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Land use/land cover dynamics and their impact on selected soil properties in an Ethiopian highland ecosystem

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Abstract

Change in land use/land cover can impact soil quality either negative or positive effects. Therefore, it is crucial to evaluate these changes and their impacts on soil properties for sustainable soil management practices. Thus, the objectives of this study were to analyze land use/land cover dynamics over a 30 years and to investigate the impact of land use types on soil properties in the Shemit watershed, northwestern Ethiopia. ERDAS Imagine 2010 software was utilized to conduct the LULC classification and image analysis on Landsat satellite images from 1989, 2004, and 2019. Four land use types (plantation forest, cultivation land, natural forest, and grazing land) were chosen to evaluate the impact of land use types on soil properties. 24 soil samples were gathered from three representative sampling plots across each land use type at two soil depths (0-20 and 20-40 cm), and examined their soil properties. The study found that cultivated land and settlement increased by 3.65% and 6.33%, respectively, while grazing and forest lands declined by 7.23% and 2.76% from 1989 to 2019. Soil analysis revealed that, clay content (54.33%), pH (6.34), total nitrogen (0.28%), soil organic matter (5.32%), available phosphorus (6.24 mg kg-1), exchangeable basic cations, and cation exchange capacity (28.77 cmolckg-1) were higher on the natural forest than on other land use types. In the same manner, clay (49.33%), bulk density (1.29 g cm-3), pH (5.97), and exchangeable basic cations increased with depth across all types of land use. In general, land use/land cover dynamics have adversely affected soil quality owing to population growth, deforestation, and the expansion of settlement and cultivated areas. These transformations have degraded soil fertility and natural ecosystems. Promoting sustainable practices such as agroforestry, mixed farming, and the use of plant residues can help restore soil health, enhance carbon storage, and mitigate climate change. Immediate adoption of integrated land management and soil fertility strategies is essential to rehabilitate degraded lands and ensure sustainable agricultural productivity.

Keywords: Soil fertility, ERDAS Imagine, Landsat, Remote sensing, Sustainable Land management

Article Type: Research Article

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1. Introduction

Land use/land cover (LULC) dynamics are serious global concern with profound ecological and socio-economic implications. Population pressure, agricultural intensification, urban expansion, and other anthropogenic activities have accelerated LULC changes, resulting in widespread forest fragmentation, land degradation, biodiversity loss, and alterations to the hydrological cycle (Mekonnen and Manderso, 2023; Miju et al., 2025; Woldemariam et al., 2025). These transformations affect ecosystem services, including soil fertility, water regulation, carbon storage, and biodiversity, with cascading consequences for environmental sustainability and human well-being (Hurni et al., 2010; Meles and Molla, 2024). Globally, the transformation of forests and grasslands to cultivated land and settlements has been a major driver of soil erosion, nutrient depletion, and ecosystem disruption, posing significant challenges for sustainable agriculture (Molla et al., 2022; Gabisa et al., 2025).

East Africa, including the Horn of Africa, has experienced pronounced LULC changes due to both natural and anthropogenic factors. In Ethiopia, accelerating population growth, resettlement programs, climate variability, and poor land use planning have intensified pressure on land resources, resulting in extensive deforestation, forest land conversion, and soil degradation (Meles and Molla, 2024). Agricultural expansion, fuelwood collection, overgrazing, and settlement development have not only reduced forest cover but also altered hydrological processes, exacerbated soil erosion, and diminished soil fertility (Zeleke & Hurni, 2001; Workie and Teku, 2025). These changes have damaged ecosystem services, reduced agricultural productivity, and increased food insecurity, particularly in the Ethiopian highlands, which are dominated by rain-fed subsistence farming constitutes the principal source of income and a cornerstone of economic growth (FAO, 2021; Fantahun et al., 2024; Belay et al., 2025).

Soil erosion, a direct consequence of LULC changes, is a major form of land degradation worldwide (Borrelli et al., 2017). Water-induced erosion is particularly severe, leading to the loss of fertile topsoil, depletion of essential nutrients, reduced vegetation cover, and decreased crop productivity (Borrelli et al., 2017; Uddin et al., 2018). In Ethiopia, soil erosion rates are among the highest in Africa, with the highlands experiencing annual losses of 40–300 t ha^{-1} yr^{-1} due to steep slopes, intense rainfall, deforestation, and unsustainable agricultural practices (Bekele, 2019; Tamene et al., 2022). The resulting soil degradation not only threatens agricultural productivity and food security but also leads to increased sedimentation in water bodies and reservoirs, affecting water resource management and hydroelectric power generation (Borrelli et al., 2017; Uddin et al., 2018). Despite the implementation of soil and water conservation programs since the 1970s, land degradation continues to be a major challenge, emphasizing the importance of accurately assessing soil erosion risks and implementing focused conservation measures (Weldu and Edo, 2020).

Agriculture serves as the foundation of the national economy, contributing over 60% of GDP and employing 85% of the labor force (Zerssa et al., 2021). With the country's population increasing at a rate of 3.1%–2.6% between 2000 and 2024 (World Bank, 2025), the growing demand for agricultural land and natural resources has accelerated LULC change processes (FAO, 2021). In Ethiopia, LULC change poses a significant environmental concern (Molla et al., 2022; Miju et al., 2025). Conversion of forests and grasslands to cropland, grazing land, and plantations, including eucalyptus, has been observed across various parts of Ethiopia (Meles and Molla, 2024; Miju et al., 2025; Mekonnen and Manderso, 2023; Woldemariam et al., 2025). The decline of natural forests has also prompted large-scale plantation initiatives to rehabilitate degraded lands, with fast-growing species such as eucalyptus increasingly planted to meet the rising demand for fuelwood, construction materials, and land restoration (Hundera, 2010; Kassa et al., 2019; Bitew et al., 2025; Yenesew et al., 2025). This transformation has led to declines in soil organic carbon, total nitrogen, exchangeable cations, cation exchange capacity, and pH, thereby reducing soil fertility and crop productivity (Jaleta, 2020; Molla et al., 2022; Meles and Molla, 2024). These effects are further worsened by poor land management practices, such as overgrazing, continuous monocropping, and removal of crop residues, which further exacerbate nutrient depletion and soil degradation (Debebe et al., 2024; Bitew et al., 2025). Understanding the spatial variability of soil properties under different land uses is therefore crucial for optimizing fertilizer application, improving crop yields, and implementing sustainable land management strategies (Gebresamuel et al., 2020; Gerbi et al., 2024).

