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Research article

Soil property and crop yield responses to variation in land use and topographic position: Case study from southern highland of Ethiopia

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ABSTRACT

Understanding soil property and crop yield responses to variations in land use and topographic gradient is vital for designing targeted soil and agronomic management practices. This study investigated the interrelationships between land use, topographic position, soil properties, and crop yield. Three replicates of three land use types - enset agroforestry, cropland (annual crop), and grazing land - were selected along a toposequence (upper, middle and lower) for the study. A total of 54 composite soil samples were collected and analyzed. Grain yield and above ground biomass were also gathered from the cropland and analyzed. Soil profile descriptions revealed notable variations in soil physical properties, including soil texture, bulk density, color, horizons, and depth among the pedons of the three topographic positions. Clay and silt fractions exhibited significant differences between land uses and topographic positions, while the sand fraction was influenced by topographic position alone. Crop and grazing lands displayed higher clay content compared to the enset field. A decreasing trend in clay fraction was observed from upper to lower topographic positions. The enset field had significantly higher soil pH, OC, TN, and K+ contents than crop field. A significantly higher available P of 16.61 mg kg^{-1} was measured from lower slope position followed by 14.08 mg kg^{-1} in middle slope. The upper slope position had the highest exchangeable acidity of 3.09 cmol(+) kg^{-1}), followed by middle slope with 2.77 cmol(+) kg^{-1}), 2.45 cmol(+) kg^{-1}) in the lower slope position. Grain yield and above ground biomass decreased from lower slope to middle slope and upper slope positions. These observed variations in soil properties and crop yield among land uses and topographic positions underscore the necessity for tailored soil management strategies and agronomic practices specific to land use types and the specific localized topographic conditions to optimize agricultural productivity.

1. Introduction

Smallholder agriculture constitute the predominant economic activity supporting livelihoods of vast majority of Africans [1]. However, poor soil management and the subsequent soil fertility decline is hampering the sustainability of smallholder agriculture,

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crucial for ensuring livelihoods [2]. In recent decades, changes to traditional practices, such as abandonment of fallows, complete removal of crop residues, use of animal manure as a source of fuel instead of for soil fertility, and sub-optimal use of fertilizer accelerated soil fertility decline [3]. These changes stem from multiple factors, such as social changes (e.g., rapid population growth), economic challenges (e.g., poverty, poor market integration and soaring input costs such as increased fertilizer prices) and institutional constraints (e.g., land property rights, fertilizer supply systems [2].

Assessing variations in soil properties and productivity across different land use types along a toposequence is crucial for identifying effective land use practices and implementing soil and agronomic management strategies that mitigating soil degradation. In Ethiopia, numerous studies have been conducted to investigate the impact of land use and management on soil properties [4–7]. These investigations consistently reveal gradients in soil fertility both between and within farms, influenced by variations in tillage intensity, on-farm tree density and arrangement, and soil management practices. Notably, there is a rapid decline in soil fertility with increased tillage intensity [4], and distance from the homestead [5,8,9].

Topography plays a vital role as a natural factor in determining gradients in soil fertility by influencing geomorphic and hydrologic processes, thereby impacting physical, chemical, and biological soil properties [10–12]. Topographic position is an important local parameter that influences the processes and intensity of soil erosion and deposition, affecting organic matter and nutrient distribution along slopes [13]. The interplay between topography, land use, and soil management can result in different patterns of soil property changes, influencing agronomic requirements and the level of applied fertilizers [11,13]. Consequently, the combined effects of land use and toposequence on soil properties and crop yield have been the focus of soil research for many decades [11–14]. For instance, Negasa et al. [11] showed an increase in soil organic carbon (SOC), soil nutrient status, and clay fraction in lower slopes compared to the upper slope in Southern Ethiopia. Similarly, Wang et al. [14] reported higher SOC levels at the lower slope than the upper slope of the Loess Plateau in China. Other studies by Amede et al. [13] and Desta et al. [15] found significantly higher soil nutrient and grain yield in footslope than middle and hillslope in Ethiopia.

This study aims to explore the combined effects of land use, soil depth and topographic position on soil properties and crop yield. The farming landscape in the stud area exhibits a complex mix of land uses and soil management practices due to diverse agro-ecology and topography. Understanding the relationship among land use, topography, soil properties, and crop yield is crucial for designing effective soil and agronomics management practices tailored to varying slope gradients. This is essential for maintaining soil health and ensuring sustainable agricultural practices. Therefore, the objective of this study was to investigate variations in soil properties under three major land use types (enset based agro-forestry, crop land and grazing land) across three landscape positions (upper, middle, and lower) in the southern highland of Ethiopia. The study also investigates the grain yield response to N fertilizer levels along toposequence, using barley as a test crop.

2. Materials and methods

2.1. Description of the study area

The study was carried out in Gedeo Zone, Bule district, in southern Ethiopia (Fig. 1a). The area spans an altitude range of 1700 and 3000 m above sea level, with geographic coordinates between 60°4′16″ and 6°23′50″N latitude and 38°16′20″ to 38°26′11″E longitude. The district covers an estimated area of 125,430 ha [16].

