DOI: https://doi.org/10.20372/star.V14.i3.13
ISSN: 2226-7522 (Print) and 2305-3372 (Online)
Science, Technology, and Arts Research Journal
Sci. Technol. Arts Res. J., July–Sep. 2025, 14(3), 154-166
Journal Homepage: https://journals.wgu.edu.et
Original Research

Dynamics of land use and land cover (LULC) change and its consequential impact on soil health in the Fincaha'a Watershed, Northwest Nile Basin, Western Ethiopia

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Abstract

Land use and land cover (LULC) changes affect soil health, particularly in ecologically sensitive highlands. This study explores LULC dynamics and their influence on selected soil parameters in the Fincaha'a Valley watershed, Upper Nile Basin, Ethiopia. Landsat images from 1990, 2000, and 2020 were subjected to supervised classification in ArcGIS. Soil texture, water-holding capacity, soil organic carbon (SOC), bulk density (BD), total nitrogen (TN), pH, and available phosphorus (AvP) were measured in soil samples (0–20 cm depth) from forest, farmed, grazing, and fallow fields. Forest cover dropped from 41.3% to 21.7%, while cultivated land rose from 32.5% to 56.8%. Significant differences ($p < 0.05$) were observed among land use types. SOC was highest in forest soils (3.74%) and lowest in cultivated soils (1.08%). BD rose from 1.12 g cm^{-3} (forest) to 1.42 g (cultivated). AvP and TN decreased significantly in intensively used fields. These findings indicate that LULC conversion adversely affects soil health, affecting long-term land productivity and ecological services. To improve soil quality and resilience in the Fincaha'a watersheds, agroforestry and conservation farming are recommended.

Article Information

Article History:
Received: 01-04-2025
Revised: 25-08-2025
Accepted: 28-09-2025

Keywords:
Land Use, Soil Health, Fincaha'a Watershed, Nile Basin, Soil Management, Land Degradation,

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INTRODUCTION

Land use and land cover (LULC) changes affect soil characteristics. Deforestation, urbanization, agricultural intensification, and industrial activities can alter soil structure, water retention, and health. Bulk density (*BD*), texture, water-holding capacity, and erosion susceptibility are critical indicators of soil quality and productivity. This study examines how LULC modification affects physical soil health indicators (Alemu et al., 2021; Kitila et al., 2018; Asmare, 2023).

The Fincaha'a watershed in Western Ethiopia's Northwestern Nile Basin is environmentally and socioeconomically significant. This valley supports diverse agricultural activities and serves as a vital water source for local people. However, fast land use and land cover (LULC) changes are threatening ecosystem services and sustainability. These changes greatly impact soil fertility, erosion, and land production (Kitila et al., 2018; Buraka, 2023).

Population growth, agricultural expansion, deforestation, and urbanization drive land use and land cover changes (LULCC). Recent studies indicate that LULCC can worsen soil degradation, disrupt hydrological cycles, and enhance climate vulnerability. Understanding how LULCC affects soil characteristics and functionality is essential for effective land management since soil health is critical for sustainable agriculture and environmental resilience. In other parts of Ethiopia and Sub-Saharan Africa, unsustainable land use practices reduce soil organic carbon (*SOC)*, increase soil erosion, and decrease soil productivity (Demelash et al., 2010). These findings highlight the need for targeted land management strategies to promote ecological sustainability to mitigate negative effects.

In Fincaha'a watershed, agricultural intensification, forest cover changes, and land conversion affect soil quality and ecosystem services. This study examines LULC variations across decades and their effects on soil health. Focusing on this watershed can reveal ways to optimize land management methods to improve soil sustainability and resilience in similar contexts across the region.

Land use and land cover (LULC) changes influence environmental change, including soil health and sustainability. The Fincaha'a watershed in Western Ethiopia's Upper Nile Basin is undergoing fast land use changes due to agricultural growth, deforestation, urbanization, and infrastructure development. These changes threaten soil fertility, erosion control, water retention, and ecosystem equilibrium. Maintaining agricultural productivity, biodiversity, and ecosystem resilience against climate change requires robust soil health.

The Fincaha'a watershed, noted for its agricultural activity and strategic importance to local communities, is undergoing significant LULC changes that may degrade soil quality. Without a comprehensive understanding of how LULC changes affect soil attributes, management and policy measures to mitigate degradation and improve soil health are insufficient. Thus, this study examines land use and land cover change in the Fincha'a watershed and its effects on soil health. Data-driven insights are provided to support sustainable land management practices and inform policy decisions to protect soil quality, productivity, and ecological integrity in Western Ethiopia's Upper Nile Basin (Golchin, 2018).