In the Shemit watershed, changes in land use have significantly impacted soil properties. The major factors of these changes are population pressure, which has led to deforestation, settlement expansion, the establishment of eucalyptus plantations, an increase in cultivated land, and free grazing practices. However, the effects of LULCC on soil properties in this area have not been thoroughly investigated or documented. Therefore, it is essential to comprehend how LULC change influences soil properties in the study area to determine the best management strategy, maintain soil health, and restore degraded areas. Hence, this study examined the land use dynamics and their impact on soil properties across various land uses in the Shemit watershed, north-western Ethiopia. The findings are expected to inform policy, guide sustainable agricultural practices, and contribute to mitigating land degradation and enhancing food security in the region.

2. Materials and Methods

2.1. Study area

The study area, the Shemit watershed, is located in the Estie District of the South Gondar Zone in the Amhara Region, approximately 107 km northeast of Bahir Dar and 667 km northwest of Addis Ababa. It is coordinated between 11°35'46"N - 11°37'58"N and 38°4'41"E -38° 6'21" E with an area coverage of about 637.0 hectares (Figure 1). The elevation of the area ranges from 2430 to 2842 m. a.s.l. Based on thirteen years of climate data (2006–2018) from the Ethiopian National Meteorology Agency (ENMA, 2019), the study area has an annual mean maximum temperature of 23.97 °C and a minimum of 8.16 °C, with an average annual rainfall of 1294.3 mm (Figure 2). Most of the study falls under the system of a gentle slope to an undulating plain. Based on the FAO legend of classification (FAO, 2005), the primary soil types of the area are Nitisols and Vertisols.

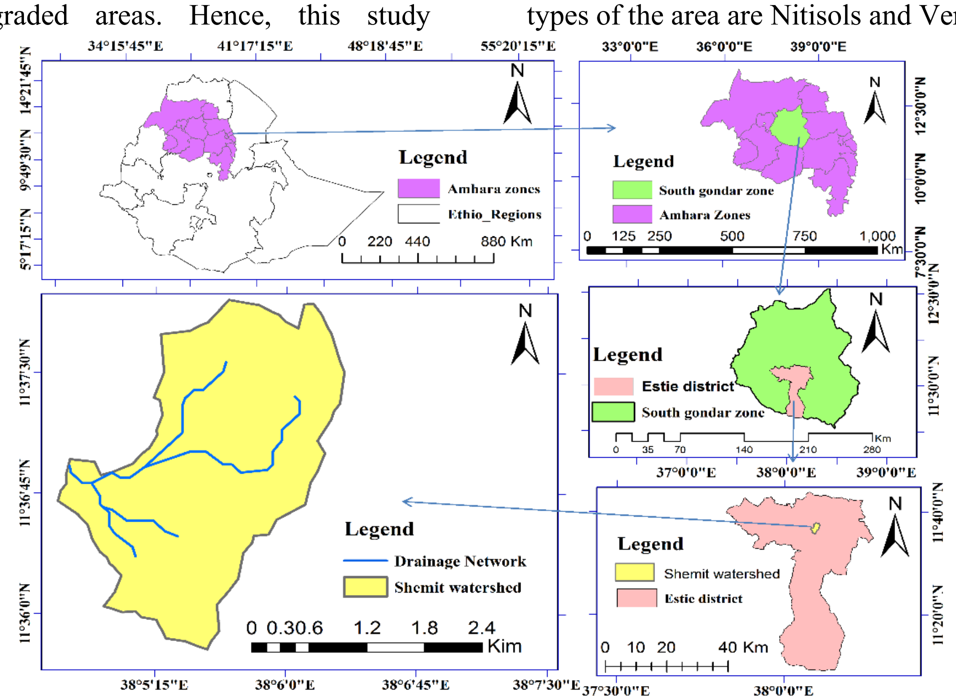

Figure 1. Location map of the study area (Shemit watershed)

In the Shemit watershed of Estie District, trees and shrubs are predominantly concentrated around homesteads and forestlands to enable better management and protection. The dominant tree species include Cordia africana, Olea africana, Eucalyptus globulus, Ficus vasta, Acacia abyssinica, and Ficus sycomorus. Fodder trees and shrubs play a significant role in providing nutrition for grazing animals, especially during dry and crop-fallow seasons. Recently introduced exotic nitrogen-fixing species include Tree Lucerne and Sesbania. Eucalyptus globulus serves as the main source of construction material and income. Rural households depend heavily on forest products, services, and agricultural land for their livelihoods. Cultivated land (59.91%) constitutes the largest land use type in the watershed, followed by forest (20.62%), grazing and grassland (10.63%), and settlement areas (8.84%). The area is suitable for rainfed production of crops, including wheat, teff, barley, and potato under rainfed conditions. Sheep, cattle, and horses are the main livestock species raised by the community in the Shemit watershed.