The climate of the area is characterized by a tepid moist and cool weather, typical of Ethiopian highland agro-ecology. The area receives rainfall from both equatorial and monsoon currents [17]. Rainfall in the area follows a bimodal pattern, with the short rainy season occurring from March to May and the main rainy season taking place from August to October [17]. The mean annual rainfall

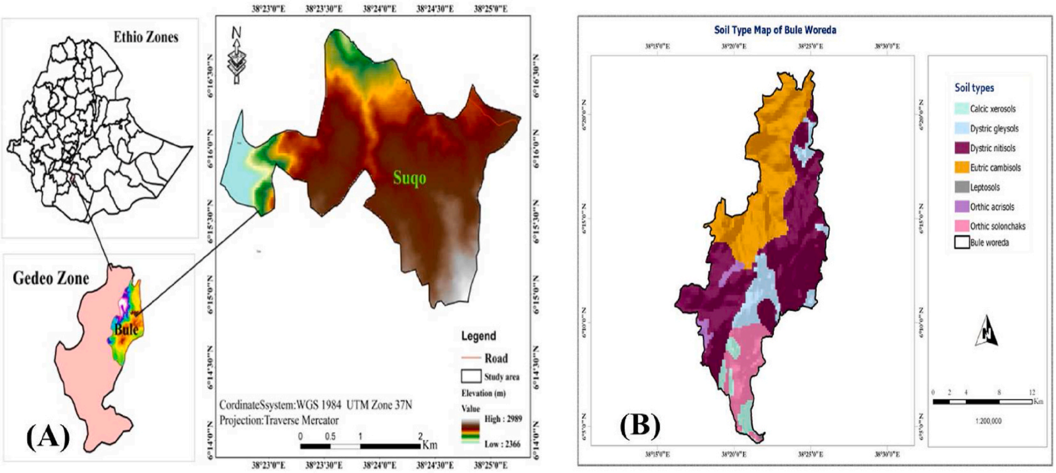

Fig. 1. (A) Study area location map in Gedeo Zone, including Kebel (Suqo) and Blue district. (B) Soil type map of Bule Woreda.

and temperature in the area range from 1200 to 1800 mm and 12–20 °C, respectively [16].

The landforms of the area exhibit diverse topographic features, including plain to a hill or steep land, undulating to rolling plateaus, scattered moderate hills, dissected side slopes, and river gorges [17]. This diversity has resulted in a wide variety of soil types. The major soil types of the Gedeo Zone include Dystric Nitisols, Eutric Cambisols, Calcic Xerosols, Dystric Gleysols, Leptosols, Orthic Acrisols and Orthic Solonchaks (Fig. 1b). The current study was conducted on Dystric Nitisols, which appear to have originated from unconsolidated sedimentary rock (field observation). The dominant soil textural class of the surface layer is clay loam in the upper and middle slope positions and clay in the lower slope position (Table 1).

Mixed farming system that integrates crops, livestock, and trees is the dominant farming practice in the area. Out of the total area of the study district, perennial crops cover 11,876 ha (46 %), annual crops cover 10,115 ha (39 %), forests cover 1855 ha (7 %), and grazing land cover 459 ha (1.8 %) [17]. Annual crops grown in the area include barley, wheat, beans, peas and potato, and a perennial crop enset (*Ensete ventricosum*) is also widely cultivated. Enset is a perennial and herbaceous flowering plant in the banana family, Musaceae, and one of the staple food crops used by about 20 million people in southern and southwestern Ethiopia [18].

In the Gedeo Zone, the traditional multi-story agro-forestry system is the dominant land use [19]. The upper story is occupied by a mixture of tree species, while the middle story is occupied by enset and coffee, the lower story comprises various annual crops and tubers (root crop) The composition of plant species, density, and vertical stratification of the agro-forestry system in Gedeo vary with altitudinal gradients [19]. For instance, in the upper altitude, enset is planted alone with sparsely retained native trees. In the middle altitude, enset is planted in combination with coffee and native trees. At lower altitudes, coffee is integrated with fruit trees. Similarly, management of the agro-forestry system varies based on proximity to homestead and crop importance [19]. Enset fields, often located near homestead areas, receive various organic fertilizer inputs such as manure, compost, and other household wastes, but seldom receive inorganic fertilizers. Annual crops are cultivated in outlying farms, situated farther from homesteads, and are fertilized with inorganic fertilizer.

2.2. Soil sampling and laboratory analysis

The study landscape was divided into three distinct landscape categories: lower slope (0–5 %), middle slope (5–15 %), and upper slope (>15 %), following the approach by Amede et al. [13]. Three soil pedons, each representing one of the landscape positions, were opened and characterized in-situ using field FAO soil description guidelines [20]. Soil color was identified using Munsell chart, while physical characteristics such as textural class and bulk density were described using feel and core methods, respectively.

To investigate the influence of land use types on soil properties, three major land use types - enset field (a perennial crop), cropland (annual crop), and grazing lands were selected, with each practiced within each landscape position. Each landuse type was replicated three times per topographic position. The replicates were located nearby each other on similar soil types and under similar climatic conditions (rainfall and temperature) but differed in their relative landscape positions, and/or soil management practices.

On the enset field, the enset plant (*Ensete ventricosum*), a perennial and herbaceous crop, predominates. However, farmers typically cultivate a diverse array of crops, including both annuals (grains and vegetables) and perennials (such as coffee, multipurpose tree species, and shrubs) within the enset field. Moreover, Enset fields are usually situated close to homestead, hence receives the most organic matter provided by the farmers such as manure (both fresh and dry), compost, household wastes and ash, and other green manure such as enset leaf and residues.

In contrast, cropland is an area used for growing annual food crops such as barley, wheat, potatoes, beans, and peas. Inorganic fertilizers, specifically Urea for nitrogen and NPS for phosphorus, are commonly applied on croplands to supplement nutrient levels

Table 1
Morphological characteristics of soils of different landscapes at field conditions.

