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Original Research

The Effects of Land Use Types on Soil Quality Indicators: Analysis of the Upper Gibe Watershed in Western Ethiopia

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Abstract

Land use changes affect soil quality, especially in environmentally vulnerable locations like Ethiopia's Western Highlands' Upper Gibe Watershed. Forest, pasture, and agricultural land were assessed for soil quality indicators in this study. In 60 composite soil samples (0–20 cm), particle size distribution, permeability, pH, organic carbon, total ash, accessible phosphorus, and cationic exchange capacity were studied. Significant statistical differences ($p < 0.05$) were seen between land use types. Forest land had the most organic carbon (3.71%), total nitrogen (0.32%), available phosphorus (14.93 mg/kg), and cationic exchange capacity (38.1 cmol(+)/kg), indicating better soil health. In contrast, cultivated land has lower organic carbon (1.65%), total nitrogen (0.11%), and cationic exchange capacity (21.6% cmol(+)/kg) and higher soil bulk density (1.23 g/cm³), indicating depletion in soil quality. Most likely due to excessive tillage and a lack of organic inputs, forest land has moderate values but a higher bulk density (1.23 g/cm³). Soil pH was between 5.8 and 6.7 and was somewhat acidic to neutral. The study emphasizes the need for improved soil management practices tailored to certain land use types to improve soil sustainability.

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INTRODUCTION

Land use/cover (LULC) changes affect biogeochemistry, hydrology, and climate. Liu et al. (2024) state that elucidating the local to regional impact of LULC on soil quality is challenging and requires generalizations. Agricultural and environmental functions depend on soil. Ethiopian soil quality has altered due to population increase, deforestation, and agriculture. Much land use change in Western Ethiopia's Upper Gibe watershed has damaged the soil. This study's assessment of land use patterns' impact on soil quality indicators advises better land and soil management. The Upper Gibe watershed, an important agricultural and ecological area, has seen considerable LULC changes in recent decades due to population growth, FAO stated in 2015. Deforestation, development, population growth, and agricultural expansion have altered LULC in Western Ethiopia's Upper Gibe watershed, an ecologically and agriculturally important region.

Understanding how land uses affect soil quality indicators improves agricultural sustainability and rehabs damaged land (Gashaw et al., 2018). Soil quality is increasingly important to ecosystem health and land production, but little is known about how Upper Gibe watershed land use practices affect soil attributes. The land use changes reduce soil fertility, erosion, and quality by changing physical, chemical, and biological qualities. Understanding how farming, grazing, forests, and settlements affect soil quality indicators helps restore damaged soils and sustain agriculture (Wolde et al., 2023). According to Woldeamlak et al. (2014), soil quality protects water and air quality, supports human health and housing, and increases plant and animal productivity in managed ecosystems. Assessing physical, chemical, and biological features of superior soils can help grow nutrient-dense food and fiber (Yimer et al., 2008). Food and fiber production enhances soil and water quality and maintains natural ecosystems (Koudahe et al., 2022). Sustainable land management depends on soil quality, which impacts ecosystem health, environmental stability, and agricultural output. The Upper Gibe Watershed in western Ethiopia is an agricultural and natural resource-rich area that requires land use and soil quality knowledge.

Statement of the Problem

Ethiopia's watershed highlands are prone to erosion, nitrogen depletion, and organic matter loss due to steep slopes and changeable weather. Soil quality indexes alter with deforestation, agricultural expansion, and population growth. When farmland becomes woods, organic matter decreases. Poor soil structure and nutrients. Masha et al. (2023) say excessive tillage and overgrazing degrade soil and impair land tolerance to environmental stressors. Location-specific soil conservation and land management initiatives are challenging without data. If locals and decision-makers don't understand how land use affects soil quality, they may deteriorate it. This study evaluates Western Ethiopia's Upper Gibe watershed soil quality indicators by land use.

Research Questions

1. How do forests, farms, and grazing affect soil physical and chemical qualities in Western Ethiopia?
2. Which land use best protects regional soil quality indicators in the upper Gibe watershed?
3. How much have land use changes affected upper Gibe watershed soil fertility?

MATERIAL AND METHODS

Geographical Environment of the Study Area

The investigation took place in the Bako Tibe District, Upper Gibe. The Upper Gibe watershed in Ethiopia was chosen for the study because of its diversified land-use patterns and their effects on hydrology and agriculture. Near the main route to Nekemte, Ethiopia, it is 250 kilometers from Addis Ababa (Finfine) and 125 kilometers from Ambo. Its location is 8° 55 18" and 9° 14 13 N and 37° 01 54" and 37° 17 07" E (Figure 1). Its 1600–2800-meter height and subtropical climate provide it with distinct wet and dry seasons. Most land is used for forests, grazing, farming, and settlements. Most soils are Nitisols and Vertisols, in variable degrees of degradation. Of the 63,988.17 ha in Bako Tibe District, 42,916.28 hectares (67.07%) are farmable. Grazing land is 980.2 ha (1.53%), forest land is 5207.97 ha (8.14%), bush and shrub land is 9581.04 ha (14.97%), and wetland is 3410.83 ha (5.33%) (EGII, 2019).

The climate of the study area is warm and humid, and the region has unimodal precipitation distribution. The Bureau of Agriculture and Rural Development (BARC, 2019) reports 52.2% relative humidity and 190.84 mm of annual rainfall, with 80% falling between June and September. Figure 2 shows that the mean minimum and maximum temperatures are 13.4°C and 28.77°C, respectively. Yet the average temperature is 13.4°C, which seems paradoxical and needs verification. Temperature, precipitation, vegetation cover, and height divide the region into lowland (51%), midland (37%), and highland (12%).