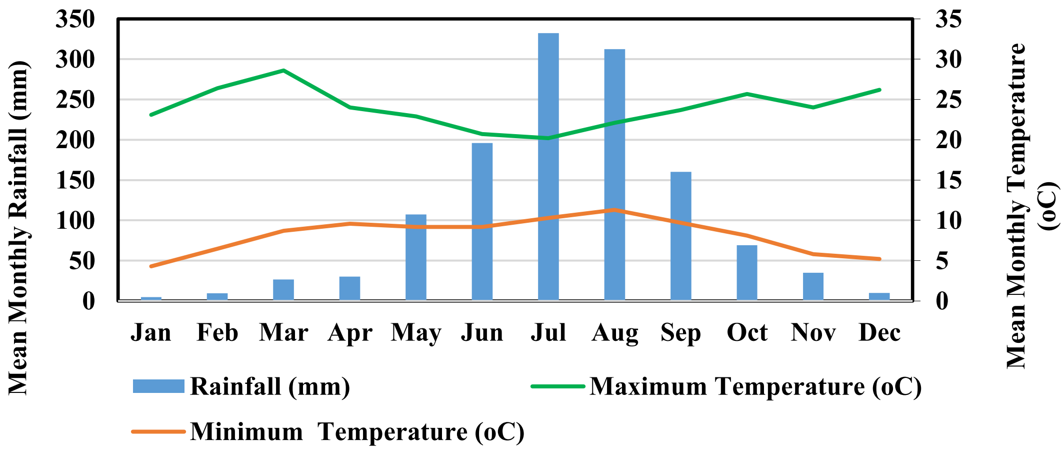

Figure 2. Mean monthly total rainfall and mean monthly air temperatures of the Shemit watershed from 2006-2018.

2.2. Data source and land-cover change analysis

The satellite images were acquired from the United States Geological Survey (USGS) Earth Explorer (https://EarthExplorer.usgs.gov/) for the periods of 1989, 2004, and 2019 to detect LULC dynamics (Table 1). The government launched an afforestation program in 1989 and mobilized the local communities in the watershed to implement it (Bishaw, 2001). But since 2004, deforestation has gotten worse (Molla et al., 2022). For this reason, the 2004 Landsat image was chosen for this investigation. Furthermore, the current state of LULC was depicted using a 2019 Landsat image.

Supervised image classification was conducted on Landsat imagery using ERDAS Imagine 2010 to map LULC. Pixels were assigned to predefined classes based on training samples, yielding greater accuracy than unsupervised approaches, though results rely heavily on training data quality. Four LULC categories were delineated (settlement, grazing land, cultivated land, and forest land). Due to the scale of analysis, it was challenging to isolate natural forests and plantation forests: these came together as forest land. Also, grassland was grouped into grazing lands since it was difficult to distinguish one from the other as they had a similar quality on the image (Molla et al., 2010). Training samples were developed for each LULC class, and corresponding signatures were created to facilitate image classification. The maximum likelihood classification technique was utilized to assign each pixel from the training samples to the class with the greatest probability. Lastly, land-use/land-cover maps were generated for the years 1989, 2004, and 2019, enabling a comparative analysis of the outcomes.

To assess the accuracy of classified LULC maps, 30 ground control points (GCPs) per land use type were collected, total of 120 reference points across the entire study area using GPS. Classification performance was evaluated with overall accuracy, user accuracy (total for row), producer's accuracy (column total), and the kappa coefficient (K) (column and row) derived from the LULC types classified images. Validation of the final LULC classification was carried out by comparing the map with the ground control points. The rate and magnitude of LULC change were calculated using the formula (Alemayehu et al., 2019).

$$r = \frac{Q1 - Q2}{T} \quad (1)$$

Where: r represents the rate of change, Q_1 indicates the area of LULC in the initial year (ha); Q_2 is the area of LULC in the recent year (ha), and T is the time interval between the two years.

Table 1. Satellite image type, number of bands, acquisition date, and resolution

Image	Date of Acquisition	No Bands	Spatial Resolution (m)	Sensor Type
P170R052	13/02/1989	7	30 m x 30 m	Landsat TM
P170R052	06/02/2004	7	30 m x 30 m	Landsat ETM$^+$
P170R052	18/02/2019	11	30 m x 30 m	Landsat OLI

2.3. Experimental design and soil sampling

Four types of land use (grazing land, cultivated land, plantation, and natural forest) were chosen in the watershed based on their similarity in physiographic parameters. Three plots, 10 m * 10 m plots, were created for each land use type adjacent to natural forest areas. Soil samples were collected at two depths of 0–20 cm and 20–40 cm for each plot. Composite soil samples were gathered using a sampling auger from each sampling plot. For each plot, five subsamples were gathered from the four corners and the center, which were merged to create a composite sample for each depth, yielding 1 kg of soil per sample. A total of 24 composite samples were obtained (4 land uses x 2 depths x 3 replications). Moreover, 24 undisturbed core samples were gathered in order to analyze bulk density for every land use category at both depths. All samples were air-dried, crushed, and filtered through a 2 mm mesh for subsequent physicochemical analysis (Table 2).

2.4 Statistical analysis

A two-way analysis of variance (ANOVA) was conducted following the General Linear Model (GLM) method in SAS version 9.4 to examine the variation in soil physicochemical characteristics across various land uses and soil depths (SAS, 2013). When significant differences were detected, means were contrasted using the Least Significant Difference (LSD) technique at a 5% probability level. Furthermore, Pearson's correlation coefficient was employed to evaluate the strength and associations among measured soil properties.