MATERIALS AND METHODS

Description of the Study Area

The Fincaha'a watershed in Western Ethiopia's Northwestern Nile Basin was studied. The watershed covers 1,202 square kilometers (120,200 hectares) between latitude 9°15′N and 9°45′N and longitude 37°00′E and 37°45′E. The road from Finfinnee (Addis Ababa) to the Fincaha'a watershed averages 330 kilometers. It's located 45 km southeast of Horro Guduru Wallaga Zone's capital, Shambu. Secondary gravel roads reach inner farming settlements and villages from the Addis Ababa-Nekemte-Shambu-Fincaha'a road corridor. The Fincaha'a Valley occupies parts of Oromia's Horro Guduru Wallaga Zone. It borders the Abbey (Blue Nile) River basin to the north and northeast, the Guder River catchment to the southeast, and undulating highlands and escarpments to the west and south. The watershed is part of Fincaha'a sub-basin, which feeds the Blue Nile with surface water (Abebe et al., 2023).

The area has plateaus, valley bottoms, hills, and escarpments at 1,750–2,750 meters above sea level. Several Ethiopian hydropower and irrigation systems are in the valley, which is drained by the Fincaha'a River and its tributaries (Figure 1). The area's biodiversity is important for local agriculture and water-dependent inhabitants.

The Fincaha'a has a semi-arid to sub-humid climate with wet and dry seasons. The climate is sub-humid, highland tropical with unimodal rainfall. The average annual rainfall is 1,300–1,800 mm, mostly between May and October. Annual temperatures are 15°C to 22°C, colder at higher altitudes. Agriculture, grazing, and forests thrive in this climate. The dry season, from November to April, reduces precipitation, making water management and land usage difficult (Figure 2).