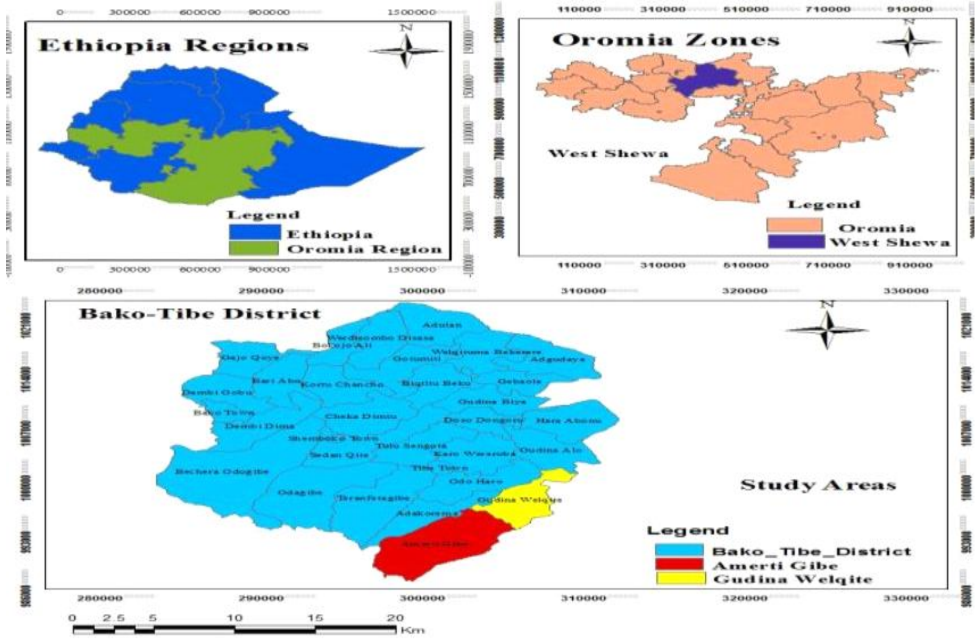

Figure 1. *Location map of the study area*

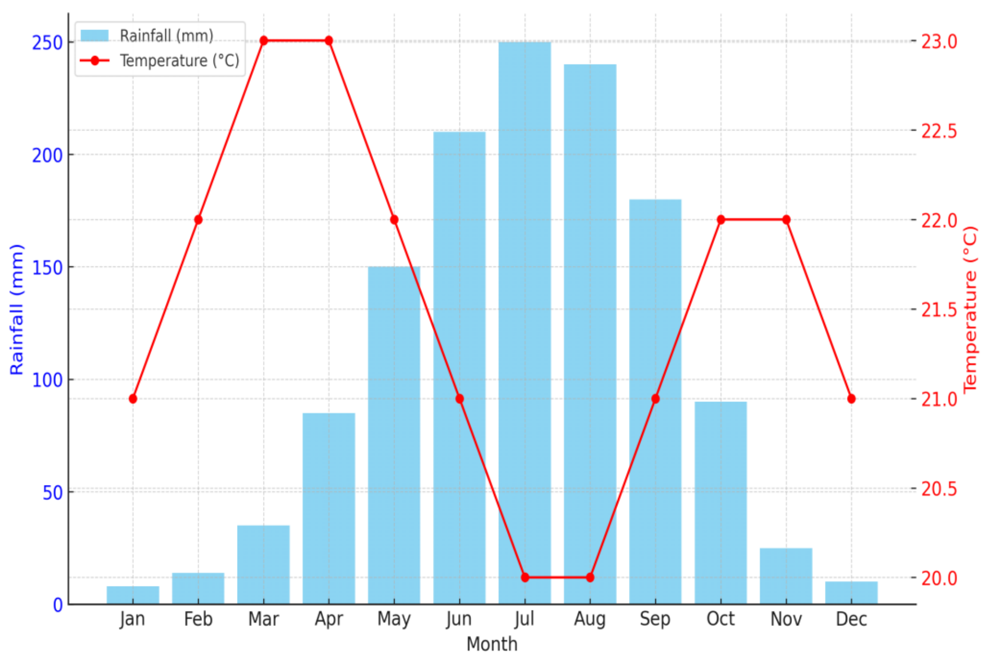

Figure 2. *Mean monthly rainfall and mean monthly minimum and maximum temperatures of the study area.*

Land Use and Soil Characteristics of the Study Area

Most people in the research region work in agriculture. The Bureau of Agriculture and Rural Development (2014) reports that reddish-brown Nitisols are the most common soil type in the watershed, followed by black cotton (Vertisols, 15%) and brown (25%). To assess land-use trends, a complete categorization was done. This approach combined high-resolution satellite images with GPS ground-truthing data and assessed it using GIS software. Following classification, the watershed's most common land-use types are listed. The four primary land use types in the research region were determined via ground truthing and satellite imagery. Forests cover 40% of the landmass, the most. This includes any tree-covered area that meets national greenhouse gas inventory guidelines. 35% of the land is used for food and fiber, whether permanent or temporary. Most of the world's 15% grazing land is rangelands and pastures. Last, 10% is fallow land, which is intentionally not farmed to improve soil fertility.

Design of the Experiment and Soil Sampling

Different land use types were evaluated utilizing a randomized complete block design (RCBD) on soil physico-chemical properties at two representative sites. Forest, pasture, and cultivated fields each had three replications in the experimental pattern. Before site selection, a visual field survey and reconnaissance observation provided land use, topographical, slope gradient, and vegetation cover information. Climate and slope were similar, and the objective land use categories were prevalent, or soil erosion or degradation was observable at the research sites. Within each land use category, zigzag soil samples were taken at 0-20 cm deep to guarantee spatial representativeness.

Three duplicates of 14 composite soil samples were taken from each treatment plot. No organic materials, stones, gravel, or plant roots were found in the soil samples. The samples were air-dried, crushed, and sieved through a 2 mm mesh for general physicochemical research. SOC and total nitrogen were measured by passing subsamples through a 0.5 mm mesh screen. About 1 kilogram of each composite soil sample was tagged, packaged, and transported to the Bako Agricultural Research Center Soil Laboratory for analysis.