Table 2. Soil physicochemical analysis methods

Soil properties	Methods	Source
Texture	Hydrometry	(Bouyoucos, 1962)
Bulk density	Core	(Black et al., 1965)
pH (H_2O)	pH meter	(Van Reeuwijk, 1992)
OC	Oxidation	(Walkley and Black, 1934)
TN	Kjeldahl	(Bremner and Mulvaney, 1982)
Av. P	Bray II	(Bray and Kurtz, 1945)
CEC	Titration	(Chapman, 1965)
Exchangeable Ca and Mg	AAS)	(Rowell, 1994)
Exchangeable Na and K	Flame photometer	(Rowell, 1994)

3. Results and Discussion

3.1. LULC analysis

3.1.1. Cultivated land

The analysis of LULC changes in the Shemit watershed from 1989 to 2019 revealed considerable variations among the major land use types. The cultivated land area had increased from 358.38 ha (56.26%) in 1989 to 381.65 ha (59.91%) in 2019 (Figure 3-5, Table 3). The expansion was most significant between 1989 and 2004 (+6.15%) because of the transformation of forest and grazing land to agricultural land to accommodate the rising rural population density that depends on agriculture (Gashaw et al., 2017; Asmare and Abegaz, 2018). However, from 2004 to 2019, it declined by 15.94 ha (2.50%) (Table 4), mainly due to the conversion of degraded land into plantation forests and settlements. In recent years, many smallholder farmers in northwestern Ethiopia have shifted from using degraded croplands to establishing eucalyptus plantations to satisfy wood product demand and supplement household income (Molla et al., 2022; Meles and Molla, 2024). The annual rate of change was 2.61 ha yr^{-1} in 1989–2004, compared with a decline of 1.06 ha yr^{-1} in 2004–2019 (Figure 3-5, Table 5).

Table 3. Area of LULC classes from 1989, 2004, and 2019

LULC type	Area covered by the respective LULC type					
	1989		2004		2019	
	Area (ha)	Area (%)	Area (ha)	Area (%)	Area (ha)	Area (%)
Cultivated land	358.38	56.26	397.59	62.42	381.65	59.91
Forest land	148.93	23.38	108.17	16.98	131.36	20.62
Grazing land	113.73	17.85	86.12	13.52	67.69	10.63
Settlement	15.96	2.51	45.12	7.08	56.30	8.84
Total	637.00	100.00	637.00	100.00	637.00	100.00

3.1.2. Forest land

Results of Land cover analysis exhibited that the area of forest land had declined by 40.76 ha (6.40%) over the first fifteen years (1989-2004) and increased by 23.26 ha (3.64%) between 2004-2019 (Figure 3-5, Table 4). This decrease in forest area during the first study period was primarily caused by the transformation of natural forests into other land uses. In contrast, the increase in forest area observed in the second period is largely due to the extensive planting of eucalyptus trees (Molla et al., 2022; Meles and Molla, 2024). These fast-growing trees are favored for their use in construction materials, as well as for providing income and energy sources, according to insights from key informants (Meshesha et al., 2016). However, the overall pattern of forest land declined by 2.76% over 30 years, corresponding to a negative annual rate of –0.09% (Table 5). The results of this investigation align with those of (Molla et al., 2010; Yeshaneh et al., 2013).

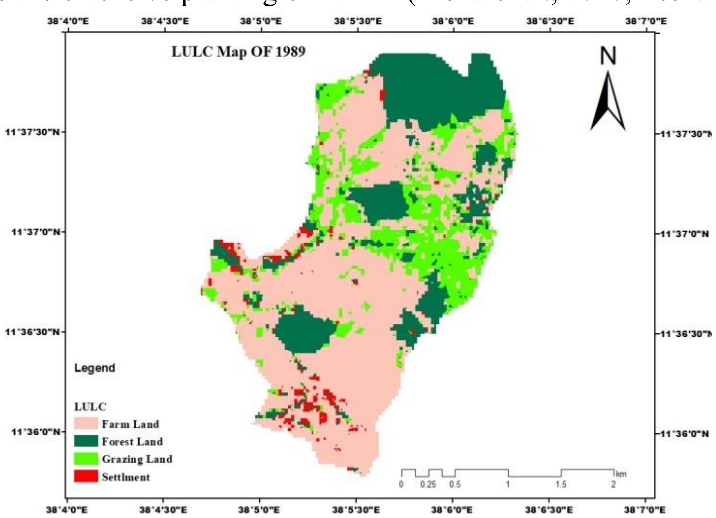

Figure 3. The LULC map of 1989.

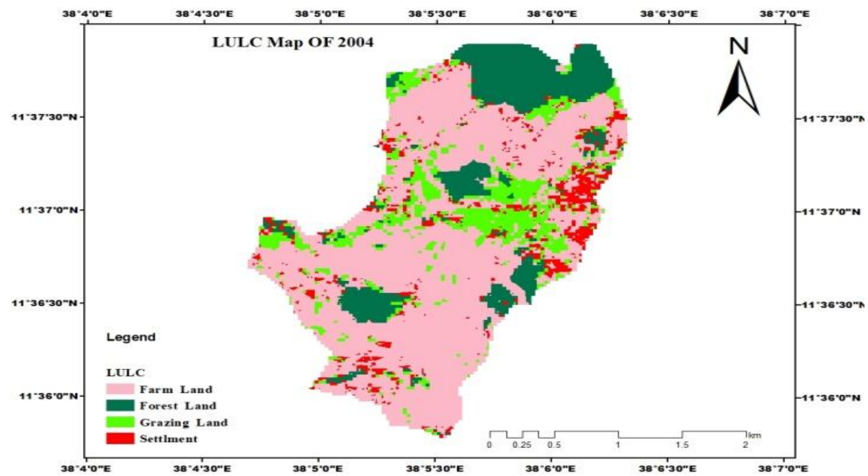

Figure 4. The LULC map of 2004.

