 2011). The undisturbed soil samples were placed in steel core samplers, while the disturbed soil samples were placed in polythene bags, according to the field survey and laboratory methods manual. All collected samples were transported to the laboratory for further analysis. Soil properties, including both physicochemical characteristics, were analyzed at the Amhara Design and Supervision Works Enterprise Laboratory.

The selected physicochemical properties of the soil were analyzed using standard laboratory procedures. Raw soil samples were taken with a steel-core sampler in order to estimate bulk density (Bufebo and Elias, 2020). Total porosity (TP) was calculated using Equation 1, from the values of BD and particle density (PD) with the latter assumed to have the used average value of 2.65 g cm^{-3}.

$$Total\ porosity\,(\%) = \left(1 - \frac{BD}{PD}\right) *100 \tag{1}$$

The hydrometer method described in the simplified procedure was used to determine the soil particle size distribution (Gee and Bauder, 1979). The USDA system's soil textural triangle was used to determine the textural classes of the soil (Moreno-Maroto and Alonso-Azcarate, 2022). The pH of the soil in the supernatant suspension of a 1:2.5 soil to solution ratio of H_2O was measured potentiometrically using a digital pH meter (Rayment and Lyons, 2011). The Olsen method (Richardson and Reddy, 2013) was used to determine the available phosphorus (P) content, the Kjeldahl method (Sikora and Stott, 1997) was used for total nitrogen (N) content, and the wet oxidation method (Rowland and Grimshaw, 1985) was used to measure soil organic carbon (OC). The CEC was determined using the 1N ammonium acetate method at a soil pH of 7. The soil was first saturated with ammonium ions (NH_4^+) by leaching it with 1N ammonium acetate solution. Excess ammonium ions were then displaced with 1N sodium acetate, and the displaced ammonium was quantified by distillation and titration (Dume et al., 2016). Exchangeable bases were found by leaching the soils with ammonium acetate (Cech, 1990), and their concentrations were determined by an atomic absorption spectrometer.

2.4 Statistical analysis

A two-way analysis of variance (ANOVA) was performed to assess the significance of differences in soil parameters between slope classes, land uses and its interaction effects. Data were subjected to ANOVA with RCBD method using statistical analysis system. The least significant differences (LSD) by Fisher's test were used to separate significantly differing treatment means after main effects were found significant at $P \le 0.05$ using SAS software version 9.4. Moreover, simple correlation analyses were employed using Pearson's correlation coefficient to determine the degree and direction of associations between selected soil physicochemical properties.

3 Results

3.1 Variations in physical properties of soil across land use and slope gradients

Land use types and slope gradient significantly influenced soil texture. A statistically significant difference ($p < 0.05$) was observed in the sand content percentage between eucalyptus plantations (21.50%) and natural forests (32.0%), while no notable difference was found between cultivated and grazing land (Table 1). The mean percentage of clay content was 48.33% in eucalyptus plantations, whereas it was higher in forest land (58.66%). Among the different land uses, cultivated land had the highest mean silt content (25.83%), while eucalyptus plantations and grazing land had the lowest silt contents (19.66% each). On gentle slopes, higher clay (55.41%) and silt (22.83%) contents were recorded, whereas steep slopes had lower clay (48.83%) and silt (19.67%) contents (Table 1).

The highest mean bulk density value was observed in cultivated land (1.11 g cm^{-3}), while the lowest was recorded in forest land (1.05 g cm^{-3}) Table 1. Bulk density values were highest in the upper slope class (1.12 g cm^{-3}) and lowest in the lower slope class (1.05 g cm^{-3}). The highest total porosity was recorded in natural forests (60.06%), whereas the lowest was observed in grazing land (57.59%) and cultivated land (57.84%) Table 1. Total porosity was lowest in the upper slope area (57.69%) and highest in the lower slope area (59.96%).

Table 1, shows there is a significance difference in soil texture among land use types and slope gradients. The highest soil total porosity was found in natural forests (60.06%), while the lowest total porosity was recorded in grazing land (57.59%) and cultivated land (57.84%). Among the slope gradient total porosity values in Table 1, the lowest value of 57.69% was recorded in the upper sloping area (9%–15%), while the highest value of 59.96% was recorded in the lower sloping area (0%–8%).

3.2 Variations in chemical properties of soil across land use and slope gradients

Among the land use types, natural forest had the greatest soil PH mean value (5.7), while eucalyptus plantations had the lowest mean values (5.10) Table 2. Among the slope gradients, the soils on the upper

TABLE 1 Main effects of land use and slope gradient on physical properties of the soils.