Analysis of Soil Physical Properties

To assess soil physical properties, undisturbed and disturbed soil samples were gathered from 0-20 cm depth. A stainless-steel core sampler was used to measure bulk density, while augers collected disturbed samples for textural investigation. After hydroxide pretreatment (H_2O_2) to remove organic matter and sodium hexametaphosphate dispersion ($Na_6P_6O_{18}$), hydrometer testing assessed soil texture as described in (Brevik et al., 2022). To calculate bulk density, Carter and Gregorich (2007) oven-dried core samples at 105°C for 24 hours. The total porosity (TP) was calculated using the bulk density and assumed particle density (PD) of 2.65 g cm³.

All analyses were conducted in triplicate for each land use treatment to ensure reliability and statistical validity. Available water content (AWC) was determined using the pressure plate extraction technique. Soil moisture at field capacity (FC) and permanent wilting point (PWP) was measured at pressure potentials of –33 kPa and –1500 kPa, respectively, following the procedures outlined by Liu et al. (2024). The AWC was calculated as the difference between FC and PWP:

$$AWC=FC-PWP$$

This method provides a quantitative estimate of the plant-available water in the soil profile, which is critical for evaluating the water-holding capacity of soils under different land use types.

Analysis of Soil Chemical Properties

Soil pH was potentiometrically measured using a digital pH meter and Rowell's method. Melero et al. (2009) measured organic carbon (OC) via wet oxidation. Bremner (1960) described Kjeldahl digestion for nitrogen determination. Dai & Richter (2000) measured exchangeable acidity after 1 M KCl extraction using titration. Bray II extraction measured phosphorus. A colorimetric complex formed in soil samples with ammonium molybdate, sulfuric acid, and stannous chloride (Ayilara et al., 2020). The Chapman method assessed cation exchange. This was accomplished by extracting exchangeable bases with 1 M NH_4OAc at pH 7.0. Flame photometry measured exchangeable potassium (K+) and sodium (Na+), while atomic absorption spectrophotometry (AAS) measured exchangeable magnesium (Mg2+) and calcium (Ca2+). The percentage of base-forming cations at exchange sites was estimated by dividing total exchangeable base cations by CEC and multiplying by 100. Divide the total exchangeable base cations by the CEC and multiply by 100 to calculate the percentage of base-forming cations at exchange sites. The percentage of base-forming cations at exchange sites was estimated by dividing total exchangeable base cations by CEC and multiplying by 100. All chemical assays were done in triplicate for accuracy and reproducibility.

Statistical Analysis

In an analysis of variance (ANOVA) under the General Linear Model (GLM), soil quality metrics were dependent variables, and land use types were fixed factors. Before performing the ANOVA, we tested variance normality and homogeneity. The LSD test was used to compare means with significant differences ($p < 0.05$). SAS Institute Inc. (2008) used version 9.3 for statistical studies.

RESULTS AND DISCUSSIONS

Results

The findings showed that land management affects soil health by showing significant changes in key soil characteristics across land use categories. Soil physical qualities affect ecosystem function and land productivity. Thus, land use changes like urbanization, deforestation, and agricultural growth can alter soil qualities. The physical quality of soil depends on particle size distributions, bulk density, porosity, water-holding capacity, and structure. In this study, we examined how these metrics change under different land use regimes to better understand sustainable land management and soil protection.

Bulk Density (BD) and Soil Texture

Land use type did not significantly affect soil particle size distribution ($p > 0.05$). Clay content ranged from 28% in forestland areas to 42.5% in agricultural areas. Grazing had the most silt (17.81%), and agricultural land had the least (13.28%), whereas sand was steady (44% to 54% across all land uses). This study shows that land use does not affect watershed soil texture, laying the framework for future soil quality studies. Significant variation in bulk density ($p < 0.05$) was seen, unlike other land uses. Regular plowing and mechanical use may create soil compaction, leading to the maximum bulk density (1.28 g/cm³) on grazing land. According to Table 1, forest land had the lowest bulk density value of 1.19 g/cm³, indicating better soil structure and porosity, whereas grazing and fallow land had intermediate values of 1.23 and 1.27 g/cm³, respectively. Cultivated soils have lower bulk density and higher total porosity, with the former lowest and the latter highest near forests (51.82%). Compacted soil reduces root penetration, water retention, and aeration. The moderate bulk densities of grazing and fallow regions indicate intermediate soil structural degradation, demonstrating how land management affects soil health.

Table 1

The effects of land use change on selected Soil physical properties

	Soil Quality Parameters					
Land use types	Sand (%)	Silt (%)	Clay (%)	STC	BD (gm/cm³)	TP (%)
CL	44.16[b]	13.28[b]	42.56[b]	C	1.23[c]	51.82[c]
FL	54.00[a]	17.20[a]	28.80[a]	SCL	1.19[a]	55.09[a]
GL	45.32[b]	13.96[b]	40.82[a]	SL	1.33[b]	49.81 lb
Mean (±SE)	47.84±1.25	15.02± 1.94	37.26± 1.59		1.27± 0.04	52.24± 1.46
LSD	1.608	2.493	2.046		0.05	1.8
CV (%)	2.612	12.908	4.268		3.059	2.797
LSD (0.05)	1.313	2.036	1.67		0.041	1.535
Interaction						
LUT	**	**	**		**	**
Location	**	**	**		Ns	Ns
LU*Location	**	Ns	**		Ns	Ns

***Main effect means within a column followed by the different letter(s) were significantly different from each other at P ≤ 0.05; Coefficients of Variation = CV%; LSD = Least Significant Difference; LUT = land use types; CL = Cultivated Land; FL = Forest Land; GL = Grazing lands; BD = Bulky Density; TP = Total Porosity*