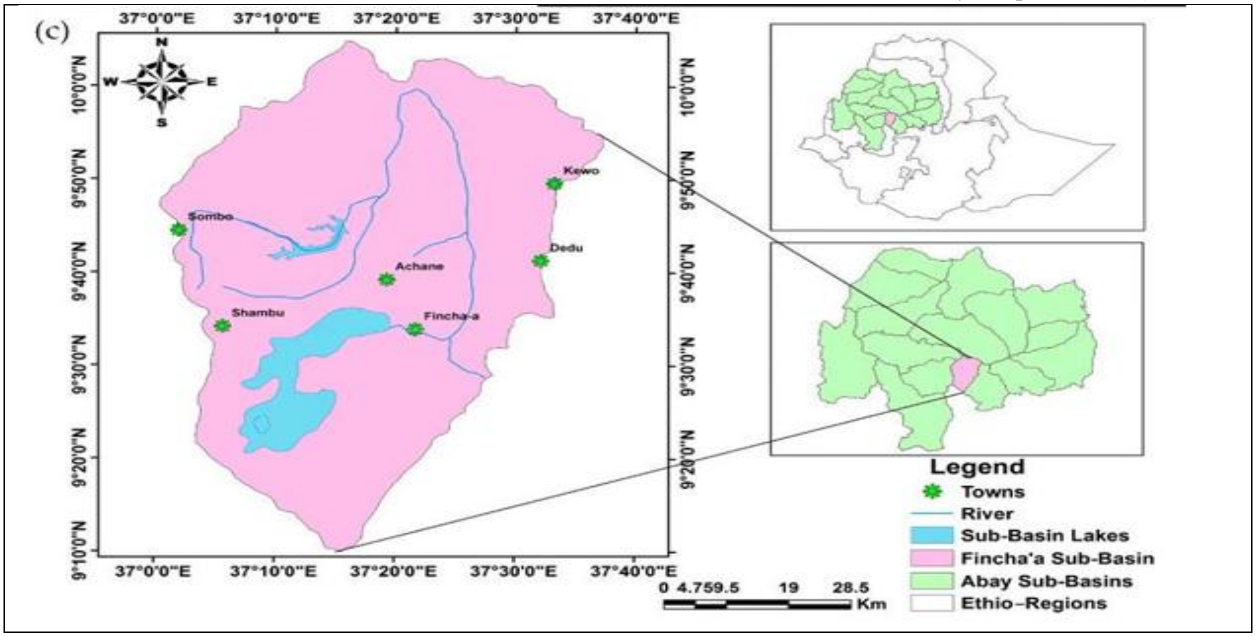

Figure 1. *Location map of the study area.*

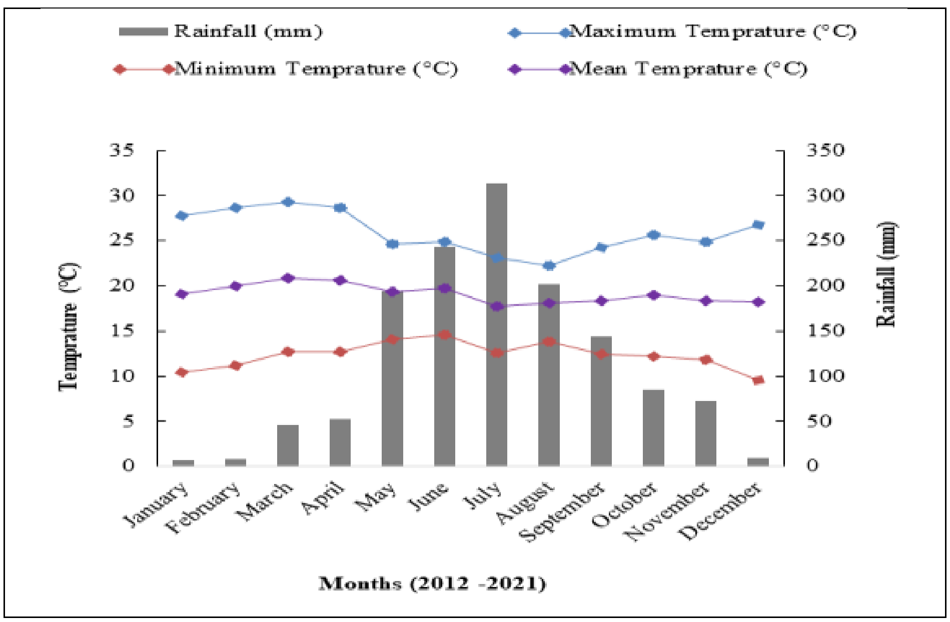

Figure 2. *Mean monthly meteorological data averaged over 10 years (2012-2021) recorded at the experimental site, Fincaha'a Watershed (Source: Fincaha'a Sugar Meteorological Data Station)*

Due to elevation changes, the Fincaha'a watershed has a subtropical climate with temperate and tropical traits. Wet and dry seasons dramatically affect land use and cover in this region. Elevation gradient affects the mean annual temperature, with higher altitudes being cooler.

Geology and Soils

Geologically, the Fincaha'a watershed lies within the Ethiopian highland volcanic complex, with dominant rock types including basalts and tuffs. Soils are primarily Nitisols, Cambisols, and Vertisols, which are generally fertile but susceptible to erosion and degradation under intensive land use. Soil depth and structure vary with topographic position and land cover type (Kitila et al., 2018).

Land Use and Land Cover Dynamics

Over the past few decades, agricultural expansion, population growth, and deforestation have altered Fincaha's Valley's land use and cover. The area was once covered with forests and grasslands with various ecosystems. However, human activity has caused large-scale conversion of woodland and grassland areas to farms and communities. Land degradation and soil erosion have resulted from monocropping and unsustainable farming practices (Kitila et al., 2018; Kourouma et al., 2022; Kebebew, 2020).

Agriculture and Economic Activities

Agriculture drives the local economy, with smallholder farms dominating. Crops such as teff, maize, barley, pulses, and root crops are cultivated. Popular livestock husbandry contributes to food security and economic stability. However, high human density has exacerbated land use, reduced soil fertility, and created erosion risks. Land cover change has also been caused by hydropower infrastructure development (Kourouma et al., 2021; Kebebew, 2020).

Soil Health Implications

The Fincaha'a watershed shows how land use and cover change affect soil health. Land degradation, organic matter loss, and nutrient depletion result from deforestation and agricultural conversion. This affects the watershed's moisture retention and sustainable agriculture. Topsoil, essential for soil productivity and water retention, has also been lost due to erosion.

Environmental and Social Consequences

These land use changes affect water quality and availability in the watershed beyond soil health. The watershed's ability to filter water decreases with plant loss, causing sedimentation and poor water quality in downstream rivers and lakes. Soil degradation reduces agricultural productivity, contributes to food insecurity, and drives migration.

Conservation and Management Efforts

To address these issues, conservation projects have focused on sustainable land management, reforestation, and soil protection. The government, NGOs, and local communities have promoted agroforestry, degraded land restoration, and sustainable farming to increase soil health and erosion resilience. This extensive study of the Fincha'a Valley watershed shows how land use and land cover change and emphasizes the need for sustainable land management to ensure soil health and ecological balance.

Land Use and Land Cover Change

Over the past few decades, population growth, agricultural expansion, deforestation, and climate variability have changed land use and cover in the Fincaha'a Valley watershed. These changes have affected soil fertility, erosion, and water retention.

Evapotranspiration in Fincaha'a Valley Watershed

Evapotranspiration (ET) is essential for understanding the Fincaha Valley's water balance. It represents soil and surface water evaporation and plant transpiration. This parameter is crucial to watershed moisture assessment. Vegetation, climate, and soil affect ET in this region. By disrupting the natural water cycle, LULC changes like deforestation, agricultural expansion, and urban development affect ET. A decrease in wooded areas affects ET rates due to less transpiring plant material, which can worsen water stress and soil moisture levels.