Sampling units	Soil texture				BD (g cm^{-3})	TP %
Land uses	Sand %	Silt %	Clay %	Classes		
Natural forest	21.50^{c}	19.83^{b}	58.66^{a}	Clay	1.05^{b}	60.06^{a}
Cultivated land	25.16^{b}	25.83^{a}	49.00^{c}	Clay	1.11^{a}	57.84^{b}
Grazing land	27.83^{b}	19.66^{b}	52.50^{b}	Clay	1.10^{a}	57.59^{b}
Eucalyptus plantation	32.00^{a}	19.66^{b}	48.33^{c}	Clay	1.06^{b}	59.80^{a}
P-value	***	***	***	ns	***	***
Slope classes						
Lower slope (0%–8%)	21.75	22.83	55.41	Clay	1.05	59.96^{a}
Upper slope (9%–15%)	31.50	19.66	48.83	Clay	1.12	57.69^{b}
CV	9.05	8.92	2.79		2.02	1.63
P-value	**	**	**	ns	***	***

**highly significant ***very highly significant at P < 0.001; Av. P, available phosphorus; TN, total nitrogen; OM, organic matter; ppm, Parts per million; CV, coefficient of variation; P, probability.
Least Significant Difference (LSD) test at a 5% significance level (p < 0.05).

TABLE 2 Main effects of land use and slope gradient on soil chemical properties.

Land uses	pH (H_2O)	SOM (%)	TN (%)	Av. P (ppm)
Natural forest	5.67^{a}	3.93^{a}	0.16^{a}	6.15^{bc}
Cultivated land	5.31^{b}	3.00^{b}	0.15^{a}	8.61^{a}
Grazing land	5.50^{a}	3.24^{b}	0.15^{a}	6.34^{b}
Plantation eucalyptus	5.10^{c}	2.33^{c}	0.12^{b}	5.30^{c}
P-value	***	***	**	***
Slope classes				
Lower slope (0%–8%)	5.58^{a}	3.55^{a}	0.18^{a}	7.25^{a}
Upper slope (9%–15%)	5.20^{b}	2.70^{b}	0.11^{b}	5.95^{b}
CV	2.67	15.79	12.03	12.21
P-value	***	***	***	**

**highly significant ***very highly significant at P < 0.001; Av. P, available phosphorus; TN, total nitrogen; OM, organic matter; ppm, parts per million; CV, coefficient of variation; P, probability.
Least Significant Difference (LSD) test at a 5% significance level (p < 0.05).

slope (9%–15%) had the highest pH value (5.6), whereas the lower slope (0%–8%) had the lowest pH value (5.2) Table 2. On natural forest land, the mean SOM was the highest at 3.93%, while that of eucalyptus plantations was the lowest at 2.33% (Table 2). The soils of the lower sloping areas had a higher organic matter content (3.55%), whereas the soils of upper sloping areas had a lower OM content (2.70%).

Land use types and slope gradients significantly influence total nitrogen (TN) content the in soil. Among the various land-use types, natural forests exhibited the highest TN concentration (0.16%), whereas eucalyptus plantations had the lowest (0.12%). As presented in Table 2, the TN content was highest (0.18%) in the lower slope areas and decreased progressively with elevation, reaching its lowest value (0.11%) in the upper slope areas.

The application of diammonium phosphate (DAP) inorganic fertilizer in cultivated land use types has led to an increase in the available phosphorus (P) content. Among various land use types, cultivated land exhibited a significantly higher concentration of available P. Specifically, cultivated land had the highest available P content (8.61 ppm), whereas eucalyptus plantations the lowest (5.30 ppm) Table 2. Furthermore, variations in slope gradient had a highly significant effect on available P levels (p < 0.01) Table 2. The lower concentration of available P in the upper slope (5.95 ppm) and its subsequent accumulation in the lower slope (7.25 ppm) suggest that phosphorus is being transported downslope, likely due to soil erosion and runoff processes.

The higher concentration of SOM and clay in natural forests relative to other types of land use may be the cause of the cation exchange capacity of the land use type's (Table 3). The lower slope of

TABLE 3 Main effects of land use and slope gradient on properties of exchangeable cations.

Sampling unites	CEC	Ex, Ca	Ex, Mg	Ex, K	Ex, Na	PBS %
	Cmol $_{(+)}$ kg^{-1}					
Land uses						
Natural forest	21.86[a]	7.19[a]	5.92[a]	1.13[a]	0.89[a]	72.89[a]
Cultivated land	17.13[b]	6.30b[c]	1.85[b,c]	0.80[b]	0.72[b]	56.83[b]
Grazing land	17.15[b]	6.79[a,b]	2.05b	0.68[b]	0.40[c]	59.3[b]
Plantation eucalyptus	15.50[b]	5.85[c]	1.67[c]	0.42[c]	0.34[c]	53.71[b]
P-value	***	**	***	***	***	***
Slope						
0%–8%	21.35[a]	7.44[a]	3.19[a]	1.05[a]	0.77[a]	63.44[a]
9%–15%	14.37[b]	5.62[b]	2.55[b]	0.47[b]	0.41[b]	57.95[a]
CV (%)	9.50	7.43	10.54	18.03	20.33	10.86
P-value	***	***	*	***	***	ns