Slope category	Horizon	Thickness (cm)	Observation	Color				BD (g/cm3)	Textural class
				Dry		Moist			
upper	Ap	0–40		Reddish brown	5 YR 4/3	Dark reddish brown	5 YR 2.5/2	1.09	Clay loam
	AB	41–55	Shiny, not firm	Yellowish red	5 YR 4/6	Dark reddish brown	5 YR ¾	1.24	Clay loam
	Bc	56–104	Ethological discontinuity	Greenish grey	Grey1/6	Dark grey	10 YR 4/1	1.05	Silt loam
	B	105–160	Shiny, stick, plastic	Dark red	10R3/6	Dusky red	10R3/3	0.97	Clay
Middle	A1	0–90	Visible root	Dark reddish brown	5 YR 3/3	Dusky red	10R 3/3	1.26	Clay loam
	A2	91–110	No visible root	Dark reddish brown	2.5 YR 3/3	Dark reddish brown	2.5 YR 2.5/3	1.44	Clay loam
	E/Bc	111–120	white futans	Light red	10 YR 6/8	Yellowish brown	10 YR 5/6	1.4	Silty clay
Lower	A	0–70		Dark reddish brown	5 YR 3/4	Very dark greyish brown	10 YR 3/2	1.01	Clay
	E	71–105		Yellowish red	5 YR 4/6	Yellowish red	5 YR 4/6	1.27	Sandy clay
	B	106–145		Brownish yellow	10 YR 6/8	Dark yellowish brown	10 YR 4/6	1.17	Clay loam

and support crop growth. The cultivation practices employed on these fields are geared towards maximizing annual crop yields, without much attention to sustainability.

Experimental design and plot layout were established using a transect line [21]. A total of 54 composite soil samples (3 land use types, 3 replicates from 3 landscape positions (upper, middle, and lower) and 2 soil depths (0–15 cm, 15–30 cm) were collected for laboratory analysis. Additionally, an equal number of undisturbed soil samples were collected separately from each soil depth using a 5 cm diameter × 5 cm tall (98.2 cm^3) core sampler for soil bulk density and moisture content determination.

The soil samples were air-dried at room temperature, grounded to passed through a 2 mm diameter sieve size as a preparation for laboratory analysis of soil pH, available P, CEC, exchangeable cation (K^+ and Na^+), exchangeable acidity (Al^{3+} and H^+). For organic carbon and total nitrogen analysis, soil samples were ground to pass through 0.5 mm sieve size.

Standard laboratory procedures were followed for the analysis of the physicochemical properties of the collected soil samples. Laboratory analyses were carried out at the Hawassa soil testing laboratory. The soil textural fractions (clay, silt, and sand) were determined using the hydrometer method after soil dispersion with a sodium hexametaphosphate solution in the laboratory [22]. The pH values of the soil samples were measured in water and potassium chloride suspension in a 1:2.5 (soil: water ratio) potentiometrically using a glass-calomel combination electrode. Soil organic carbon (SOC%) was determined according to the Walkley and Black method [23]. Soil available phosphorus was determined using Olsen method [24]. Total Nitrogen (TN%) was determined using the Kjeldahl method [25]. Soil Cation Exchange Capacity (CEC) was determined using the ammonium acetate saturation method at pH 7.0 [21]and exchangeable cations (K^+ and Na^+) were determined by ammonium acetate extraction method using the flame photometer [21]. Exchangeable acidity (exchangeable H^+ and Al^{+3}) was determined by extraction with 1 N KCl followed by titration using the Mehlich-3 method.

2.3. Crop yield study

The effects of landscape position and nitrogen rate (N rate) on crop yield were studied using barley as a test crop. Lime was applied to all crop fields before sowing. The quantity of lime applied per field was calculated based on the mass of soil per 15 cm hectare-furrow-slice, soil sample density, and the exchangeable Al^{+3} and H^{+1} of each slope category [26]. Barley seeds were sown at a rate of 90 kg ha^{-1}, and planting took place on August 14, 2021.

For the yield study, a total of 18 crop fields were selected = incorporating two fertilizer levels (no fertilizer as a control and 100 kg ha^{-1} Urea), three landscape positions, and three replications per landscape position. Data on total above-ground biomass and grain yield were collected from an inner quadrant measuring 12 m^2 (4 m*3 m) in each replicate field. Grain yields were reported as edible grain at 12.5 % moisture content. The grain yield and biomass were quantified in kg $plot^{-1}$ and then converted to a ha^{-1} basis. The yield was adjusted to 12.5 % seed moisture content using a hand seed moisture tester instrument.

2.4. Statistical analysis

Analysis of variance (ANOVA) was performed to assess the extent of variations in the selected physical and chemical soil properties across the land use types, topographic positions, and soil depths, as well as their interaction effects. The following model (Equation (1)) was employed for the ANOVA:

$$Y_{ijk} = \mu + Ai + Bj + Ck + (A^*B)ij + (A^*C)ik + (B^*C)ik + (A^*B^*C)ijk + e\ldots\ldots \tag{1}$$

where Yijk is total observation, μ = grand mean, Ai = effect of the land use, Bj(i) is the effect of slope category, C the effects of soil depth, A*B interaction effects of land use and slope category, B*C interaction effects of slope category and soil depth, A*B*C interaction effect of land use, slope category and soil depth and eijk is the random error.

Soil parameters, including texture, moisture content (MC), BD, pH, OC, TN, available P, Exchangeable Acidity (EA), Exchangeable Potassium and CEC were analyzed using R software version 4.1.1, developed by the R Development Core Team (2010). When the ANOVA indicated a significant difference at $P \leq 0.05$), mean separation was conducted using the least significant difference (LSD) at a 5 % probability level.

3. Results and discussion

3.1. Soil morphological characteristics

The variation in soil texture, color, and horizons was evident along the toposequence. The A horizon (zone of elluvation) exhibited a clay loam texture in the upper and middle sections of the landscape, transitioning to a clay textured lower section. This difference may suggest an increased migration or transport of clay from the upper to the lower portion of the landscape.