Relative Humidity in the Study Area

Evapotranspiration and relative humidity (RH) influence soil health and land use patterns. Altitude, seasonality, and land cover affect RH. Increased RH promotes dense vegetation and increased transpiration, retaining soil moisture and reducing erosion. Lower RH conditions, generally caused by

LULC shifts like forest land conversion to agricultural land or urban areas, can diminish atmospheric moisture and dry soil. This can lead to reduced soil health, low agricultural productivity, and increased soil degradation. The conversion of wooded regions to agricultural lands and the destruction of native vegetation have reduced soil organic matter and raised erosion risk. Degradation affects the watershed's agricultural output and ecosystem services. However, agroforestry and regulated grazing promote soil health and watershed sustainability. In the Northwestern Nile Basin, western Ethiopia, the Fincaha'a watershed illustrates the complex relationship between land use and climate. Human activities and climate variability alter the terrain, making land management and soil health difficult. Understanding these dynamics is crucial for devising strategies to mitigate adverse impacts and promote resilience in this key watershed.

Design of the Experiment and Soil Sampling

A randomized complete block design (RCBD) was used to assess soil physico-chemical parameters at two representative sites for different land use patterns. The experimental design included three replications for forest, pasture, and cultivated fields. Before site selection, a visual field survey and reconnaissance observation provided data on land use, topography, slope gradient, and vegetation cover. Sites with similar climate and slope, objective land use classifications, or evidence of soil erosion or degradation were selected. To ensure spatial representativeness, zigzag soil samples were taken 0-20 cm deep within each land use category. Three copies of 14 composite soil samples were taken from each treatment plot. No organic materials, stones, gravel, or plant roots were discovered in soil samples. For general physico-chemical investigation, samples were air-dried, crushed, and sieved through a 2 mm mesh. SOC and total nitrogen were determined by screening subsamples through a 0.5 mm mesh. Tags, packages, and 1 kilogram of each composite soil sample were sent to the Bako Agricultural Research Center Soil Laboratory for analysis.

Land Use and Land Cover Analysis

Landsat 5 and 8 satellite imagery from 1990 and 2020 was obtained from the USGS Earth Explorer. Images were processed for LULC classification. ERDAS IMAGINE 2014 used a Maximum Likelihood Classifier for supervised classification. LULC classes included forests, cultivated land, grazing land, urban areas, and water bodies. Field visits and high-resolution images were used to validate classification accuracy using Kappa statistics.

Laboratory Analysis

Undisturbed and disturbed soil samples were collected from 0–20 cm depth to evaluate soil parameters. A stainless-steel core sampler measured bulk density, while augers collected disturbed samples for textural analysis. Following hydroxide pretreatment (H_2O_2) and sodium hex metaphosphate dispersion ($Na_6P_6O_{18}$), hydrometer testing evaluated soil texture (Brevik et al., 2022). Core samples were oven-dried at 105°C for 24 hours to calculate bulk density. Bulk density and assumed particle density (PD) of 2.65 g/cm³ were used to compute total porosity (TP).

All land use treatments were analyzed in triplicate for reliability and statistical validity. Water content was measured using pressure plate extraction. Soil moisture at field capacity (*FC*) and permanent wilting point (*PWP*) was tested at –33 kPa and –1500 kPa, respectively, following Liu et al. (2024). The available water capacity (*AWC*) was calculated as: 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 measured potentiometrically using a digital pH meter following Dinnis (1994). Organic carbon (*OC*) was measured via wet oxidation (Melero et al., 2020). Kjeldahl digestion was used for nitrogen determination (Bremner, 1960). Exchangeable acidity was measured after 1 M KCl extraction using titration (Dai & Richter, 2000).

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 (1965) 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 (Mg^{2+}) and calcium (Ca^{2+}) (Dinnis, 1994). 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. Measured exchangeable K and Na (Dinnis, 1994). The percentage of base-forming cations at exchange sites was calculated by dividing total exchangeable base cations by CEC and multiplying by 100. All chemical assays were done in triplicate for accuracy and reproducibility.

Data Analysis:

The variance of soil parameters among land use types was examined using ANOVA and Tukey's post-hoc test for multiple comparisons in SAS (SAS Institute Inc., 2008). The mean and standard deviation of soil characteristics were computed for each land use category. Excel was used to handle data, calculate means, standard deviations, and soil parameter change rates. The rate of soil parameter change over 30 years was computed by comparing soil property values from 1990 to 2020. Spatial analysis and visualization of LULC changes and soil quality indicators were done in ArcGIS (Version 10.8). ArcGIS was used to map land usage in the research area. After 30 years, LULC maps showed the magnitude of each land use class in 1990 and 2020. Soil health indicators were mapped across the study area to depict regional heterogeneity in critical soil properties under diverse land uses.