*Significant at P < 0.05; **highly significant at P < 0.01; ***very highly significant at P < 0.001; ns, non-significant; CEC, cation exchange capacity; Ex, Ca, exchangeable calcium; Ex, mg, exchangeable magnesium; Ex, K, exchangeable potassium; Ex, Na, exchangeable sodium; CV, coefficient of variation; P, probability.
Least Significant Difference (LSD) test at a 5% significance level (p < 0.05).

natural forests had the highest CEC value (28.35 cmol $_{(+)}$ kg^{-1}). While eucalyptus plantations had the lowest CEC (13.11 cmol $_{(+)}$ kg^{-1}), this was primarily because of poor undergrowth, deforestation for charcoal, and firewood production, which reduced soil organic matter. Although the upper slope had the lowest CEC (14.37 cmol $_{(+)}$ kg^{-1}), erosion lead to the removal of clay and soil organic matter.

Exchangeable cations were significantly influenced by both land-use types and slope gradients. The highest concentrations of exchangeable cations were observed in the lower slopes of the natural forest land, whereas the lowest concentrations were recorded in the upper slopes of eucalyptus plantations. This variation can be attributed to soil erosion and the acidic nature of eucalyptus plantation soils, which contributes to the depletion of essential cations (Table 3) Figure 4. The correlation matrix showed that exchangeable Ca^{2+} had a strong positive correlation with CEC (r = 0.96***) and SOM (r = 0.86**), indicating its contribution to soil fertility. Conversely, Ca^{2+} was negatively correlated with sand content (r = -0.86**) and bulk density (r = -0.59ns), suggesting its lower presence in coarse-textured and compacted soils (Table 4).

The maximum percentage of base saturation (PBS) was found beneath the upper slope of a natural forest, accounting for 72.89% of the interaction effects between land use type and slope. The lowest mean PBS value was found under the upper slope of the eucalyptus plantations (52.20%) Table 3.

4 Discussions

4.1 Impacts of land use and slope gradients on the chemical properties of soil

4.1.1 Soil texture

The variations in soil texture across land use types and slope gradients reflects the influence of anthropogenic activities and topographical process on soil formation and degradation. The higher sand content in eucalyptus plantations relative to natural forests suggests not only that these plantations are often established on previously degraded or erosion-prone lands, but also that their management practices (e.g., minimal understory and frequent harvesting) may exacerbate erosion and reduce finer particles such as silt and clay. Sandy texture on various types of land is likely the result of erosion's selective removal of clay particles (Soto et al., 2019). This erosion process has led to the formation of sand in certain areas, causing the predominance of sand soil texture in eucalyptus plantations. This finding aligns with the observations of Tellen and Yerima (2018), who reported that on steep slopes (9%–15%), the mean sand fraction was higher (31.50%) compared to gentler slopes (0%–8%), which had a lower mean sand fraction (21.75%). This variation is likely due to erosion, which selectively removes finer soil particles and increases the proportion of coarser particles such as sand on steeper slopes. This finding aligns with the results of Selassie et al. (2015).

The lower clay content in eucalyptus plantations compared to forest land suggests that soil degradation and erosion processes have contributed to the depletion of finer soil particles. Natural forests, with minimal disturbance, tend to retain higher clay content due to better soil structure and organic matter accumulation. This is because natural forests typically have high levels of organic matter, which helps bind soil particles together, improving soil structure and stability (Chaikaew and Chavanich, 2017). This enhanced structure prevents clay particles from dispersing and eroding easily. In contrast, eucalyptus plantations often receive insufficient organic matter, leading to poorer soil structure and lower clay content (Fialho and Zinn, 2014). As a result, the soils in eucalyptus plantations generally have less clay compared to those in natural forests, due to the reduced input of organic matter that is essential for maintaining soil integrity (Osman and Osman, 2013).

TABLE 4 The relationship (Pearson's product movement coefficient of correlation) between soil physicochemical properties.