The pedon on the upper part comprised four horizons (Ap, AB, Bc, and B), while the pedons on the middle and lower topographic positions consisted of three horizons each (A1, A2, E/Bc, and A, E, B, respectively). This variation suggests a more pronounced development of horizons on the upper side, potentially influenced by the higher amount of rainfall received. The thickness of the three pedons decreased in the sequence of upper slope (160 cm), middle slope (145 cm), and lower slope (120 cm) as outlined in (Table 1).

The A-horizon thickness, specifically, exhibited notable variation, ranging from 40 cm on the upper slope to 120 cm on the middle slope and 70 cm on the lower slope. The observed pattern in A-horizon thickness could be attributed to a combination of factors across the different sections of the slope. These factors include variations in local topography, the length and shape of the slope (concave vs. convex), and soil formation processes such as the removal of soil constituents from the A horizon and their accumulation in the B horizon.

Shiny and loose characteristics were observed in the (AB) horizon of the upper slope, with the (B) horizon displaying shiny, sticky, and plastic features. Additionally, ethological discontinuity was noted in the (BC) horizon (Table 1). Soil consistency, stickiness (i.e., the ability of a soil material to adhere to the surface), and plasticity (i.e., the capacity of the soil to be molded) constitute the B horizon of the upper slope, features that are influenced by clay migration and subsequent accumulation from the A horizon. In the Pedon of the middle slope, white futans were observed in the E/Bc horizon, somewhat mixed with A2 horizon (Table 1). The Pedon of lower slope showed an abrupt change in horizon boundary which could have resulted from deposition of soil constituents in the lower slope. The E horizon (bleached horizon) could be created due to the intensive leaching of clay.

The color of the surface layer of the three Pedons varied from reddish brown (5 YR 4/3 dry) in the upper slope to dark reddish brown (5 YR 3/3 dry) in the middle and dark reddish brown (5 YR 3/4 dry) in the lower slope (Table 1). The red color in the subsurface layer is the result of illuvial accumulation of sesquioxides (i.e., Fe oxides), which is often responsible for the reddish soil color. Similar variation in soil color was also observed across soil depth implying the influence of slope and soil depth on soil color patterns through their influence on the rate of chemical reaction, surface runoff, erosion, and deposition.

3.2. Soil physical properties

Clay fraction varied significantly by both land use ($p < 0.01$) and landscape position ($p < 0.01$) (Table 2). Significantly higher clay fraction of 61.8 % and 60.0 % were found in the soils of the cropland and grazing land, while low clay fraction of 51.4 % was recorded in soils of the enset field. Similarly, significantly higher clay fractions of 61.6 and 59.9 % were measured in upper and middle landscape positions, while a lower clay fraction of 51.7 % was measured in lower landscape position.

This finding aligns with the work of [27], who reported higher clay contents in cropland than other land uses in Southern Ethiopia. The higher clay content in cropland may be attributed to the effect of tillage, while the higher clay content in grazing land could be linked to a permanent grass cover, which may enhance accumulation by preventing loss of fine clay fraction. Moreover, prolonged tillage over the years can increase clay content in the plow layer though enhanced weathering process. Moreover, tillage shears and pulverizes the soil, modifying soil conditions such as moisture, aeration, and temperature regimes, thereby affecting the rate of chemical reactions [28,29]. The observed increase in clay fraction from upper to lower topographic position agrees with the study of [30]. The presence of higher clay fraction in the lower slope position could be the result of clay migration from upper and middle slope and deposition on the lower slope [28,29,31].

Silt fraction varied significantly by land use ($p < 0.01$) but not by landscape position and soil depth (Table 2). A significantly higher silt fraction of 29.9 % was found in the soil of the enset field followed by the soil of the cropland (23.3 %) and in the soil of the grazing land (21.9 %). Additionally, sand fraction varied significantly by landscape position ($p < 0.000$) (Table 2) but not by land use, soil depth, and their interaction effects. The upper landscape position exhibited a significantly higher sand fraction of 21.7 %, followed by 15.9 % in the middle and 14.1 % in the lower position (Table 2).

Both field and lab data consistently indicate the dominance of clay fraction in the lower slope position leaving coarser fraction to accumulate in the upper slope position (Tables 1 and 2). The observed higher sand fraction in upper slope may be attributed to the

Table 2
Effects of land use, landscape position and soil depth on soil physical properties.

Source of variation	BD	MC%	Soil Texture		
			Clay	Silt	Sand
Land use types					
Enset Field	0.94	30.5a	51.39a	29.4a	18.67
Crop land	1.03	30.06a	61.78b	23.3b	14.89
Grazing land	0.99	33.73 b	60.00b	21.89b	18.11
Significance level	**NS**	***	***	***	**NS**
LSD (0.05)	**0.21**	**7.33**	**6.14**	**3.4**	**4.41**
SC(Slope category)					
Upper slope	0.97	30.36	51.67b	26.67	21.7b
Middle slope	1.00	31.55	59.89a	24.22	15.9a
Lower slope	0.99	31.84	61.61a	24.28	14.1a
Significance level	**NS**	**NS**	***	**NS**	***
LSD (0.05)	**0.31**	**7.33**	**6.14**	**3.46**	**4.41**
Soil depth					
0–20 cm	1.07a	31.6	55.85	25.8	18.3
20–40 cm	0.91b	30.85	59.59	24.29	**16.1**
Significance level	***	**NS**	**NS**	**NS**	**NS**
LSD (0.05)	**0.25**	**5.99**	**5.01**	**2.82**	**3.6**
CV (%)	11.29	8.39	15.85	20.4	37.8

SC= Slope Category (upper slope (15–30 %), middle slope (5–15 %) and lower slope (1–5%), LU = Land Use types (enset field, cultivated land and grazing land).

residual accumulation of coarser particles, while fine particles are removed from steeper slopes and deposited at the lower slope positions. These findings align with previous studies [30,31] that reported an increasing trend of sand particles with steeper slope gradients in Ethiopia. In summary, despite soil texture being an inherent characteristic, both field and lab results for textural fractions clearly demonstrate variations in distribution among slope gradients and land use types (Tables 1 and 2).