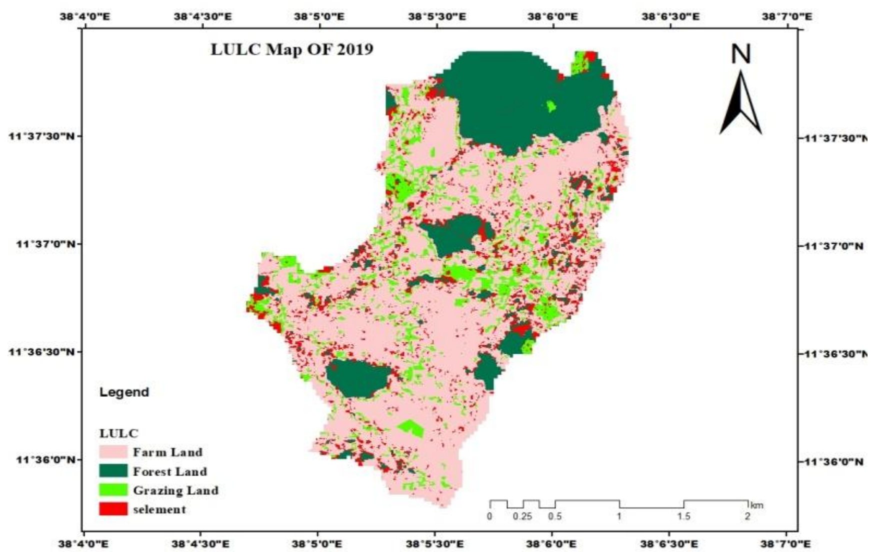

Figure 5. The LULC map of 2019.

3.1.3. Grazing land

The grazing land coverage was decreased from 113.73 ha (17.85%) in 1989 to 86.12 ha (13.52%) in 2004 and to 67.69 (10.63%) in 2019 (Figure 3-5, Table 3) with the annual diminishing rate of 1.84 ha yr^{-1} and 1.23 ha yr^{-1} between 1989–2004 and 2004–2019 periods, respectively (Table 5). Significant loss of grazing land is mainly caused by its conversion to settlement and cultivated land, driven by rapid population growth that increases the demand for food and housing, particularly in the highlands of Ethiopia (Bitew et al., 2025; Gabisa et al., 2025). This loss negatively affects biodiversity, soil health, and ecosystems, consistent with observations from other Ethiopian regions (Habte et al., 2021; Regasa et al., 2021; Mekonnen and Manderso, 2023; Meles and Molla, 2024; Miju et al., 2025). This evidence highlights the urgent need for sustainable land management practices that balance agricultural expansion with environmental conservation to safeguard natural resources for future generations.

Table 4. LULC change matrix

LULC type	Change in LULC area (ha and %) coverage; gain (+) or loss (-)					
	1989-2004		2004-2019		1989-2019	
	Area (ha)	Area (%)	Area (ha)	Area (%)	Area (ha)	Area (%)
Cultivated land	+39.21	+6.15	-15.94	-2.50	+23.26	+3.65
Forest land	-40.76	-6.40	+23.19	+3.64	-17.57	-2.76
Grazing land	-27.61	-4.33	-18.43	-2.89	-46.04	-7.23
Settlement	+29.16	+4.58	+11.18	+1.76	+40.34	+6.33
Total	0.00	0.00	0.00	0.00	0.00	0.00

Table 5. Annual rate of LULC changes

LULC type	Annual change in the area (ha and %/year)					
	1989-2004		2004-2019		1989-2019	
	Area (ha)	Area (%)	Area (ha)	Area (%)	Area (ha)	Area (%)
Cultivated land	+2.61	+0.41	-1.06	-0.17	0.78	+0.12
Forest land	-2.72	-0.43	+1.55	+0.24	-0.59	-0. 09
Grazing land	-1.84	-0.29	-1.23	-0.19	-1.54	-0.23
Settlement	+1.95	0.31	+0.74	+0.12	+1.35	+0.20
Total	0	0	0	0	0	0

3.1.4. Settlement

Results of land cover analysis showed that area of settlement increased from 15.96 ha (2.51%) in 1989 to 56.30 ha (8.84%) in 2019 (Figure 3-5, Table 3). During the 1989–2004 and 2004–2019 periods, the settlement increased by 29.16 ha (4.58%) and 11.18 ha (1.76%), respectively (Table 4). This was due to a continually rising population pressure that needs land for rural settlement. The result is similar to (Assefa et al., 2020; Molla et al., 2022; Mekonnen and Manderso, 2023) who stated an increase in settlement from the conversion of forest land in different Ethiopian highlands. Furthermore, the overall pattern of settlement was increased by 40.34 ha (6.33%) over 30 years with an annual rate of 1.35 ha yr^{-1} (0.20%) (Table 4-5).

3.1.5. Accuracy assessment

The accuracy evaluation of land cover indicated overall accuracy assessments of 82.50%, 87.50%, and 90.83%, along with kappa coefficients of 0.75, 0.83, and 0.88 for the images from 1989, 2004, and 2019, respectively (Table 6). These results demonstrate a strong degree of concordance between the reference data and the classified images (Anderson, 2003).

Table 6. Accuracy assessment of LULC mapping

Class Name	1989		2004		2019	
	UA	PA	UA	PA	UA	PA
Settlement	83.33	62.50	78.26	94.74	86.11	96.88
Cultivated land	69.05	93.55	100.00	68.57	93.10	90.00
Forest land	96.55	77.78	88.89	97.56	88.46	85.19
Grazing land	86.05	82.22	82.14	92.00	96.55	90.32
Overall Accuracy	82.50		87.50		90.83	
Kappa coefficient	0.75		0.83		0.88	

UA is the user's accuracy; PA is the producer's accuracy.