RESULTS AND DISCUSSIONS

Results

Land Use and Land Cover (LULC) Change

Land use trends in the Fincaha'a Valley changed significantly from 1990 to 2020. Natural forests were converted into agricultural land, especially for cereal cultivation and grazing, over 30 years. By 2020, forest cover decreased from 40% to 15%, while agricultural land increased from 30% to 55% due to population growth and food production demands (Figure 3).

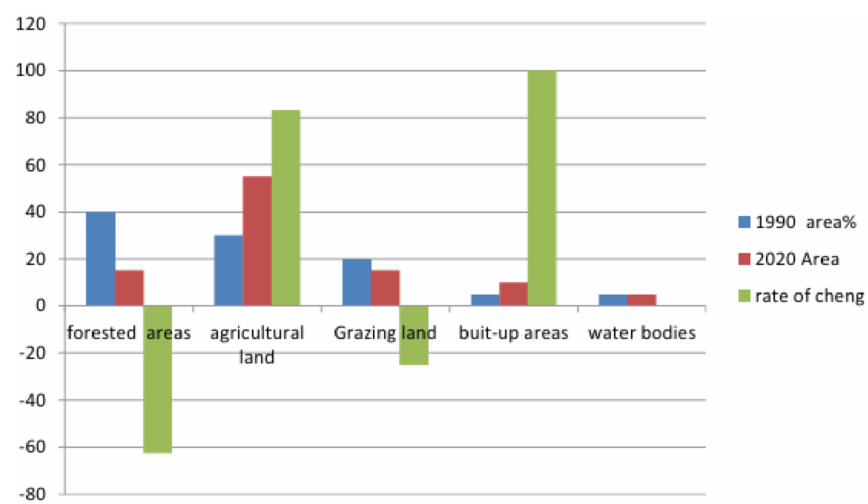

Figure 3. *Land Use and Land Cover Classification in Fincaha'a (1990-2020)*

Similarly, built-up areas increased steadily, indicating urbanization trends. Wetlands and water bodies, essential for biodiversity and soil moisture retention, declined along with these changes. Satellite imagery corroborated these patterns, with vegetation indices showing reduced cover, particularly in agricultural areas.

Soil Health Indicators and Their Response to Land Use Changes

The study examined how land use and land cover (LULC) changes affected Fincaha's watershed soil physical quality parameters. Table 1 shows significant soil physical property differences between forested, agricultural, and grazing regions. Land use types significantly affected bulk density ($F = 22.15$, $p = 0.001$**). Forests had lower bulk density (1.10 ± 0.05 g/cm³), indicating better soil structure and organic matter concentration. In contrast, agricultural ground had the highest bulk density (1.35 ± 0.10 g/cm³), indicating compaction from intensive agriculture and less organic input. Intermediate readings (1.25 ± 0.08 g/cm³) in grazing land indicate moderate disturbance.

Sand, silt, and clay proportions varied slightly among land use types but not significantly ($F = 3.87$, $p = 0.054$). Forested land had a 45:30:25 (sand:silt:clay) texture, while agricultural land had 50% sand and 15% clay, which may reduce water retention. Forage had a 48:32:20 texture. Land use categories vary considerably in water storage ($F = 9.53$, $p = 0.003$**). Forest soil had the maximum moisture retention (40.5 ± 5.4%), followed by grazing land (35.4 ± 3.2%), while agricultural land had the lowest capacity (30.2 ± 4.6%). This graph shows how vegetation cover and soil organic matter affect soil water dynamics. Different soil porosities were also found ($F = 5.72$, $p = 0.021$*). Forested terrain showed the maximum porosity (52.5 ± 3.2%), facilitating improved aeration and root penetration. Agricultural land exhibited lower porosity (47.8 ± 4.1%), indicating higher bulk density, while grazing land (50.0 ± 3.7%) was in between. The greatest significant change was soil erosion rates ($F = 34.91$, $p = 0.000$**). Forests had minimal erosion (5.6 ± 1.4 ton/ha/yr), while agricultural fields had substantial erosion (15.4 ± 2.5 ton/ha/yr) due to tillage and lack of permanent cover. Grazing land experienced considerable erosion (9.3 ± 1.9 ton/ha/yr) due to trampling and diminished vegetation.

Land conversion from forest to agricultural or grazing land has degraded soil physical quality, particularly compaction, water retention, and erosion susceptibility, with serious implications for soil health and sustainable land management. Most soil physical quality indicators across forest, agricultural, and grazing land use systems showed statistically significant differences, indicating that land use/land cover (LULC) change influences soil health (Table 1).