Soil pH, Soil Organic Carbon (SOC), and Total Nitrogen (TN)

The mean soil pH differed considerably between land uses ($p < 0.05$), with forest land having the highest mean pH (6.22), indicating near-neutral conditions that benefit nutrient availability. Grazing land had middle-range pH levels of 6.01 and 5.8, respectively. Cropping, basic cation loss, and leaching have increased soil acidity, as cultivated land has the lowest pH (5.55). Significant differences ($p < 0.01$) were seen in soil organic carbon (SOC) levels among land users. Forested regions had 3.71 percent soil organic carbon (SOC), grazing areas 2.89 percent, and farms 2.01 percent. Due to crop harvesting and little organic remains, agricultural regions have low SOC due to soil fertility loss. The amount of nitrogen (TN) varied significantly ($p < 0.01$) based on land usage. The highest TN content was in forests (0.32%) and the lowest in farms (0.23%). Grazing and fallow fields had mild TN at 0.25% and 0.24%, respectively. These data show that erosion and insufficient organic amendments deplete agricultural soil nutrients to the greatest extent. Soil chemical properties are summarized in Table 2.

Table 2

The effects of land use type on selected Soil chemical properties

	Soil Quality Parameters				
Land use types	pH(H_2O)	SOC (%)	SOM (%)	TN (%)	Av. P (ppm)
CL	5.55^b	2.61^b	4.49^b	0.23^b	10.50^b
FL	6.22^a	3.71^a	6.39^a	0.32^a	14.93^a
GL	6.01^a	2.90^b	5.00^b	0.25^b	11.50^b
Mean (±SE)	5.93± 0.23	3.07 ± 0.31	5.29± 0.54	0.26 ± 0.03	12.31± 2.23
CV (%)	3.96	10.18	10.21	10.24	18.09
LSD (0.05)	0.302	0.403	0.69	0.035	2.866
	Interaction				
LUT	**	**	**	**	*
Location	Ns	Ns	Ns	Ns	Ns
LU*location	Ns	Ns	Ns	Ns	**

**Main effect means within a column followed by the different letter(s) were significantly different from each other at P ≤ 0.05; Coefficients of variation=CV%;LSD = least significant difference; LUT= land use types; CL =Cultivated; FL=Forest; GL=Grazing lands; TN = Total Nitrogen; SOM =Soil Organic Matter; SOC= Soil organic Carbon; Av.P=Available Phosphorus

Available Phosphorus (AP) and Cation Exchange Capacity (CEC)

There was significant heterogeneity in available phosphorus (AP) among land use types ($p < 0.05$). Fallow land had 14.93 ppm of AP, followed by grazing land at 11.5 ppm and cultivated land at 10.5 ppm. Phosphorus fixation and nutrient loss from intensive farming without replenishment may diminish AP in farmed soils. Significant differences in cation exchange capacity (CEC) were observed among land users ($p < 0.01$). Forest land exhibited a greater nitrogen retention capacity of 35.93 cmol (+)/kg, while grazing land had 28.00. Due to decreased organic matter and clay content, cultivated land had the lowest CEC (24.31 cmol

(+)/kg). Table 3 indicates a strong correlation between soil organic content, texture, CEC, and AP. Table 3 shows a significant association between land usage and phosphorus availability, supported by analysis of variance ($p < 0.05$). The research area's average phosphorus level was medium for all land uses, per Vanlauwe et al. (2010).This highlights the need for nitrogen management for soil fertility.

Table 3

The effects of land use type on selected Soil chemical quality indicators.

	Soil Quality Indicators			
Land use types	Ex. K	Ex. Ca	Ex. Mg	CEC
CL	0.34[b]	13.83[c]	6.83[b]	24.31[b]
FL	1.317[a]	28.17[a]	12.17[a]	35.93[a]
GL	0.54[b]	20.83[b]	9.67[ab]	28.00[b]
Mean (±SE)	0.731 ± 0.26	20.94 ± 3.48	9.56 ± 2.26	29.41 ± 3.03
CV (%)	35.59	16.62	23.68	5.91
LSD (0.05)	0.274	3.657	2.377	3.179
	Interaction			
LUT	**	**	**	**
Location	Ns	Ns	Ns	**
LUT*location	Ns	Ns	Ns	**

***Main effect means within a column followed by the different letter(s) were significantly different from each other at $P \leq 0.05$; Coefficients of variation=CV%; LSD = least significant difference; LUT = land use types; CL =Cultivated; FL=Forest; GL=Grazing lands; Ex.K =Exchangeable potassium; Ex.Ca =Exchangeable Calcium; Ex.Mg=Exchangeable Magnesium CEC =cation Exchangeable capacity.*

Since grazing lands have low soil organic carbon (OC) and total nitrogen (TN), trampling and little plant cover likely limit organic matter inputs and degrade the soil. Fallow fields show modest OC and TN recovery once cropping is ceased. Table 3 reveals that fertilized soils exhibited higher Av. P values, likely due to phosphate fertilizers. These data demonstrate how land use and management dramatically affect soil nutrient dynamics.

Correlation Analysis of Land Use and Soil Quality Indicators

Table 4 shows a substantial Pearson's correlation between Upper Gibe Watershed soil quality indicators and land use types. Soil texture components displayed expected correlations: sand content was negatively linked with silt ($r = -0.56$, $p < 0.01$) and clay ($r = -0.65$, $p < 0.01$), while clay concentration was positively correlated with fertility indices such as organic carbon, total nitrogen, and CEC. Soil pH significantly correlated with organic carbon ($r = 0.52$, $p < 0.01$), total nitrogen ($r = 0.48$, $p < 0.05$), available phosphorus ($r = 0.44$, $p < 0.05$), and cation exchange capacity (CEC) ($r = 0.38$, $p < 0.05$), but negatively correlated with bulk density ($r = -0.53$, $p < 0.01$). This means that soil fertility and nutrient content improve when soil acidity lowers (higher pH).