3.2. Effect of land use type and soil depth on soil physical properties

3.2.1. Soil texture

Land use types and soil depth had a notable influence ($P < 0.05$) on sand particle whereas land use type significantly affected clay particle ($P < 0.05$) (Table 7). The highest sand content (30.66 %) was found in cultivated land, and the lowest (21.5 %) occurred under natural forest. Moreover, the clay fraction exhibited the lowest value (38.66 %) in cultivated land and the highest value (54.33%) in the natural forest (Table 7). The highest sand fraction and the lowest clay in the cultivated land are caused by the breakdown during tilling and differential loss of clay particles through erosion, which leaves the sand fractions remaining in the field (Fetene and Amera, 2018; Bitew et al., 2025). Similar observations were reported by Selassie et al. (2015), who presented the highest clay and lowest sand fractions in the natural forest of Zikre watershed, Northwestern Ethiopia. Similarly, Tufa et al. (2019), Assefa et al. (2020), and Molla et al. (2022) indicated lower clay content in cultivated land. Conversely, the topsoil had a higher sand fraction than the subsoil across all land use (Table 7). This phenomenon may be linked to the downward movement (eluviation) of clay particles within the soil profile, accompanied by the selective loss of finer particle fractions from the topsoils. The findings of this investigation concur with those of Tufa et al. (2019) and Molla et al. (2022), who reported a similar pattern

Table 7. Effects of land use and soil depth on selected soil physical properties

Land use or Soil depth	Particle size (%)			Textural class	BD (gcm^{-3})
	Sand	Silt	Clay		
Land use					
Natural forest	21.5^{c}	24.16	54.33^{a}	C	1.08^{b}
Cultivated land	30.66^{a}	31.00	38.66^{b}	CL	1.37^{a}
Grazing land	23.5^{bc}	25.33	51.16^{a}	C	1.34^{a}
Plantation forest	25.33^{b}	28.83	46.16^{ab}	C	1.32^{a}
LSD(0.05)	2.98	-	9.29	-	0.06
P-values	0.00^{**}	0.27^{ns}	0.02*		0.00^{**}
SEM (±)	1.07	2.21	2.64	-	0.02
Soil depth (cm)					
0-20	26.5^{a}	27.66	45.83	C	1.26^{b}
20-40	24.00^{b}	27.00	49.33	C	1.29^{a}
P-values	0.02^{*}	0.80^{ns}	0.27^{ns}		0.15^{ns}
SEM (±)	1.20	1.86	2.63	-	0.04
CV (%)	9.66	23.7	15.95	-	3.83

Mean values followed by the different letters were significantly different at $P \leq 0.05$; and * represents p-value ≤ 0.05; ** represents p-value ≤ 0.01; ^{ns} represents not significant ($p \geq 0.05$); SEM (±) = standard error of means; CV = coefficient of variation.

3.2.2. Bulk density (BD)

The result of ANOVA depicts highly significant influences ($P < 0.01$) in soil BD in the land use types (Table 7). The highest BD (1.37 g cm^{-3}) was found in cultivated land, while the lowest (1.08 g cm^{-3}) was observed in natural forest (Table 7). The elevated BD in cultivated soils is attributed to the compaction caused by trampling during tillage and open grazing following crop harvest, and the addition of little OM inputs (Selassie and Ayanna, 2013; Molla et al., 2022). Conversely, the lowest BD found in natural forest is attributed to its high OM and clay content (Bore and Bedadi, 2015; Selassie et al., 2015; Tufa et al., 2019; Fekad et al., 2020). Bulk density (BD) rises with depth across all types of land uses (Table 7), which results from the higher OM content in the upper soil layers. The finding agrees with (Fetene and Amera, 2018; Tufa et al., 2019; Molla et al., 2022) who explained the lower BD in the surface soil due to the decline of SOM with depth. Generally, the values of BD were within acceptable limits (less than 1.4 g cm^{-3}) for agricultural soils (Bohn et al., 2002). This implies that the study areas are unlikely to restrict root growth, water movement, or air flow, and they provide sufficient aeration and soil aggregation to support crop development and microbial activity.

3.3. Effect of land use type and soil depth on soil chemical properties

3.3.1. Soil reaction (pH)

Soil pH was significantly impacted by land use types ($P < 0.01$) (Table 8). The natural forest exhibited the highest pH value of 6.34, while the plantation forests recorded the lowest at 5.77 (Table 8). Under natural forest, the highest value of soil pH can be linked to its greater content of SOM (Molla et al., 2022). Conversely, the highest absorption of basic cations by plants and a very low rate of return to the soil may result in the lowest pH value under a plantation forest. The outcome agrees with (Fekad et al., 2020; Tiruneh et al., 2021; Kebebew et al., 2022) who noted the lowest soil pH levels in eucalyptus plantations compared to other land use categories. According to Tadesse et al. (1991), soil pH varies from slightly acidic (for Eucalyptus plantation) to moderately acidic (for the remaining land uses). The land conversion from natural forest to other land uses has led to soil pH decline (Selassie et al., 2015; Fekad et al., 2020).

3.3.2. Soil organic matter (SOM)

Soil OM content was also significantly ($P < 0.01$) influenced by both land use and soil depth (Table 8). Natural forest had the highest (5.32%) SOM, while the lowest (2.47 %) SOM was detected in cultivated land (Table 8). The highest SOM in the natural forest can be linked to the deposition of plant residues in the topsoil, with their slower rate of decomposition and less disturbance. Conversely, SOM level loss in the farmland is due to repeated farming, total removal of the crop residues, poor crop rotation, and soil erosion. The result also concurred with the study of Selassie et al. (2015); Fetene and Amera (2018); Molla et al. (2022), and Yenesew et al. (2025), who documented that natural forests contained the highest SOM, whereas cultivated lands had the lowest. For soil depth, SOM content declined in the downward direction for all land uses (Table 8). This may be because of relatively better application of organic materials and greater microbial processes in topsoil than in subsoil surface (Habtamu et al., 2014; Takele et al., 2014; Tufa et al., 2019; Meles and Molla, 2024).