Soil bulk density varied significantly between soil depths (Table 2) but not between land uses, landscape positions and their interaction effects. A significantly higher bulk density of 1.07 gm/cm^3 was measured in the subsurface soil layer of 20–40 cm, which could be associated with underlying soil weight and decreases in organic matter content increasing depth (Table 2). The soil bulk density of the top horizon of the three pedons ranged from 1.26 g/cm3 on the middle slope to 1.01 g/cm3 in lower slope g/cm3 (Table 1). The lower bulk density in the lower slope position may be linked to a higher organic carbon (OC) content, resulting in a loose and porous soil structure. Except for the middle slope, the observed bulk density values are consistently below the critical threshold of 1.4 g/cm3 for agricultural practices [32]. This suggests the presence of low soil compaction to restrict root penetration, which is attributed to the minimum tillage practices in the study area.

Land use and the interaction of land use and soil depth had significant impacts on gravimetric moisture contents (Table 2). A significantly higher gravimetric moisture content of 33.73 % was found from grazing land followed by cropland and enset field indicating the importance of grass cover for conserving soil moisture contents.

3.3. Soil chemical properties

3.3.1. Soil reaction, exchangeable Acidity and cation exchange capacity

The soil pH varied significantly between land uses but not among the landscape position and their interaction effects (Table 3). The highest pH value of 5.9 was measured from the soils of the enset field, while the pH values of 4.7 and 4.8 were recorded from the soils of crop and grazing lands, respectively (Table 3). The observed higher soil pH in enset field soils could be linked to its location and soil management. Enset field is often situated close to homesteads, hence receive high organic matter such as household wastes, cow dung, wood ash, and its own crop residues. These inputs on the long run causes increased concentrations of exchangeable bases (Ca^{2+}, Mg^{2+}, Na^{+} and K^{+}), which in turn increases soil pH. Similar studies reported high concentrations of Ca^{2+}, Mg^{2+}, and K^{+} and correspondingly high pH under enset system compared to other land uses in Ethiopia [5,7,11].

On the contrary, the observed low soil pH in soils of the cropland could be associated with use of inorganic fertilizers such as Urea, DAP and NPS, which over time cause soil acidification. The poor soil conservation practices in outer farm also could contribute to increased loss of basic cation through erosion, continuous crop harvest, and from leaching [5,11]. Particularly, basic cations mainly Ca^{++}, Mg^{++}, and K^{+} could be removed from croplands through leaching leaving behind residual hydrogen ions that increase soil pH [11,33]. Frequent cultivation may also result in more rapid decomposition of organic matter and weakening of soil structure, which over time cause lowering in soil pH regardless of slope position [34].

Other studies [e.g., [3,11,28,35]] reported similar lower pH values in soils of cropland than agro-forestry in Central and Southern Ethiopia. Another study from Nigeria [36] also reported similar lower soil pH from continuously cultivated cropland compared to other land uses. There are also studies [e.g., 10] that reported higher pH values in soil of cropland than grazing land, findings that are contrary to this study. The lower soil pH in the soils of grazing land could be linked to the intrinsic nature of land allocated for grazing. Farmers often allocate degraded land, which are not suitable for crop production, as grazing land.

Although the effects landscape position on soil pH was not significant, higher pH values of 5.61 was recorded on the lower landscape position (Table 3). This could be attributed to the accumulation of basic cation and soil organic matter down slope [31].

Exchangeable acidity (EA) was significantly affected by land use ($p = 0.001$), landscapes position ($p = 0.05$), the interaction of land use and landscape position (Fig. 2a), but not by soil depth (Table 3, Fig. 2). The soil of the enset field had significantly lower EA values

Table 3
Effects of land use slope categories, and soil depth on soil chemical properties.

Source of variation	pH	Avail. P mg/kg	OC (%)	TN (%)	EA (cmol(+) kg^{-1})	K^{+} (cmol(+) kg^{-1})	CEC (cmol(+) kg^{-1})
Land use types							
Enset field	5.94a	14.83	2.16a	0.14a	0.73b	0.44	31.44
Cropland	4.7b	14.11	1.61b	0.1b	3.83a	0.41	31.83
Grazing land	4.8b	11.41	1.64b	0.1b	3.73a	0.3	31.83
Significance level	***	NS	***	***	***	NS	NS
LSD (0.05)	0.21	7.33	0.23	0.014	1.72	0.43	3.53
Slope category							
Upper slope	4.5a	9.68a	1.75	0.11	3.09 a	33	30.72
Middle slope	4.8a	14.08 ab	1.76	0.11	2.77 ab	0.39	31.56
Lower slope	5.61b	16.61b	1.9	0.12	2.45b	0.39	32.17
Significance level	**	*	NS	NS	*	NS	NS
LSD (0.05)	0.31	7.33	0.23	0.01	1.72	0.14	3.53
Soil depth							
0–20 cm	5.51	16.78a	1.88	0.12	2.62	0.36	31.74
20–40 cm	4.9	10.12b	1.73	0.11	2.9	0.41	31.22
Significance level	NS	*	NS	NS	NS	NS	NS
LSD (0.05)	0.25	5.99	0.19	0.01	1.4	0.11	2.88
CV (%)	8.36	8.04	19.07	18.55	9.1	5.38	16.55

of 0.73 0.73 cmol(+) kg^{-1}, while the soil of the cropland and grazing land had EA values of 3.83 and 3.73 cmol(+) kg^{-1}, respectively (Table 3). The observed low EA in the enset system may be attributed to its location, and soil management practices. Due to its proximity to homesteads, the enset field receives relatively a large quantity of organic matter inputs such as manure (dry and fresh), and household wastes, which could increase the buffering capacity of the soil [7]. The soil pH and EA of the crop and grazing lands are below the optimum range for acid sensitive crops and pasture and require soil acidity amendment for improving their productivity.