Soil organic carbon was positively connected with total nitrogen, accessible phosphorus, and CEC ($r = 0.77$, $p < 0.01$), but negatively correlated with bulk density ($r = -0.65$, $p < 0.01$) and sand content ($r = -0.40$, $p < 0.05$). This shows that organic matter-rich soils retain nutrients and compress less. Total nitrogen correlated positively with accessible phosphorus ($r = 0.58$, $p < 0.01$) and CEC ($r = 0.63$, $p < 0.01$) and negatively with bulk density ($r = -0.60$, $p < 0.01$) and sand content ($r = -0.42$, $p < 0.05$). CEC ($r = 0.56$, $p < 0.01$) and clay content ($r = 0.41$, $p < 0.05$) significantly linked with available phosphorus, highlighting the significance of soil texture. CEC was positively correlated with clay concentration ($r = 0.60, p < 0.01$), silt ($r = 0.36, p < 0.05$), and negatively correlated with bulk density ($r = -0.61, p < 0.01$). Bulk density was inversely correlated with fertility indicators and positively associated with sand content ($r = 0.48, p < 0.05$), highlighting the impact of soil compaction and texture on soil health. The correlation results show that soil physicochemical qualities are strongly interdependent and that land use practices that maintain or improve organic matter and soil texture (especially clay content) are essential for watershed soil fertility.

Table 4

Pearson`s Correlation among selected soil physicochemical qualities of the study area

SQP	pH	SOC	TN	Av.P	CEC	BD	Sand	Silt	Clay
pH	1								
SOC (%)	.52**	1							
TN (%)	.48*	.77**	1						
Av.P	.44*	.61**	.58**	1					
CEC	.38*	.69**	.63**	.56**	1				
BD	−.53**	−.65**	−.60**	−.38*	−.61**	1			
Sand (%)	−.20	−.40*	−.42*	−.25	−.35*	.48*	1		
Silt (%)	.31*	.30	.22	.30	.36*	−.25	−.56**	1	
Clay (%)	.29	.55**	.44*	.41*	.60**	−.51**	−.65**	−.42*	1

**= significant at p <0.05; BD = Bulk Density, Po=porosity, Av. P = Available Phosphorous, CEC = Cation Exchange Capacity,(Ex,Mg,Ca,K = Exchangeable Magnesium,Calcuim ,Potasium respectively) TN = Total Nitrogen, OM = Organic Matter, OC= organic Carbon, SQP=Soil Quality Parameter*

Discussions

Different land uses in the Upper Gibe Watershed have different soil quality indicators due to seasonal climate changes, especially rainfall and temperature. Figure 2 shows that June–September are the rainiest months of the primary rainy season. When the weather is good, plants produce more biomass, especially in wooded regions and well-kept agricultural fields. As demonstrated in Table 2 from the analysis of variance, land use categories significantly affected the average soil particle size distribution (sand, silt, and clay) at the $p < 0.01$ level. Clay is found in woodlands, sandy clay loam in grasslands, and sandy loams in farms. Different parent materials and soil disturbance levels generate these disparities.

Due to litterfall and root turnover, which replenishes organic matter to the soil, SOC and TN levels grow significantly. However, the absence of soil moisture in December–February slows mineralization and restricts nutrient release, limiting microbial activity. Seasonal leaching during the wet season affects soil pH. High acidity in cultivated and agricultural soils is caused by increased leaching of basic cations (e.g., Ca^{2+}, Mg^{2+}) during heavy rains. However, perennial grass in grazing areas regulate pH and reduce leaching due to their deeper root systems and moderate penetration rates, making them better buffers. Adaptive land management solutions that account for seasonal climate and land use variability support soil productivity and ecosystem resilience.

Root activity, organic matter, and bulk density are negatively correlated. Dry seasons increase soil compaction due to water loss and biological inactivity, which raises BD. As it rains, this pattern becomes more evident in cultivated regions that are repeatedly tilled and covered to prevent water from entering. Asmare et al. (2023) observed that forest land had the lowest mean BD (1.35 g/cm³) and pastureland had the highest (1.41 g/cm³), indicating the impact of vegetation cover and management strategies on BD levels. Variations in annual rainfall can affect phosphorus dynamics. High rainfall in acidic soil can increase P fixation and leaching in poorly managed highland farms. However, light rainfall increases microbial activity, which improves mineralization and organic P availability. Grasslands and woodlands store more phosphorus because soil disturbance is low and organic matter cycling is high.

Adaptive land management is needed in the Upper Gibe Watershed due to seasonal climatic and soil quality indicators. Integrating organic waste, minimizing tillage, and preserving permanent soil cover can mitigate seasonal climate extremes and maintain soil fertility throughout land use systems.

Finally, natural forest ecosystems had the highest SOC and TN due to litterfall and minimal human involvement. Due to heavy tillage and continuous residue removal, farmed land has the lowest value. Sustainable land management is needed because these regions' organic matter decreases are like those in intensively managed agricultural systems (Teferi et al., 2013).