Table 8. Effect of land use and soil depth on soil chemical properties

Land use / Soil depth	pH -H_2O (1: 2.5)	SOM (%)	Total N (%)	Av. P (mg kg^{-1})
Land use				
Natural forest	6.34^{a}	5.32^{a}	0.28^{a}	6.24^{a}
Cultivated land	5.78^{b}	2.47^{b}	0.14^{b}	2.94^{c}
Grazing land	5.86^{b}	2.62^{b}	0.15^{b}	2.36^{c}
Plantation forest	5.77^{b}	2.52^{b}	0.15^{b}	4.14^{b}
LSD(0.05)	0.19	0.62	0.038	1.11
p-values	0.00^{**}	0.00^{**}	0.00^{**}	0.00^{**}
SEM (±)	0.05	0.21	0.01	0.33
Soil depth (cm)				
0-20	5.91	3.54^{a}	0.19	4.21^{a}
20-40	5.97	2.93^{b}	0.16	3.63^{b}
p-values	0.38^{ns}	0.00^{**}	0.06^{ns}	0.05^{*}
SEM (±)	0.08	0.39	0.02	0.50
CV (%)	2.68	15.70	17.03	23.17

Mean values followed by the different letters were significantly different at $P \leq 0.05$; and * represents p-value ≤ 0.05; ** represents p-value ≤ 0.01; ^{ns} represents not significant ($p \geq 0.05$); SEM (±) = standard error of means; CV = coefficient of variation.

3.3.3. Total Nitrogen (TN)

TN contents on forest land were significantly higher ($P < 0.01$) than other studied land uses (Table 8). Consistent with this, TN content was high (0.28%) in natural forest areas and low (0.14 %) in cultivated land (Table 8). Low TN in cultivated can be attributed to intensive cultivation, complete removal of crop residues, use of animal manure as fuel, limited external inputs, plant uptake, erosion, and nitrogen volatilization, whereas the high TN in forest soils is linked to their greater organic matter content (Bitew et al., 2025). These findings agree with previous studies in various Ethiopian highlands (Selassie et al., 2015; Tufa et al., 2019; Assefa et al., 2020; Molla et al., 2022), which revealed lower TN in cultivated soils and higher TN in forest soils. The TN contents of cultivated land soils were low, while soils from the remaining land uses were medium according to the ratings of Tadesse et al. (1991).

3.3.4. Available phosphorus (Av.P)

The soil Av. P levels were significantly ($P < 0.05$) impacted by both soil depth and land use category (Table 8). Hence, the highest Av. P was found in the natural forest at 6.24 mg kg^{-1}, while the lowest was recorded in grazing land at 2.36 mg kg^{-1} (Table 5). The highest Av. P in forest land attributes to its higher OM, which releases Av. P during mineralization (Asmamaw and Mohammed, 2013; Fetene and Amera, 2018; Fekad et al., 2020). Regarding the depth, the Av. P content was decreased with increasing soil depth (Table 8). This pattern is mainly due to higher organic matter decomposition and Av. P mineralization near the surface, while reduced biological activity and organic inputs at deeper layers limit Av. P release (Frossard et al., 2000). Moreover, the high clay content at lower depths can increase phosphorus fixation due to the extreme adsorption of phosphate ions onto aluminum and iron oxides, along with clay minerals, thereby reducing P availability (Sanchez, 2019). Similar depth-related decreases in available phosphorus have been observed in different Ethiopian soils (Selassie and Ayanna, 2013; Tufa et al., 2019). According to Landon (2014), classification, the Av. P status of the watershed ranged from medium (for natural forest) and low (for other land uses).

3.3.5. Exchangeable basic cations (Ca^{2+}, Mg^{2+}, K^{+}, and Na^{+})

Exchangeable basic cations were significantly impacted by land use types ($P < 0.01$) (Table 9). The highest Ca^{2+} (14.13 $cmol_c kg^{-1}$), Mg^{2+} (2.57 $cmol_c kg^{-1}$), K^{2+} (1.11 $cmol_c kg^{-1}$), and Na^{2+} (1.04 $cmol_c kg^{-1}$) were shown in the natural forest. In contrast, the lowest contents of Ca^{2+} (9.96 $cmol_c kg^{-1}$), Mg^{2+} (1.84 $cmol_c kg^{-1}$), K^{2+} (0.61 $cmol_c kg^{-1}$), and Na^{2+} (0.40 $cmol_c kg^{-1}$) were observed in the plantation forest (Tables 9). This could be because forest soil has a higher OM and clay particle concentration than other land uses. The lowest levels of exchangeable basic cations in the eucalyptus plantation may be due to the greater uptake of these cations by the trees.

Table 9. Effect of land use and soil depth on exchangeable basic cations and CEC

Land use /Soil depth	Exchangeable bases ($cmol_c kg^{-1}$)				C E C ($cmol_c kg^{-1}$)
	Ca	Mg	K	Na	
Land use					
Natural forest	14.13^{a}	2.57^{a}	1.11^{a}	1.04^{a}	28.77^{a}
Cultivated land	11.90^{b}	2.02^{bc}	0.62^{b}	0.50^{b}	23.29^{c}
Grazing land	12.43^{b}	2.23^{b}	0.66^{b}	0.85^{a}	24.86^{b}
Plantation forest	9.96^{c}	1.84^{c}	0.61^{b}	0.40^{b}	23.65^{c}
LSD(0.05)	1.22	0.39	0.19	0.23	1.01
p-values	0.00**	0.00**	0.00**	0.00**	0.00**
SEM (±)	0.35	0.13	0.06	0.08	0.33
Soil depth (cm)					
0-20	11.83	2.05	0.69	0.60^{b}	25.39
20-40	12.37	2.29	0.80	0.79^{a}	24.90
p-values	0.21^{ns}	0.07^{ns}	0.11^{ns}	0.02*	0.16^{ns}
SEM (±)	0.51	0.12	0.07	0.09	0.69
CV (%)	8.27	14.75	21.43	27.03	3.27