Soil properties	pH (H_2O)	Sand	Silt	Clay (%)	OC (%)	OM	TN	AV. P ppm	EX. Ca	Ex. mg Cmol $_{(+)}$ kg^{-1}	Ex-k Cmol $_{(+)}$ kg^{-1}	Ex-Na Cmol $_{(+)}$ kg^{-1}	CEC	BD g cm^{-3}	TP (%)	PBS (%)
PH (H_2O)	1.000															
Sand (%)	−0.85**	1.000														
Silt (%)	0.19^{ns}	−0.53^{ns}	1.000													
Clay (%)	0.89**	−0.87**	0.04^{ns}	1.000												
OC (%)	0.92**	−0.91**	0.22^{ns}	0.95***	1.000											
OM (%)	0.92**	−0.91**	0.23^{ns}	0.95***	0.99***	1.000										
TN (%)	0.76*	−0.90**	0.47^{ns}	0.79*	0.84**	0.84**	1.000									
Av, P (ppm)	0.30^{ns}	−0.60^{ns}	0.95***	0.15^{ns}	0.36^{ns}	0.36^{ns}	0.52^{ns}	1.000								
Ex. Ca	0.78*	−0.86**	0.31^{ns}	0.84**	0.86**	0.86**	0.96***	0.36^{ns}	1.000							
Ex. mg Cmol $_{(+)}$ kg^{-1}	0.63^{ns}	−0.58^{ns}	−0.20^{ns}	0.80*	0.74*	0.74*	0.35^{ns}	0.09^{ns}	0.43^{ns}	1.000						
Ex. k Cmol $_{(+)}$ kg^{-1}	0.78*	−0.90**	0.40^{ns}	0.83*	0.89**	0.89**	0.90**	0.42^{ns}	0.94***	0.58 ^{ns}	1.000					
Ex. Na Cmol $_{(+)}$ kg^{-1}	0.76*	−0.93***	0.56^{ns}	0.78*	0.84**	0.84**	0.78*	0.59^{ns}	0.71*	0.67^{ns}	0.85**	1.000				
CEC	0.71*	−0.86**	0.31^{ns}	0.83**	0.85**	0.85**	0.90**	0.32^{ns}	0.96***	0.55^{ns}	0.96***	0.76*	1.000			
BD g cm^{-3}	−0.46^{ns}	0.59^{ns}	−0.08^{ns}	−0.66^{ns}	−0.48^{ns}	−0.48^{ns}	−0.52^{ns}	−0.01^{ns}	−0.60^{ns}	−0.42^{ns}	−0.50^{ns}	−0.46^{ns}	−0.66^{ns}	1.000		
TP (%)	0.42^{ns}	−0.58^{ns}	0.06^{ns}	0.64^{ns}	0.45^{ns}	0.45^{ns}	0.49^{ns}	−0.03^{ns}	0.54^{ns}	0.49^{ns}	0.51^{ns}	0.52^{ns}	0.64^{ns}	−0.96***	1.000	
PBS (%)	0.40^{ns}	−0.18^{ns}	−0.34^{ns}	0.41^{ns}	0.38^{ns}	0.37^{ns}	−0.10^{ns}	−0.18^{ns}	−0.10^{ns}	0.75*	0.05^{ns}	0.33^{ns}	−0.06^{ns}	0.06^{ns}	0.01	1.000

*Significant at $P < 0.05$; **highly significant at $P < 0.01$; ***very highly significant at $P < 0.001$; ns, non-significant.

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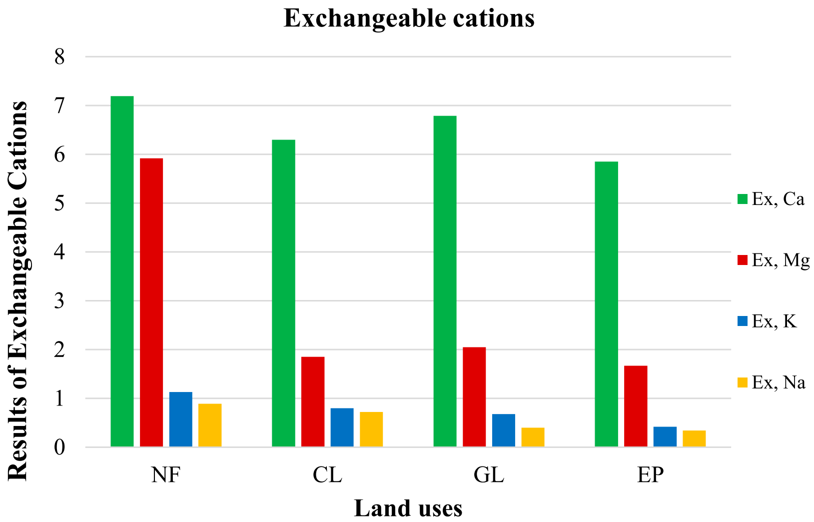

FIGURE 4
Effects of land use type on exchangeable cations.

Similarly, the variation in silt content across different land use types indicates the impact of land management practices. The higher silt content in cultivated land may be attributed to soil disturbance from plowing, which redistributes finer particles, while the lower silt content in eucalyptus plantations and grazing land suggests erosion-driven depletion of silt-sized fractions. These findings emphasize the need for effective soil conservation measures to mitigate erosion and preserve soil quality under different land uses.