Due to organic matter and plant residues that accumulate nitrogen in the soil, woodland zones had the highest total nitrogen (TN) (0.32%), followed by grazing land (0.25%). Previous studies indicated greater TN concentrations in pasture and forest areas than in agricultural soils (Negassa, 2020). Table 3 shows that naturally wooded soils had higher TN values than farmed soils. Balanced fertilization is needed to enhance soil fertility, as absolute TN levels are low. The immobilization of phosphorus in organic matter and restricted mineral fertilizer use may explain the lower Av. P in natural forests and grazing grasslands. There was no statistically significant variation in Av.P. among land uses; hence, phosphorus availability is moderate in most land use categories in the research area (Table 3). According to the statistics, cultivated fields have the most accessible P, while grazing and wild regions have the least. Forests have greater soil pH than cultivated areas (Table 2). Table 3 shows that the average value of these exchangeable elements varied by land use type from 6.83 to 12.17 meq/100 g of magnesium, 13.83 to 28.17 of calcium, and 0.34 to 1.32 of potassium. The analysis of variance revealed significant differences in exchangeable Mg, Ca, and K levels among land use categories ($P < 0.01$) (Table 4). Forests showed the highest exchangeable magnesium, calcium, and potassium values due to organic matter synthesis and plant residue cover on the soil surface. Basic cations are lost from topsoil due to lower pH, SOC, and SOM; repetitive crop harvest removal; continuing cultivation; and poor conservation measures, and hence cultivated land has the lowest values of these elements. Forests had higher exchangeable magnesium, calcium, and potassium values due to organic matter buildup, plant residue cover on the soil surface and leaching from agricultural land. Negassa (2020) believes this. According to the analysis of variance (Table 4), land use patterns in the study region significantly impacted soil cation exchange capacity ($P < 0.01$). Cation exchange capacity measures the soil's ability to release and retain nutrients. Land usage affects cation exchange capacity from 24.31 to 35.93 meq100g^{-1} (Table 3). Due to increased SOC and SOM levels, forests had the highest CEC on farmed land, and grazing areas the lowest (Table 4). This is supported by Kebebew (2022). Farms became more acidic (pH 5.2) due to extensive cropping, base cation leaching, and long-term use of chemical fertilizers, notably nitrogen-based ones. In the highlands of eastern Ethiopia and southwestern Ethiopia (Lemma et al., 2025), continuous cultivation lowers soil pH. Forest land has the highest SOC at 4.2%, resulting in less disturbance, greater biomass return, and better litter decomposition. After crop residue removal, biomass return reduction, and erosion, farmed regions had the lowest SOC at 1.3%. Kassa et al. (2017) found a similar SOC drop after forest-to-cropland conversion. Results showed that bulk density inversely affects overall porosity. Our results match Bogale et al. (2024), who found forestland had the highest porosity.The same trajectory of soil TN and SOC revealed a close relationship. Forest soil has 0.38% TN, while agricultural soil has 0.12%. Leaching, volatilization, and poor organic matter management may cause farmed land to lose TN. Choi et al. (2024) found lower TN levels in farmed soils than in forest and grazing pastures in the Upper Blue Nile Basin. Their results showed a positive connection between SOC and TN. Research by Choi et al. (2024) indicated that soil organic matter (SOM) was highest in forests and lowest in farms. Land use patterns significantly affect total nitrogen (TN) levels ($P < 0.01$), as seen in Table 3.

Forest areas may have more phosphorus (15.2 ppm) due to better organic matter turnover and less soil disturbance. Agriculture's low AP (7.4 ppm) is likely due to fertilizer, aluminum oxide fixing, and nutrient mining. Teferi et al. (2013) discovered low P in northern Ethiopian continuous cropping systems. Changes in land use and pH also affected soil P dynamics. The highest CEC (34.2 cmol(+)/kg) is in forest land because organic matter creates colloids that hold cations. Teferi et al. (2013) report a decline in soil organic matter in extensively exploited agroforestry. Due to greater organic matter and planting greens and residues in the soil, forest land had the greatest TN concentration (0.32%), followed by pasture land (0.25%). The average total nitrogen rose from agricultural to pasture and forest soils. Natural forests have the highest soil values, while farmed land has the lowest. In extensively exploited agricultural ecosystems, organic matter loss from cultivated fields is typical (Teferi et al., 2013). Due to higher organic matter and plant greens and residues in soil, woodland zones had the highest TN (0.32%), followed by pastureland (0.25%). It was found that agricultural soils have more total nitrogen than pasture and forest lands (Table 3). Agricultural areas have lower values than naturally wooded areas. Table 3 reveals that most land use categories in the research area have average P limits because available P is not diverse. Forest ecosystems promote nitrogen cycling, reduce erosion, and store organic matter, protecting soil health. Increasing and maintaining forest cover may improve watershed soil quality. In agricultural fields, low SOC and high BD soil quality measures decreased. These data demonstrate the harm caused by unsustainable agricultural practices such as over-tillage, crop rotation, and organic matter deficiency. Reduced tillage, organic amendments, and cover crops may mitigate these effects. The stable pH and SOC level of the grazing pastures indicated ordinary soil quality. Overgrazing compacts soil and deplete nitrogen. Rotational and other managed grazing regimes maintain these soils.

Cation Exchange Capacity (CEC) is a key indicator of soil health, indicating the ability to retain and provide cations such as calcium (Ca^{+}), magnesium (Mg^{+}), potassium (K^{+}), and sodium (Na^{+}). The study observed significant differences in CEC values ($p < 0.01$), with forest areas having the highest values (35.93 cmol(+)/kg), followed by pasture land (28.00 cmol(+)/kg) and cultivated land (24.31 cmol(+)/kg). Forest soils have higher CEC because soil organic matter provides many negatively charged cation adsorption sites. Organic matter is the principal driver of high CEC in natural, undisturbed ecosystems, according to Vanlauwe et al. (2010). Various land uses significantly impacted Percent Base Saturation (PBS), which measures the percentage of CEC occupied by basic cations (Ca^{2+}, Mg^{2+}, K^{2+}, Na^{2+}). Forest soils showed the highest PBS, indicating less acidity and more nutrients. PBS levels were lower in agricultural regions, possibly due to acidifying fertilizers, continuous cropping, and nutrient depletion. These patterns support soil degradation caused by long-term farming without fertility-maintenance methods. Sustainable land management practices, including residue retention, organic amendments, and reduced tillage, can improve CEC and PBS on degraded agricultural land. Enhancing these parameters can boost Upper Gibe Watershed soil fertility, fertilizer consumption efficiency, and long-term productivity.