Table 1

Variation of the Mean Soil Physical Quality Indicators and Significant Differences

Soil Physical Quality Indicator	Forested Area (Mean ± SD)	Agricultural Land (Mean ± SD)	Grazing Land (Mean ± SD)	F-value (ANOVA)	p-value
Bulk Density (g/cm³)	1.10 ± 0.05	1.35 ± 0.10	1.25 ± 0.08	22.15	0.001**
Soil Texture (Sand:Silt:Clay)	45:30:25	50:35:15	48:32:20	3.87	0.054
Water Holding Capacity (%)	40.5 ± 5.4	30.2 ± 4.6	35.4 ± 3.2	9.53	0.003**
Soil Porosity (%)	52.5 ± 3.2	47.8 ± 4.1	50.0 ± 3.7	5.72	0.021*
SoilErosionRate (ton/ha/yr)	5.6 ± 1.4	15.4 ± 2.5	9.3 ± 1.9	34.91	0.000**

Overall means within rows and columns followed by different letters are significantly different ($p < 0.05$) with land use and soil depth. Separation when the analysis of variance showed statistically significant differences ($p < 0.05$). ρb = Bulk density, TP = Total porosity, FC = Field capacity, PW

The study also examined the effects of land use and land cover (LULC) changes on selected soil chemical quality indicators. The results (Table 2) reveal statistically significant differences across forested, agricultural, and grazing lands in all the assessed parameters.

The mean SOC concentration varied significantly by land use ($F = 58.21$, $p = 0.000$**). Forested land had the highest *SOC* (3.12 ± 0.45%), indicating higher leaf litter input and less disturbance. The agricultural area had the lowest SOC (1.25 ± 0.28%) due to intensive cultivation, biomass removal, and organic matter oxidation. SOC levels in grazing pastures were moderate (1.80 ± 0.34%) due to partial vegetation and animal manure input. Soil pH varied significantly ($F = 4.12$, $p = 0.029$*), with agricultural land (5.2 ± 0.2) being slightly more acidic than forested (5.6 ± 0.3) and grazing land (5.4 ± 0.2). Continuous application of acidifying fertilizers, organic matter depletion, and leaching may lower agricultural soil pH.

As with SOC, total nitrogen concentration (TN) was highest in forested land (0.18 ± 0.03 g/kg), followed by grazing (0.15 ± 0.04 g/kg) and agricultural land (0.12 ± 0.05 g/kg) ($F = 9.61$, $p = 0.004$**). Long-term cropping without organic amendments or nitrogen replenishment lowers TN in farmed regions. Land use types significantly affected phosphorus availability ($F = 18.74$, $p = 0.000$**). Nutrient recycling from organic matter and litter decomposition led to the greatest P levels (28.5 ± 6.1 mg/kg) in forested soils. P levels were lowest (15.3 ± 4.7 mg/kg) in agricultural land, likely due to crop absorption and erosion. Grazing fields had moderate P levels (20.1 ± 5.3 mg/kg). Potassium levels also varied significantly ($F = 26.83$, $p = 0.000$**). Forests had the highest K levels (300 ± 45 mg/kg), followed by pasture (220 ± 55 mg/kg) and agricultural land (180 ± 50 mg/kg). Continuous crop harvesting and minimal K replenishment deplete K in cultivated soils. Due to organic inputs and natural nutrient cycling, wooded land has better soil chemical quality than agricultural land, which depletes and acidifies. The results show that unsustainable land use changes reduce Fincaha's watershed soil fertility.

Table 2

Variation of the Mean Soil Chemical Quality Indicators and Significant Differences

Soil Chemical Quality Indicator	Forested Area (Mean ± SD)	Agricultural Land (Mean ± SD)	Grazing Land (Mean ± SD)	F-value (ANOVA)	p-value
Soil Organic Carbon (%)	3.12 ± 0.45	1.25 ± 0.28	1.80 ± 0.34	58.21	0.000**
pH (H_2O)	5.6 ± 0.3	5.2 ± 0.2	5.4 ± 0.2	4.12	0.029*
Total Nitrogen (g/kg)	0.18 ± 0.03	0.12 ± 0.05	0.15 ± 0.04	9.61	0.004**
Phosphorus (mg/kg)	28.5 ± 6.1	15.3 ± 4.7	20.1 ± 5.3	18.74	0.000**
Potassium (mg/kg)	300 ± 45	180 ± 50	220 ± 55	26.83	0.000**

Overall means within rows and columns followed by different letters are significantly different ($p < 0.05$) with land use and soil depth. Separation when the analysis of variance showed statistically significant differences ($p < 0.05$).

Rate of Change of Soil Parameters (1990-2020)

The difference in soil parameters between 1990 and 2020 was evaluated and divided by 30 years to calculate the rate of change for each soil parameter due to land use changes. This estimates the average rate of change for each parameter across land use types (Table 3).