In addition, the lower rate of nutrient return to the soil further contributes to this reduction (Selassie and Ayanna, 2013; Molla et al., 2022). On the other hand, exchangeable basic cations were increased along with depth in all types of land use (Table 9). This pattern may be attributed to the downward movement of cations into the lower soil horizons and the higher concentration of clay particles in the subsurface compared to the surface soils. This outcome is in agreement with the investigations of Molla et al. (2022) and Meles and Molla (2024), which revealed greater exchangeable basic cation contents in the subsurface soil layer compared to surface soils of Agedit watershed and Embamamie watershed, Northwest Ethiopia, respectively

Table 9. Effect of land use and soil depth on exchangeable basic cations and CEC

Land use /Soil depth	Exchangeable bases ($cmol_c kg^{-1}$)				C E C ($cmol_c kg^{-1}$)
	Ca	Mg	K	Na	
Land use					
Natural forest	14.13^a	2.57^a	1.11^a	1.04^a	28.77^a
Cultivated land	11.90^b	2.02^{bc}	0.62^b	0.50^b	23.29^c
Grazing land	12.43^b	2.23^b	0.66^b	0.85^a	24.86^b
Plantation forest	9.96^c	1.84^c	0.61^b	0.40^b	23.65^c
LSD(0.05)	1.22	0.39	0.19	0.23	1.01
p-values	0.00**	0.00**	0.00**	0.00**	0.00**
SEM (±)	0.35	0.13	0.06	0.08	0.33
Soil depth (cm)					
0-20	11.83	2.05	0.69	0.60^b	25.39
20-40	12.37	2.29	0.80	0.79^a	24.90
p-values	0.21^{ns}	0.07^{ns}	0.11^{ns}	0.02*	0.16^{ns}
SEM (±)	0.51	0.12	0.07	0.09	0.69
CV (%)	8.27	14.75	21.43	27.03	3.27

Mean values followed by the different letters were significantly different at $P < 0.05$; and * represents p-value < 0.05; ** represents p-value < 0.01; ns represents not significant ($p > 0.05$); SEM (±) = standard error of means; CV = coefficient of variation.

3.3.6. Cation exchange capacity (CEC)

ANOVA results revealed that CEC varied significantly ($P < 0.01$) among land use types (Table 9). The highest CEC values were found in natural forests (28.77 cmolc kg^{-1}), while the lowest were found in cultivated land (23.29 cmolc kg^{-1}) (Table 9). Plantation forest and cultivated land were observed statistically similar results. This may align with lower clay and SOM contents in these land use types compared to natural forest (Fetene and Amera, 2018). The authors noted that natural forest conversion into cultivated land and settlement forest led to varying losses of CEC in different magnitudes (Chemeda et al., 2017; Mojiri et al., 2012). The finding is consistent with the reports of similar studies (Adugna and Abegaz, 2016; Seyoum, 2016; Tufa et al., 2019; Meles and Molla, 2024). Values of CEC declined from the topsoil to subsoil across all types of land use (Table 9), due to diminishing SOM, as values of CEC and SOM have a strong association. This result agrees with that of (Fetene and Amera, 2018; Tufa et al., 2019; Molla et al., 2022). According to Landon (2014), natural forests had a high CEC, while the other land use types had medium values.

4. Conclusions

The satellite image analysis showed clear evidence of substantial LULC changes in the Shemit watershed, northwestern Ethiopia. Over the past 30 years (1989–2019), settlement and cultivated areas were expanded by 6.33% and 3.65%, respectively, while grazing and forest lands declined by 7.23% and 2.76%, respectively. These changes were primarily driven by anthropogenic activities, resulting in the conversion of grazing and forest lands into settlement and cultivated areas and underscoring the importance of implementing sustainable watershed management strategies. The physicochemical properties of soils, such as clay, pH, TN, SOM, and Av. P, exchangeable cations (Ca^{2+}, Mg^{2+}, K^{+}, and Na^{+}), and CEC were higher under natural forest than other land use types. This can be attributed to higher litter input and slower decomposition rates in forests, which enhance SOM accumulation and nutrient retention. The release of nitrogen and phosphorus from decomposing organic matter further contributes to the higher TN and Av. P levels in forest soils. In contrast, intensive cultivation, frequent tillage, and soil erosion under cultivated land uses likely increased bulk density and reduced soil structure stability and nutrient availability. As soil depth increased, clay content, pH, BD, and exchangeable basic cations generally increased, while silt, sand, TN, SOM, and Av. P and CEC decreased. These depth-related patterns indicate that finer soil particles and basic cations tend to move downward through the soil profile, while the amount of OM and biological activity decreases with depth due to limited root growth and reduced litter input. Overall, soil fertility was relatively well preserved under natural forest due to effective nutrient recycling, whereas soils under plantation forests and cultivated lands showed declines in most fertility parameters. These findings highlight that the conversion of natural forests to other land uses without proper management practices can have detrimental effects on soil health and forest ecosystem. Hence, adopting integrated land management practices in different land uses is the most promising method to combat soil degradation and realize sustainable agricultural productivity in the Shemit watershed. Therefore, the watershed requires prompt intervention through proper land use planning and soil fertility management to prevent further soil degradation and productivity loss. This study was limited to evaluating the effects of land use type and soil depth on the physicochemical properties of soils. Therefore, future research should investigate the combined effects of landscape position, land use type, land management practices, and soil depth on soil quality dynamics.

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Conflicts of interest

The authors of this article declared no conflict of interest regarding the authorship or publication of this article.

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All data generated or analyzed during this study are included in this published article.

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