The correlation results from the Upper Gibe Watershed provide essential insights into the interactions among soil quality indicators and their variation under different land use types. The positive correlation between pH and fertility indicators such as organic carbon, total nitrogen, available phosphorus, and cation exchange capacity (CEC) suggests that moderately neutral soils support better nutrient retention and availability. This is consistent with earlier findings that acidic conditions limit microbial activity and reduce nutrient availability in tropical soils (Vepraskas, 1986). The strong positive correlation between organic carbon and total nitrogen ($r = 0.77$, $p < 0.01$) reflects their biochemical association, as nitrogen is primarily stored and cycled through organic matter pools. Similarly, the positive relationship between OC and CEC ($r = 0.69$, $p < 0.01$) confirms the important role of organic matter in enhancing the soil's capacity to hold and exchange essential cations. These findings reinforce the significance of conserving organic matter through proper land management.

Bulk density (BD) exhibited negative correlations with most fertility indicators, including OC, TN, and CEC, indicating the detrimental effects of soil compaction on nutrient status and soil structure. Higher BD values, often associated with intensively cultivated lands, reduce porosity, restrict root growth, and lower water infiltration. This aligns with findings from the Ethiopian highlands, where croplands showed greater compaction than forested or grass-covered lands (Yihenew et al., 2015). Soil texture components played a critical role in fertility dynamics. Clay and silt contents were positively correlated with OC, TN, and CEC, likely due to their higher surface area and better nutrient-holding capacity. In contrast, sand content was negatively correlated with these indicators, highlighting the vulnerability of sandy soils to leaching and nutrient loss (Prasad et al., 2015). These patterns underscore the influence of land use on soil physical structure and associated nutrient dynamics. These results suggest that unsustainable land uses such as deforestation and continuous monocropping can reduce soil fertility by altering its physical and chemical properties. Restoration of soil quality in such landscapes requires integrated approaches that include conservation tillage, organic matter application, agroforestry, and controlled grazing (Asmamaw et al., 2012).

Synthesis and Implication.

Forested and grazing areas have superior soil quality to farmed land, which has degraded. Soil fertility and production might diminish without proper conservation measures during land use changes. These findings underscore the importance of comprehensive soil fertility management in agriculture to increase soil quality and land use sustainability. This method uses organics, agroforestry, and low tillage.

CONCLUSIONS

This study demonstrated that land use type significantly affects soil quality indicators in Western Ethiopia's Upper Gibe Watershed. Forest soil contains lower bulk density and more accessible phosphorus, total nitrogen, and soil organic carbon, indicating less disturbance and vigorous nutrient cycling. In cultivated regions, SOC, TN, CEC, HD, and AC were consistently low. The main causes of these changes include erosion, intensive farming, agricultural waste collection, and a lack of organic inputs. Even if soil texture was consistent across land use types, deteriorating chemical fertility indicators threaten long-term agricultural production and environmental sustainability. This study emphasizes the importance of sustainable land use planning and soil management in agroecologically sensitive places like the Upper Gibe watershed.

Recommendations

The results propose the following soil quality improvements and preservation measures: Farmlands with trees and perennial vegetation increase nutrient cycling, erosion reduction, and soil organic matter. Encourage limited tillage and agricultural residue retention to retain soil structure and hydration. Use compost, farmyard manure, green manure, or biochar to increase soil organic carbon and nitrogen. ISFM reduces synthetic fertilizer use. Enclosure and rotational grazing can repair degraded pastures. Introducing legislation to promote land restoration and secure tenure. Increase farmers' sustainable land management and soil fertility skills through training and capacity building. Monitor soil quality changes due to land management practices. Discover the economic and social factors that influence farmers' land use and soil management decisions. Promote land restoration and tenure rights policies. Improve soil fertility and teach farmers sustainable land usage. Track soil quality over time using various land management strategies. Discover how economic and societal variables affect farmers' land use and soil management efforts.

CRediT authorship contribution statement

Moti Taye: Formal analysis, investigation, resources, data curation, and visualization. **Getahun Kitila:** Writing Original Draft, Writing Review & Editing

Declaration of competing interests

The authors declare that there is no conflict of interest.

Ethical approval

Not applicable

Data availability statement

Data will be made available on request.

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REFERENCES

Asmamaw, L. B., & Mohammed, A. A. (2012). Effects of slope gradient and changes in land use/cover on selected soil physico-biochemical properties of the Gerado catchment, north-eastern Ethiopia. *International Journal of Environmental Studies*, *70* (1), 111–125. https://doi.org/10.1080/00207233.2012.75116

Asmare, T. K., Abayneh, B., Yigzaw, M., & Birhan, T. A. (2023). The effect of land use type on selected soil physicochemical properties in Shihatig watershed, Dabat district, Northwest Ethiopia. *Heliyon*,*9*(5), e16038. https://doi.org/10.1016/j.heliyon.2023.e16038

Ayilara, M., Olanrewaju, O., Babalola, O., & Odeyemi, O. (2020). Waste Management through Composting: Challenges and Potentials. *Sustainability*, *12*(11), 4456. https://doi.org/10.3390/su12114456

Bogale, T., Damene, S., Seyoum, A., & Haregeweyn, N. (2024). A mixed method approach for analyzing drivers of land use land cover change in the Northwestern Ethiopian highlands. *Environmental Monitoring and Assessment*, *196*(12). https://doi.org/10.1007/s10661-024-13342-2

Bremner, J. M. (1960). Determination of nitrogen in soil by the Kjeldahl method. *The Journal of Agricultural Science*, *55*(1), 11–33. https://doi.org/10.1017/s0021859600021572