The higher concentrations of clay and silt in areas with gentle slopes suggest reduced soil erosion and greater retention of finer soil particles. This is likely due to lower runoff velocity, which minimizes the selective removal of clay and silt fractions. In contrast, steeply sloping areas exhibit lower clay and silt content, indicating increased erosion and preferential loss of finer particles, leaving behind coarser soil fractions. Consequently, the impact of eucalyptus plantations on soil properties may be less pronounced in flatter areas, where clay content remains relatively stable. These findings align with previous studies highlighting the influence of topography on soil texture distribution, where steeper slopes are more prone to erosion-driven depletion of fine soil particles. The presence of clay and silt at different slope positions may be the consequence of upland silt and clay fraction deposition, which enriched the lower sloping area. A study by Zádorová et al. (2023), revealed similar results.

4.1.2 Soil bulk density

The higher bulk density observed in cultivated land suggests soil compaction due to continuous agricultural activities, including frequent tillage and machinery use, which reduce soil porosity. In contrast, the lower bulk density in forestland indicates minimal soil disturbance and higher organic matter content input from litterfall and root turnover, which enhances soil structure and porosity. These findings align with those of previous studies that have highlighted the role of land use in influencing soil physical properties. Intensive cultivation tends to increase bulk density because the soil surface is constantly exposed to the direct force of raindrops (Roth-Nebelsick et al., 2022), and the loss of organic matter degrades the soil structure, resulting in soil compaction (Grosbellet et al., 2011). This compaction reduced pore space and increased soil density. Therefore, the higher densities found in the soils of cultivated land were due to the constant exposure of the soil surface to raindrops and degradation of the soil (Vaezi et al., 2017).

This increase in bulk density may also have been attributed to an extended period of continuous cultivation. This study is consistent with previous findings, which reported that the bulk density of agricultural land use was higher than that of forest land use (Vaezi et al., 2017). This could be because of the greater organic matter content of natural forest as opposed to agriculture, which has a continuous removal of organic matter with less addition to cultivated land (Guimarães et al., 2013). The highest OM content causes a lower bulk density in the soils of natural forest land because OM has a very low density compared to mineral soil particles (Rühlmann et al., 2006). This lower bulk density in natural forest soils results in an improved soil structure and increased water-holding capacity (Acín-Carrera et al., 2013).

Variations in bulk density across slope classes suggest the influence of topography on soil compaction and porosity. The higher bulk density observed on the upper slope may be attributed to increased erosion and reduced organic matter accumulation, which led to soil compaction. In contrast, the lower bulk density on the lower slope could be due to greater organic matter deposition, reduced soil disturbance, and enhanced soil structure and porosity. These findings are consistent with previous studies indicating that bulk density tends to increase in areas with higher erosion rates and decrease in depositional zones where organic matter accumulation is more pronounced. These factors could be responsible for the variations in soil bulk density among the slope classes. The results obtained from this investigation correspond to the findings reported by Aytenew and Kibret (2016), who found that the bulk density of soils on steep slopes was highest at 1.41 g cm^{-3} as compared with gentle slopes at

1.32 g cm^{-3}, which was caused by the high clay fraction, porosity, and minimal soil disturbance from erosion.

4.1.3 Soil total porosity

The higher total porosity observed in natural forests indicates an improved soil structure, primarily due to the accumulation of organic matter from continuous litter fall and minimal disturbance. Organic inputs promote soil aggregation and stabilize pore spaces, which are critical for maintaining soil aeration, water infiltration, and root penetration. In contrast, the lower porosity in grazing and cultivated lands may be a result of physical soil compaction caused by livestock trampling and repeated tillage operations. These disturbances degrade the soil structure, reduce macropores, and limit the movement of air and water within the soil profile, thereby affecting soil productivity and ecosystem functioning. This finding aligns with previous studies indicating that land use changes significantly affect soil porosity, with natural vegetation promoting better soil structure, whereas intensive land use practices lead to compaction and reduced porosity (Asmare et al., 2023). Implementing sustainable land management practices, such as reduced tillage and controlled grazing, could help mitigate soil compaction and improve soil porosity in cultivated and grazed lands.

The variation in total porosity across slope gradients suggests that soil structure and compaction are influenced by the topographic position. The lower total porosity observed in the upper sloping area (9%–15%) may be attributed to higher erosion rates, which remove finer soil particles and organic matter, leading to increased soil compaction. In contrast, the higher porosity in the lower sloping area (0%–8%) could result from the accumulation of eroded materials, which enhances the soil structure and creates more pore spaces. This result is similar to the findings of Hailemariam et al. (2023), indicating that soil porosity tends to decrease on steeper slopes due to the impact of erosion and reduced organic matter content, ultimately affecting soil water retention and aeration.