Furthermore, lower landscape positions exhibited considerably higher pH levels of 5.61 and lower exchangeable acidity of 2.45 cmol/kg. Conversely, upper and middle landscape positions displayed lower soil pH values of 4.5 and 4.8, along with higher exchangeable acidity measurements of 3.09 and 2.77 cmol per kg, respectively (Table 3). This data indicates a clear pattern of increasing soil pH and a simultaneous decrease in exchangeable acidity as slope gradients decrease, suggesting the accumulation of soil constituents in the foot slope. These findings align with previous studies [11,12,30].

Cation exchange capacity (CEC) did not vary significantly between land uses, landscape positions, soil depth and their interaction effects (Table 3). In terms of absolute value, relatively higher CEC was measured in the soil of the grazing land followed by the soil of the enset field and cropland, respectively. The observed insignificant difference in CEC goes well with the finding of [7,30] who found an insignificant difference in CEC between land use and slope and their interaction in Ethiopia. The CEC showed an increasing trend with a decreasing slope, where a higher CEC of 32.17 cmol(+) kg^{-1} was found in the lower slope followed by the middle slope (31.56 cmol(+) kg^{-1}), while a lower CEC of 30.72 cmol(+) kg^{-1} was found in the upper slope (Table 3). The findings of this study agreed with the finding of [12] who found higher CEC in lower slope than middle and upper slope which could be due to the accumulation of higher organic matter and clay contents in down slope, and this in turn increased buffering capacity which is important for agricultural soil.

3.3.2. Soil organic carbon(SOC) and total Nitrogen(TN)

Land use significantly influenced soil organic carbon (SOC), whereas the effect of landscape position and the interaction effects of land use and landscape position on SOC were not found to be significant. The mean SOC content exhibited variation in the order of enset field > grazing land > cropland (Table 3), aligning with the findings from several prior studies [e.g., 6, 11, 7]. The higher SOC in enset-based agroforestry can be attributed to the unique characteristics of the enset crop and selective addition of large quantity of organic matter due to its proximity to homestead [37]. Moreover, the enset crop produces a high quantity of organic litter and fine roots that are little removed from the field compared to crop residues that are nearly completely collected for other uses such as for animal feed and biomass fuel [19]. Crop residues left on croplands are also burnt every year to protect the fields from weeds as well as insects, causing low accumulation of organic matter. According to Bouajila and Sanaa [38] application of manure and household wastes altered soil chemical properties mainly soil organic carbon and total nitrogen contents. Lupwayi et al. [39] has also characterized the chemical composition of livestock manure and found higher contents of total N, available P and K^{+}.

Furthermore, enset fields are not plowed as frequently as that of annual crop fields. There is also low erosion due to the permanent and high soil cover from the funnel-shaped leaf of the enset crop resulting in a higher amount of SOC in the enset field. Several other studies [5,7,11,12] also reported improved soil chemical properties under the enset based garden in Central and Southern Ethiopia. On the contrary, the observed lower organic carbon contents in cropland as compared to enset field and grazing land could be due to low organic matter inputs and intensive tillage, enhance oxidation and further contribute loss of OC contents. It is obvious that long-year cultivation could reduce soil OM and nutrient content as it facilitates the breakdown of soil aggregates which in turn reduces soil cohesion [4,4]. An intermediate value of SOC was observed in soils under grazing land use types of the study area, which is similar to the finding of Dessalegn et al. [30], who found higher OC in grazing land than in cropland and forest land in Ethiopia. The relatively improved OC in grazing land could be caused due to the dominance of roots, humus, and associated soil organisms in pastureland [11].

Total nitrogen content showed a significant difference ($p = 0.000$) among the land uses but not among slope positions and soil depths (Table 3). A higher mean value of 0.14 % was recorded in the enset field followed by an equal amount of 0.1 % in both grazing

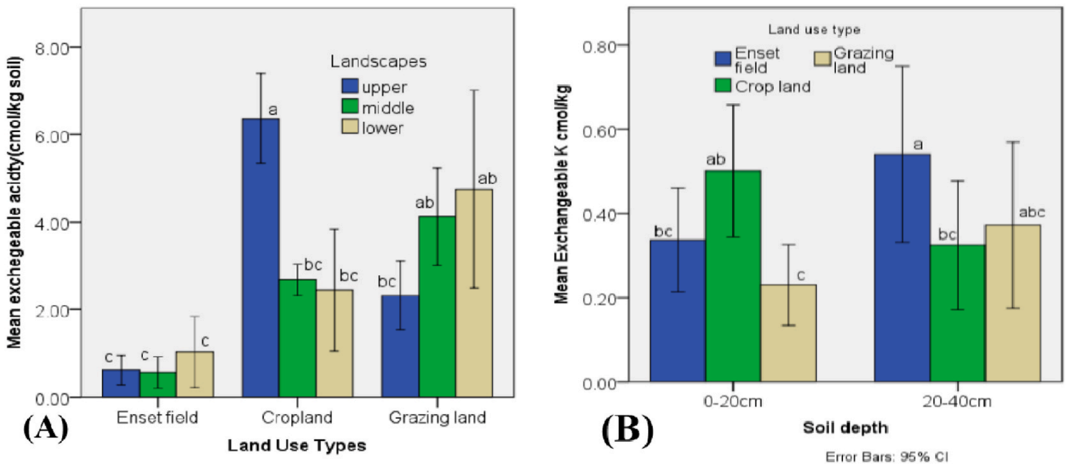

Fig. 2. (A) Effects of the interaction between land use and soil depth on exchangeable acidity. (B) Effects of slope category and land use on K+.