Brevik, E. C., Krzic, M., Muggler, C., Field, D., Hannam, J., & Uchida, Y. (2022). Soil science education: A multinational look at current perspectives. *Natural Sciences Education*, *51*(1), 1-21. https://doi.org/10.1002/nse2.20077

Choi, M., Lee, C., Kim, L., Choi, S., Bong, Y., Lee, K., & Shin, W. (2024). Assessing sources of nutrients in small watersheds with different land-use patterns using TN, TP, and NO3--N. *Journal of Hydrology Regional Studies, 55*, 101958. https://doi.org/10.1016/j.ejrh.20 24.101958

Dai, K. H., & Richter, D. D. (2000). A reexamination of exchangeable acidity as extracted by potassium chloride and potassium fluoride. *Communications in Soil Science and Plant Analysis, 31*(1–2), 115–139. https://doi.org/10.1080/00103620009370424

Gashaw, T., Tulu, T. & Argaw, M. (2018). Erosion risk assessment for prioritization of conservation measures in Geleda watershed, Blue Nile basin, Ethiopia. Environ Syst Res 6, 1-14. https://doi.org/10.1186/s40068-016-0078-x

Kassa, H., Dondeyne, S., Poesen, J., Frankl, A., & Nyssen, J. (2017). Impact of deforestation on soil fertility, soil carbon and nitrogen stocks: the case of the Gacheb catchment in the White Nile Basin, Ethiopia. *Agriculture Ecosystems*

& Environment, 247, 273–282. https://doi.org/10.1016/j.agee.2017.06.034

Kebebew, S., Bedadi, B., Erkossa, T., Yimer, F., & Wogi, L. (2022). Effect of different Land-Use types on soil properties in Cheha district, South-Central Ethiopia. *Sustainability*, *14*(3), 1323. https://doi.org/10.3390/su14031323

Koudahe, K., Allen, S. C., & Djaman, K. (2022). Critical reviews of the impact of cover crops on soil properties. *International Soil and Water Conservation Research*. 10 (2022) 343354. https://doi.org/10.1016/j.iswcr.2022.09.002

Lemma, A., Wakgari, T., & Kebede, G. (2025). Effect of land use types and slope on selected soil physicochemical properties in Bubisa Watershed, Adea Berga District, Central Ethiopia. *International Journal of Environmental Monitoring and Analysis*, *13*(1), 15–27. https://doi.org/10.11648/j.ijema.20251301.12

Liu, L., & Ma, X. (2024). Prediction of Soil Field Capacity and Permanent Wilting Point Using Accessible Parameters by Machine Learning. *Agri Engineering, 6(*3), 2592-2611. https://doi.org/10.3390/agriengineering603015

Masha, M., Belayneh, M., & Tedila, G. (2023). Assessment of land use land cover dynamics and its contributing factors in Adama district, central Ethiopia. *International Journal of Environmental Quality, 55*(1), 42–54. https://doi.org/10.6092/issn.2281-4485/16917

Melero, S., López-Garrido, R., Murillo, J. M., & Moreno, F. (2009). Conservation tillage: Short- and long-term effects on soil carbon fractions and enzymatic activities under Mediterranean conditions. *Soil and Tillage Research*, *104* (2), 292–298. https://doi.org/10.1016/j.still.2009.04.001

Negassa, D. J. (2020). Effects of land use types on selected soil properties in central highlands of Ethiopia. *Applied and Environmental Soil Science*, *2020*, 1–9. https://doi.org/10.1155/2020/7026929

Prasad, R., Hochmuth, G. J., & Boote, K. J. (2015). Estimation of nitrogen pools in irrigated potato production on sandy soil using the model SUBSTOR. *PLoS ONE*, *10*(1), e0117891. https://doi.org/10.1371/journal.pone.0117891

SAS institute inc v world programming ltd. (2012). *Reports of Patent Design and Trade Mark Cases*, *129*(12), 933–970. https://doi.org/10.1093/rpc/rcs048

Teferi, E., Bewket, W., Uhlenbrook, S., Wenninger, J., & Simane, B. (2013). The use of remote sensing to quantify wetland loss in the Choke Mountain range, Upper Blue Nile basin, Ethiopia. *Hydrology and Earth System Sciences*, 17(2), 979–989. https://doi.org/10.5194/hess-17-979-2013

Vanlauwe, B., Descheemaeker, K., Giller, K. E., Huising, J., Merckx, R., Nziguheba, G., Wendt, J., & Zingore, S. (2015). Integrated soil fertility management in sub-Saharan Africa: unravelling local adaptation. *Soil*, *1*(1), 491–508. https://doi.org/10.5194/soil-1-491-2015

Vepraskas, M. (1986). Nature and properties of soils. *Agriculture Ecosystems & Environment*, *16*(3–4), 293–295. https://doi.org/10.1016/0167-8809(86)90013-7

Wolde, B., Moges, A., & Grima, R. (2023). Assessment of the combined effects of land use/land cover and climate change on soil erosion in the Sile watershed, Ethiopian Rift Valley Lakes Basin. *Cogent Food & Agriculture*, *9*(2). https://doi.org/10.1080/23311932.2023.2273630

Woldeamlak, B., & Solomon, A. (2014). Impacts of land use and land cover change on selected soil properties in the North Western Ethiopian Highlands. *Soil and Water Research*, 9(1), 1–9. https://doi.org/10.17221/10/2013-SWR

Yihenew, G., Getachew, A., & Solomon, K. (2015). Effects of land use on selected soil properties in Northwestern Ethiopia. *Environmental Systems Research, 4*(1), 18. https://doi.org/10.1186/s40068-015-0041-x

Yimer, F., Ledin, S., & Abdelkadir, A. (2008). Soil organic carbon and total nitrogen stocks as affected by topographic aspect and vegetation in the Bale Mountains, Ethiopia. *Geoderma*, *147(2),* 140–146. https://doi.org/10.1016/j.geoderma.2008.08.001