Table 3

Rate of Change of Soil Parameters (1990–2020)

Soil Parameter	Forested Area Rate of Change (per year)	Agricultural Land Rate of Change (per year)	Grazing Land Rate of Change (per year)
Bulk Density (g/cm^3)	+0.02	+0.03	+0.02
Soil Texture (Sand:Silt:Clay)	Stable (±0%)	+0.16% Sand, +0.08% Clay	+0.11% Sand, +0.04% Clay
Water Holding Capacity (%)	-0.05	-0.07	-0.05
Soil Porosity (%)	-0.17	-0.20	-0.17
SoilErosionRate (ton/ha/yr)	+0.12	+0.33	+0.21
Soil Organic Carbon (%)	-0.10	-0.07	-0.07
pH (H_2O)	Stable	-0.13	

Correlation analysis

Correlation analysis examined relationships between physical and chemical characteristics and land use categories. The correlation coefficients between soil characteristics under different land uses are shown in Table 4. It presents correlations for SOC, TN, AvP, BD, and pH.

Table 4

Pearson's Correlation Matrix Among Selected Soil Health Indicators

Indicator	BD	SOC	TN	pH	Av.P	CEC	Ex. K	Ex. Ca
BD	1	-0.79**	-0.72**	-0.41*	-0.65**	-0.68**	-0.56**	-0.60**
SOC	-	1	0.86**	0.52**	0.75**	0.84**	0.72**	0.80**
TN	-	-	1	0.40*	0.70**	0.78**	0.66**	0.73**
Soil pH	-	-	-	1	0.42*	0.49**	0.40*	0.44*
Av. P	-	-	-	-	1	0.76**	0.68**	0.72**
CEC	-	-	-	-	-	1	0.74**	0.81**
Ex. K	-	-	-	-	-	-	1	0.76**
Ex. Ca	-	-	-	-	-	-	-	

*Note: Correlation is significant at the 0.01 level (2-tailed) = **, Correlation is significant at the 0.05 level (2-tailed) BD = Bulk Density; OC = Organic Carbon; TN = Total Nitrogen; Av.P = Available Phosphorus; CEC = Cation Exchange Capacity; Ex. K = Exchangeable Potassium; Ex. Ca = Exchangeable Calcium.*

Every land use type showed a strong positive correlation between bulk density (*BD*) and soil organic carbon (*SOC*) (r = 0.82 to 0.91). The lowest organic carbon concentration is on agricultural land, which has the largest bulk density, indicating soil compaction and organic matter loss. Water holding capacity was negatively correlated with bulk density (r = -0.78 to -0.70) and soil porosity (r = -0.80 to -0.75), indicating the importance of porosity in water retention. Water retention capacity decreases with increased bulk density in agricultural fields. Reduced porosity in agricultural areas may impede water infiltration, increasing surface runoff and soil erosion, corresponding with reported erosion rates. Soil organic carbon maintains soil structure and improves porosity (r = 0.88 to 0.87) due to its strong positive connection. Forests with the most organic carbon had the best soil structure. The relevance of organic matter in soil fertility and erosion prevention is highlighted in Table 4.

SOC correlated positively with TN (r = 0.876, p < 0.01) and AvP (r = 0.712, p < 0.01), demonstrating that organic matter-rich land use systems like forests and grasslands maintain higher nitrogen and phosphorus levels. Organic matter is crucial to soil fertility (Table 4). A significant negative association (r = -0.842, p < 0.01) indicates that soils with more organic carbon content exhibit better aggregation and less compaction. Deforestation and farming increased soil bulk density due to plowing and trampling, supporting prior findings. BD was inversely linked with TN (r = -0.799) and AvP (r = -0.702), showing that intense farming may compact soil and deplete nutrients. Soil pH is marginally linked with SOC, TN, and AvP, suggesting organic-rich systems can buffer pH and improve nutrient availability. Highly worn or eroded farmed land becomes more acidic, lowering soil fertility. These data support the idea that turning natural vegetation into agriculture impairs soil health by lowering organic carbon, nitrogen, and phosphorus and compacting it. Degraded fields should be restored with organic matter inputs, reduced tillage, and integrated nutrient management, according to statistics.