and crop lands (Table 3). This result goes well with other similar studies [6,11], [34], who reported significantly higher total N under agro-forestry land use compared to crop and grazing lands in Central and Southern Ethiopia. In contrast, the observed low OC and nutrient contents in cropland could be attributed to leaching, limited recycling of crop residues, suboptimal use of inorganic fertilizers, continuous cropping, and soil erosion [4,5], [40].

Although the difference was not significant, relatively higher OC and TN were measured in the soils of the lower slope, which goes well with other research findings [11,12]. The observed higher OC in lower landscape than those in the middle and upper landscapes positions could be due to higher water availability (Table 2) and deposition of soil constitutes (e.g. clay, OC, nutrient), which in turn resulted in more biomass production and more incorporation of organic matter. The findings of this study agreed with the findings of [13,15] who found higher organic carbon and nutrient in soils at foot slopes and middle slope compared to hill slope in Ethiopia.

3.4. Available P and exchangeable K

Land use did not significantly affect available P, but available P was significantly affected by landscapes positions and soil depth (Table 3). However, in terms of absolute values enset field and cropland had higher available P of 14.83 mg kg^{-1} followed by 14.11 mg kg^{-1} in crop land, while a lower available P of 11.41 mg kg^{-1} was found in grazing land (Table 3). The observed higher available P in the enset field as compared to grazing land could be attributed to the application of organic matter inputs such as manure, household waste, and ash. While the observed higher available P in cropland, could be associated with the application of P-containing fertilizers such as NPS and DAP on croplands. Farmers in the study area use inorganic fertilizers such as NPS at rate of 100 kg per ha and Urea at rate of 100 kg per ha for growing cereal crop. While the lower available P in grazing land could be caused due to the history of grazing land as it is converted from degraded cereal land devoid of crop production due to low P as consequence of soils acidity.

A significantly higher available P contents of 16.61 mg kg^{-1} was found in the lower slope followed by 14.08 mg kg^{-1} in the middle slope and 9.68 mg kg^{-1} in the upper slope. This finding deviates from the findings of Dori et al. [12], who reported higher available P in the order of upper slope > lower slope > middle slope in agro-forestry of Southern Ethiopia. The results are in consonance with the earlier studies [12,13] who found higher values of available P from the foot slope position compared to middle slope and upper slope positions. The higher available P content in the lower slope positions could be associated with lower erosion and higher deposition and low P fixation due to their relatively higher pH contents and buffering capacity (Table 3). The observed lower available P in the upper and middle slope positions could be caused due to the higher EA, which enhances the fixation of P. This finding is in line with the finding of several studies [[4,30,41]] who reported insignificant effects of land use on available P in Ethiopia. Available P was significantly influenced by soil depth (Table 3). A significantly higher available P of 16.61 mg kg^{-1} was present in surface soil (0–20 cm) compared to 10.12 mg kg^{-1} available P found in the subsurface layer (20–40 cm) and which could be associated with higher organic inputs in surface layer.

Exchangeable K^+ did not show significant ($p = 0.05$) variation among land use types, soil depth, and slope however, the combination of land use and soil depth significantly affected soil K^+. Relatively higher concentrations of 0.44 cmol/kg K^+ were found in enset field land while the lowest K+ value of 0.3 cmol/kg soil was found in grazing land (Table 3). This finding is different from the finding of [30] who found a higher exchangeable base (K^+, Ca^{++}, and Mg^{++}) in grassland than in forest and cultivated land in Ethiopia. This finding is in agreement with the findings of [7], who reported higher K^+ in enset fields than cropland grazing land in Central Ethiopia. The observed higher K^+ in the enset field could be attributed to the addition of organic inputs such as manure and crop resides and wood ash. In the highlands of Ethiopia, many farmers fertilize their enset gardens by applying household waste such as wood ash. According to Erich [42] the nutrient composition of wood ash, mainly P, K are comparable with that of conventional fertilizers.

The interaction of land use with soil depth significantly affected soil K^+ content (Fig. 2b). A higher K^+ value of 0.54 cmol/kg was found from a combination of enset at subsurface soil (20–40 cm), while interaction of grazing land and soil depth (0–20 cm) gave the lowest K^+ value of 0.23 cmol/kg soil (Fig. 2b). On the other hand, the interaction of cropland at upper slope had significantly higher EA of 6.36 cmol/kg soil than other (Fig. 2 a). While the lowest EA of 0.61 and 0.56 cmol/kg soils were measured from enset land at middle and upper slope, respectively (Fig. 2a). The observed significantly lower EA in enset field indicated the potential of organic soil amendments such as manure for mitigating acidic soil [43].