4.2 Impacts of land use and slope gradients on the chemical properties of soil

4.2.1 Soil pH

The lower soil pH observed in Eucalyptus plantations than in natural forests suggests that land use significantly influences soil acidity. The relatively higher pH in natural forests may be attributed to the accumulation of organic matter and nutrient cycling processes that help to buffer soil acidity. In contrast, Eucalyptus plantations influence the soil pH and chemical fertility through multiple pathways. Decomposition of acidic organic residues, such as leaf litter, releases organic acids, whereas rapid nutrient uptake by trees depletes base cations, contributing to acidification. Additionally, phenolic acids and volatile oils released from Eucalyptus leaves, bark, and roots can negatively affect neighboring plants (Birhanu and Kumsa, 2018). These compounds, along with increased soil erosion and leaching, exacerbate soil acidification and lower the overall soil chemical fertility. This outcome aligns with the findings of Koutika et al. (2014), who reported that eucalyptus plantations had significantly more acidic soil than other land use types. This increased acidity is likely attributable to the high levels of tannins and phenolic compounds present in eucalyptus leaves, which contribute to soil acidification. An additional explanation might be increased microbial oxidation, which results in organic acids and gives soil H^+, which contributes to the overall increase in soil acidity (Bolan et al., 2023).

The variation in soil pH across slope positions can be attributed to differences in soil erosion, leaching, and organic matter accumulation. The higher pH observed in the upper slope may result from the selective removal of acidic components through erosion, leaving behind less acidic soil constituents. While, previous studies suggested that cations (Ca^{+2}, Mg^{+2}, K^+, and Na^+) and clay (OM) were removed from the top and deposited at the bottom slope position, there may be an accumulation of these elements along the lower slope gradient that is responsible for the higher soil pH values (Dessalegn et al., 2014). The loss of base-forming cations through leaching and runoff accelerates erosion, lowers the soil pH, and increases the soil acidity (Ma et al., 2018).

4.2.2 Soil organic matter

The lower soil organic matter (SOM) content in eucalyptus plantations than in natural forests suggests that land use changes significantly impact soil fertility. The reason for the highest SOM content in natural forests may be attributed to litter falling from trees and shrubs. Trees with large short roots are an important source of nutrients and SOM enrichment. A higher concentration of grass roots and detrital inputs of grass litter into the layers beneath the forest might have led to a higher amount of organic matter (OM) in the forest land (Van Der Sande et al., 2023).

Leaves falling from eucalyptus plantations have fewer management practices, and fewer inputs of organic substrate as fertilizer could contribute to the low SOM accumulation in these plantations (Versini et al., 2014). This result is consistent with Bewket and Stroosnijder (2003), who stated that in the Dangule area, the highest OM was recorded in forest land and the lowest in eucalyptus plantations. According to Ashagrie et al. (2005), the amount of organic matter present in the soil decreases when natural forests are converted into eucalyptus plantations.

The variation in organic matter (OM) content across different slope positions can be attributed to soil erosion and deposition processes. Lower-sloping areas tend to accumulate organic matter because of the downward movement of eroded soil and organic residues, leading to higher OM content. In contrast, upper-sloping areas experience greater erosion, which removes surface organic material and reduces the OM levels. This pattern aligns with previous studies by Selassie et al. (2015) and Aytenew and Kibret (2016), indicating that the slope gradient influences soil fertility, with lower slopes acting as deposition zones that enhance soil organic matter accumulation, while upper slopes are more prone to degradation and nutrient loss. Effective soil conservation measures, such as contour farming and vegetative cover, could help mitigate erosion and improve soil organic matter retention in upper slope areas.

4.2.3 Total nitrogen

The higher total nitrogen content in natural forest land use is due to continuous organic matter accumulation from diverse vegetation and minimal soil disturbance. In contrast, the lower total nitrogen content in eucalyptus plantations than in natural forests suggests a decline in soil fertility, likely due to the high nutrient demand and low organic matter input associated with eucalyptus trees. Eucalyptus species are known to rapidly absorb soil nutrients, which, combined with limited litter decomposition, can lead to nitrogen depletion.

This might be because it is probable that no residues will be able to return to the soil as organic matter, and that bacteria that decompose organic matter are hindered in strongly acidic soils. This prevents organic matter from decomposing, which leads to an accumulation of organic matter (SOM) and the binding of nutrients, especially nitrogen (Coonan et al., 2020). This could be a major factor leading to low levels of soil OM and TN, which negatively affects plant growth and soil fertility. This is similar to the findings of Mohammad and Adam (2010), who found that the total N content in forest land was the highest and that, according to the classification of Walkley and Black (1934), the total nitrogen content in the soils of cultivated, grazing, and eucalyptus plantation lands was the lowest. While the lowest in cultivated land may be the result of crop residues being collected for fuel, animal feed, and temporary construction, no residues can be returned to the soil (Alaminew and Desta, 2024). Sustainable land management practices, such as integrating organic amendments or mixed-species plantations, may help mitigate nitrogen depletion in eucalyptus-dominated landscapes.