3.5. Effects on barley grain yield and above ground biomass

Barley yield and above ground biomass were significantly affected by landscape position ($p = 0.000$), by N level ($p = 0.05$) and their interactions ($p = 0.05$) (Table 4, Fig. 3a and b). Significantly higher barley yield of 5194.5 kg ha^{-1} was recording in the lower landscape position, followed by 3020.8 kg ha^{-1} in the middle landscape position and 2361.1kg ha^{-1} in upper slope (Table 4). The observed higher barley grain yield in the lower landscape position could be attributed to better soil properties and nutrient availability in this landscape position, as shown in the above results sections (Tables 2 and 3).

Similarly, a significantly higher above ground barley biomass of 14575 kg ha^{-1} was obtained from the lower landscape position, followed by 6875 kg ha^{-1} in the middle landscape position and 5520.84 kg ha^{-1} in the upper (Table 4). The lower landscape position yielded 72 % and 83 % more barley than the middle and upper landscape positions, respectively. This finding aligns with the results of [13,15], who observed higher grain yield in foot slopes compared to upslopes. The lower crop response in upslope areas could be attributed to low soil organic carbon and nutrient levels, as well as soil pH, coupled with higher exchangeable acidity and Al^{3+} (Table 3).

The interaction between landscape positions and N levels significantly affected barley grain yield and above ground biomass (Fig. 3 a & b). A relatively higher barley grain yield was obtained without Urea application (control plot) compared to 100 kg per ha

Table 4
Effects of landscape position and level of N(Urea) on barley yield and biomass.

Source of variation	Grain yield kg/ha	Above ground biomass kg/ha
Slope category		
Upper slope	2361.11^{b}	5520.84^{b}
Middle slope	3020.84^{b}	6875.00^{b}
Lower slope	5194.45^{a}	14575.00^{a}
Significance level	***	***
LSD (0.05)	**707.09**	**2064**
0 kg of urea per ha	3199.08^{a}	8378.70^{a}
100 kg urea per ha	3851.85^{b}	9601.85^{a}
Significance level	***	**NS**
LSD (0.05)	**577.3**	**1685.25**
CV (%)	14.2	16.25

where*** = 0.001 ** = 0.01 * = 0.05 NS not significant.

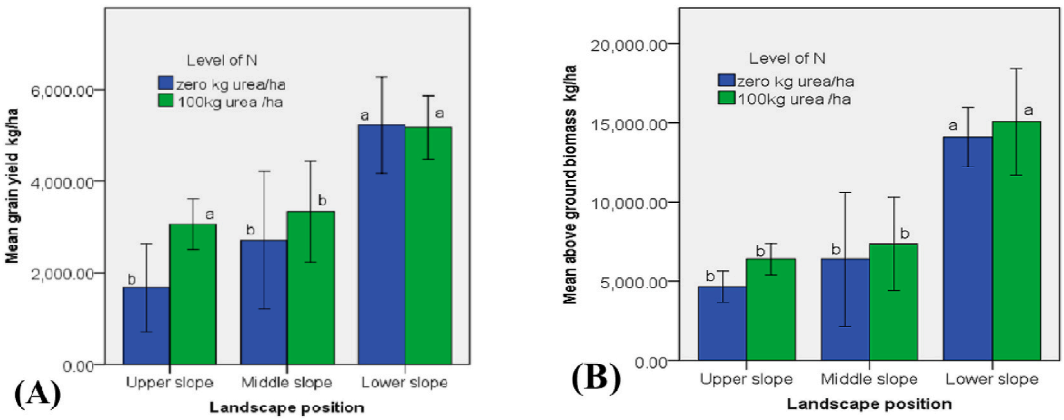

Fig. 3. (A) Effects of landscape position and N fertilizers on barley yield. (B) Effects of landscape position and N fertilizers on barley biomass.

application in the lower slope, indicating that crop fields located at lower elevations can yield better without the use of commercial fertilizers. This finding is particularly beneficial for resource-poor farmers who may struggle with the soaring costs of fertilizers. The positive response of barley yield in lower landscape position aligns with the observations of [13,15], who reported higher grain yields in footslope areas with optimal fertilizer application compared to hillslope areas in Ethiopia.

4. Conclusion

The findings of this study indicate that land use, topographic position, and soil depth affect both physical and chemical soil properties significantly. Soil pH, SOC and TN increased, while EA decreased in the soils of enset based agroforestry more than the other two land uses across the different topographic positions. Cropland consistently showed poorer soil condition, while grazing land displayed intermediate soil condition. In terms of topographic position, the lower slope exhibited better soil condition, such as available phosphorus, SOC, TN and lower pH and EA, while the upper slope was the opposite in most soil properties.

The results of the study underscore the complex interplay of land use, topography, and soil depth in shaping the physical and chemical characteristics of the soil. This further suggests the importance of careful selection of land use and management practices along toposequence for ensuring the sustainability of soil productivity. Future soil management strategies should focus on improving the soil fertility of continuously cultivated land by implementing soil conservation measures. Moreover, amending soil acidity in cereal land will be essential for enhancing the sustainability of crop production. In order to improve the long-term viability of crop production, it is crucial to address the acidity of the soil in cereal fields. However, since the pH levels and concentrations of exchangeable acidity, H^{+} and A^{l3+}, exhibit considerable variations across different positions in the landscape, it is important to apply lime at rates specific to the slope or targeted to specific landscapes. Significantly higher barley yield and biomass was found in lower slope followed by middle slope and upper indicating landscapes position dictates the priority of fertilizers. Therefore, future recommendation of fertilizers rate should consider the landscape positions to optimize the environmental, economics and agronomics advantages.

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Data availability

The data used to support the findings of this study are available from the corresponding author upon request.

CRediT authorship contribution statement

Getahun Haile: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **China Gebru:** Data curation. **Mulugeta Lemenih:** Writing – review & editing. **Getachew Agegnehu:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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