The variation in total nitrogen (N) content across different slope positions can be attributed to the influence of topography on soil nutrient distribution. Lower slope areas tend to accumulate more organic matter, which is the primary source of TN and is resistant to water erosion, and the lower slope has a higher nitrogen content. The majority of stakeholders graze on these lands communally, which causes nitrogen and other nutrients to accumulate (Sinore et al., 2018). However, because of the increased erosion, nitrogen removal occurred on the upper slope. The finding of Wubie and Assen (2020), which showed that total nitrogen has an increasing trend from a moderately steep to a sloping gradient, lends additional credence to this. This could be due to their downward movement with runoff water from the higher slope gradient and accumulation at the lower hill gradient.

In contrast, the upper slope areas are more prone to erosion, which selectively removes topsoil and associated organic matter, leading to lower nitrogen levels. Effective soil conservation measures are essential for mitigating nutrient loss and maintaining soil productivity, particularly in upper slope regions.

4.2.4 Available P

The higher available phosphorus (P) content in cultivated land compared to other land use types is maybe due to the regular application of mineral fertilizers, particularly NPS and diammonium phosphate (DAP), aimed at enhancing crop productivity. These inputs directly increase soil P levels, especially in the surface layer, where they are most commonly applied. This results supports the findings of Guelfi et al. (2022), who reported elevated available P in intensively managed croplands. In contrast, Eucalyptus plantations exhibited the lowest available P content, which may be due to the absence of P fertilizer application and minimal soil management. Additionally, Eucalyptus species are know for their high nutrient uptake and potential to deplete surface nutrients over time, especially under monoculture systems (Gonçalves et al., 2017). This result is similar to that of Bewket and Stroosnijder (2003), who reported that the greater availability of P in cultivated fields than in forests suggests that trees in forests extract more phosphorus than field crops or that a high proportion of the P pool is retained and immobilized by microbes in the litter layers of forests and eucalyptus plantations. It is also possible that the use of cattle dung as a soil conditioner in cultivated fields has a significant impact (Ndzeshala et al., 2023). According to Dagnachew et al. (2019), cultivated land use had higher available P (8.04ppm) than other land uses, possibly due to the use of organic fertilizers (e.g., compost, manure, and household wastes) and inorganic fertilizers [e.g., urea ($CO(NH_2)_2$) and diammonium phosphate (DAP)] on the cultivation land.

The primary factors determining the amount of available phosphorus (P) are soil organic matter (SOM) and landscape position. The removal of P from the upper slopes and its accumulation in the lower slope positions suggests that runoff transports soil particles enriched with P downslope, leading to higher concentrations in lower gradient areas. This outcome is consistent with the findings of El Kateb et al. (2013), who reported that lower landscape positions have higher available P than other positions. Similarly, Zebire et al. (2019) explained that this phenomenon occurs because of the accumulation and downward movement of SOM at lower elevations, resulting in a higher available P.

Generally, according to Landon (2014), selected soil chemical characteristics in the study area, including pH, total nitrogen (TN), and SOM, range from highly acidic to moderately acidic. TN and SOM were moderate across all land uses types, whereas available P was classified as moderate based on Landon's (2014) ratings. Effective soil conservation measures, such as contour farming and vegetative cover, are essential to minimize P loss from the upper slopes and enhance soil fertility sustainability.

4.2.5 Cation exchange capacity

The variation in cation exchange capacity (CEC) across different land use types can be attributed to differences in soil organic matter (SOM) and clay content. Natural forests exhibited the highest CEC, particularly in lower slope areas, likely because of the accumulation of organic matter and the presence of finer soil particles, which enhance the ability of the soil to retain and exchange nutrients. Eucalyptus plantations had the lowest CEC, primarily due to poor undergrowth, deforestation for charcoal, and firewood production, which reduced soil organic matter. As a result, the Eucalyptus plantations had a significantly lower CEC than the other areas. Land use and human activity are responsible for this decline in soil organic matter (SOM), ultimately leading to a negative impact on soil fertility and ecosystem health (Ramesh et al., 2019).

This outcome is comparable to the findings of Rezaei et al. (2015), where clay content and high availability of soil organic matter may be the causes of CEC variation across slope gradients. Although the upper slope had the lowest CEC, erosion led to the removal of clay and soil organic matter (SOM), which aligns with the findings of Ellerbrock et al. (2016). According to Landon (2014), CEC values were rated as medium, Whereas the PBS value in natural forest land use was classified as high. In contrast, for cultivated, grazing, and eucalyptus land use, PBS was rated as moderate. This indicates that vegetation cover can reduce soil erosion, which is supported by the findings of Sun et al. (2013). However, it is also important to consider other factors that contribute to soil erosion.

4.2.6 Exchangeable bases

The higher exchangeable Ca^{2+} content observed in natural forest soils than in eucalyptus plantations suggests that land use plays a crucial role in shaping soil nutrient availability. Natural forests typically have higher organic matter inputs through leaf litter and root turnover, which contribute to the replenishment and retention of base cations such as Ca^{2+}. In contrast, the lower exchangeable Ca^{2+} levels in Eucalyptus plantations may be associated with accelerated nutrient depletion due to rapid growth of species, high biomass accumulation, and a deep rooting system, which extracts nutrients from deeper soil layers. Additionally, Eucalyptus trees are known to contribute to soil acidification through the accumulation of acidic litter and organic acids, which can displace Ca^{2+} from the exchange complex and increase leaching. These findings are consistent with previous studies (Demessie et al., 2012), where there is a greater likelihood of leaching downward by runoff and water percolation through no vegetation cover and fewer management activities practiced. This could result in less nutrient retention and a greater potential for erosion in eucalyptus plantations.

The variation in exchangeable Ca^{2+} across different land use types and slope gradients can be attributed to soil erosion and organic matter dynamics. The higher exchangeable Ca^{2+} content in the lower slope of the forest suggests the accumulation of leached nutrients and organic matter due to the downslope movement of soil materials. Forested areas generally contribute to higher organic inputs, which enhances cation retention and nutrient availability.

Conversely, the lower exchangeable Ca^{2+} observed in the upper slope of the eucalyptus plantations may be linked to erosion-induced nutrient loss and reduced organic matter input. Eucalyptus plantations are often associated with lower soil fertility owing to their susceptibility and the possibility of easy downward leaching by runoff from the upper slope of eucalyptus plantations, as well as the association of biological accumulation with the biological activity of plant residues from the upper slope and deposition in the lower slope of the natural forest. This is in line with the findings of Tamene et al. (2020), who reported that deforestation, leaching, limited recycling of dung and crop residues in the soil, and erosion have contributed to the depletion of exchangeable Ca^{+2}, Mg^{+2}, K^{+}, Na^{+}, and CEC on steep slopes of agricultural lands.

The strong positive correlation between exchangeable Ca^{2+} and cation exchange capacity (CEC) suggests that soils with higher Ca^{2+} levels tend to have greater nutrient retention capacity, which enhances soil fertility. Additionally, the positive correlation between exchangeable Ca^{2+} and soil organic matter (SOM) indicated that organic matter plays a crucial role in maintaining calcium availability. Soil organic matter (SOM) is one of the most prevalent basic cations near colloidal soil surface. The recorded exchangeable base values are believed to be insufficient to restrict crop growth and productivity. Instead, other factors such as nutrient availability and soil management practices may play a larger role (Thomas et al., 2007). Conversely, the significant negative correlation between exchangeable Ca^{2+} and sand content suggests that sandy soils, which have lower CEC and a limited ability to retain nutrients, tend to have reduced calcium levels. Similarly, the negative correlation with bulk density (BD) implies that compacted soils may restrict calcium availability, potentially owing to reduced porosity and impaired root penetration. These findings highlight the importance of maintaining organic matter content and managing soil texture to sustain soil fertility and nutrient availability.

The maximum percentage base saturation (PBS) was found beneath the upper slope of a natural forest, accounting for 72.89% of the interaction effects between land use type and slope. This is because natural forests have low H^{+} concentrations and exchangeable cation accumulations (van Der Heijden et al., 2013). The degradative effect of eucalyptus plantations on soil properties, the removal of basic exchangeable cations, and the high concentration of H^{+} all contribute to decreased PBS (Kebebew et al., 2022). The lowest mean value of PBS was found under the upper slope of eucalyptus plantations, This aligns with the reference (Selassie et al., 2015). Although there is numerical variation, the main effect of slope did not significantly affect the percent base saturation value. This suggests that the slope of eucalyptus plantations does not have a significant impact on the percent base saturation value.

5 Conclusion

Both land use change and slope gradient significantly affected the selected physicochemical properties of soils. The interaction between these factors influences soil fertility, which was categorized as low, medium, or high based on the observed values of soil fertility indicators. For instance, natural forest land use on the lower slopes exhibited the highest soil fertility, while eucalyptus plantation land use on the upper slopes showed the lowest values. To address soil degradation and promote sustainable agricultural production, integrated soil and water management practices should be implemented across diverse land use systems and slope gradients. Reducing eucalyptus plantation and replacing it with *Acacia decrunce* in watershed areas can enhance soil fertility. Furthermore, alternative land use systems should replace current cropping practices on sandy and steep slopes. Additional research is needed to explore a broader range of soil properties under diverse land uses and slope gradients to enhance generalizability. Incorporating long-term monitoring and varied land management practices would also help identify causal relationships and reduce potential biases.

Data availability statement

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

Author contributions

TE: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review and editing. YS: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review and editing. EM: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review and editing. HA: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review and editing. AG: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review and editing.

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