DISCUSSIONS

The findings of this study underscore the significant impact of LULC changes on soil health in the Fincaha'a watershed. The observed reduction in forest cover from 40% to 15% between 1990 and 2020, coupled with a substantial increase in agricultural land from 30% to 55%, aligns with regional trends of agricultural expansion and deforestation in Ethiopia (Kitila et al., 2018). These changes have led to significant degradation in soil physical and chemical properties, particularly in cultivated areas. The higher BD (1.35 ± 0.10 g cm^{-3}) in agricultural land compared to forested land (1.10 ± 0.05 g cm^{-3}) indicates soil compaction, likely due to intensive tillage and heavy machinery use, which reduces porosity and water-holding capacity (F = 9.53, p = 0.003). This compaction exacerbates erosion, with agricultural fields showing significantly higher erosion rates (15.4 ± 2.5 t ha^{-1} yr^{-1}) compared to forests (5.6 ± 1.4 t ha^{-1} yr^{-1}). These results are consistent with studies in similar agroecological zones, where conversion of natural vegetation to cropland increases soil susceptibility to erosion and nutrient loss.

The chemical properties of soil, particularly SOC, TN, and AvP, were also adversely affected by LULC changes. Forested soils exhibited the highest SOC (3.12 ± 0.45%), reflecting greater organic matter inputs from leaf litter and minimal disturbance. In contrast, the low SOC in agricultural soils (1.25 ± 0.28%) is likely due to continuous cropping, biomass removal, and oxidation of organic matter, which depletes soil fertility (Demelash et al., 2010). The strong positive correlation between SOC and TN (r = 0.876, p < 0.01) and AvP (r = 0.712, p < 0.01) highlights the critical role of organic matter in maintaining nutrient availability. The slight acidity in agricultural soils (pH 5.2 ± 0.2) compared to forested soils (pH 5.6 ± 0.3) suggests that intensive farming practices, including the use of acidifying fertilizers, contribute to soil acidification, further reducing nutrient availability.

The decline in ET due to reduced forest cover has implications for the watershed's hydrological balance. Forests facilitate higher ET through transpiration, maintaining soil moisture and reducing erosion. The conversion to agricultural land, with lower ET, increases water stress and runoff, as evidenced by the negative correlation between BD and water-holding capacity (r = -0.78 to -0.70). Similarly, the influence of RH on soil moisture retention is critical, with forested areas benefiting from higher RH due to dense vegetation. These findings align with previous research indicating that LULC changes disrupt hydrological cycles and exacerbate soil degradation in highland watersheds (Kourouma et al., 2022).

The socioeconomic implications of these changes are profound. The reduction in soil fertility and productivity in agricultural areas threatens food security and livelihoods in the Fincaha'a watershed, where smallholder farming is the primary economic activity. Increased erosion and sedimentation also degrade water quality in the Blue Nile, affecting downstream communities and hydropower systems. These challenges highlight the need for targeted interventions, such as agroforestry, conservation tillage, and organic amendments, to restore soil health and enhance ecosystem resilience (Kebebew, 2020).

This study's findings support the hypothesis that converting natural vegetation to cultivated land degrades soil health, as evidenced by reduced SOC, TN, and AvP, and increased BD and acidity. The results emphasize the importance of sustainable land management practices to mitigate these impacts and ensure long-term agricultural productivity and environmental sustainability in the Fincaha'a watershed.

CONCLUSIONS

This study demonstrates that LULC changes in the Fincaha'a watershed, driven by agricultural expansion, deforestation, and urbanization, have significantly degraded soil health. The substantial reduction in forest cover and increase in cultivated land from 1990 to 2020 have led to increased *BD*, reduced *SOC*, *TN*, and *AvP*, and higher erosion rates, compromising soil fertility and ecosystem services. These changes threaten agricultural productivity, water quality, and the livelihoods of local communities dependent on the watershed. The strong correlations between *SOC* and other soil health indicators underscore the critical role of organic matter in maintaining soil structure and nutrient availability. To address these challenges, sustainable land management practices, including agroforestry, conservation agriculture, and reforestation, are essential. These strategies can enhance soil resilience, reduce erosion, and improve water retention, ensuring the long-term sustainability of the Fincaha'a watershed. Policymakers and stakeholders should prioritize data-driven interventions to protect soil health and support ecological balance in this critical region of the Upper Nile Basin.

Recommendations

These conclusions lead to the following recommendations: Promote agroforestry, crop rotation, cover cropping, and conservation tillage to improve soil structure and organic matter. Use organic and inorganic inputs to control soil fertility. Reforest and afforest steep, erosion-prone slopes. Start community-based watershed rehabilitation programs to conserve soil and water. Local land use rules should minimize uncontrolled cultivation and settlements in forest and grazing areas. Support land certification and tenure stability to encourage sustainable land usage. Teach farmers soil health, conservation agriculture, and climate-smart techniques. Plan and monitor land usage with local stakeholders. Set up long-term soil health monitoring across land uses. Promote soil-carbon dynamics and climate interactions research in the Fincaha'a Watershed under varied land management regimes.

CRediT Authorship Contribution Statement

The author affirms sole responsibility for the conception of the study, the presentation of results, and manuscript preparation.

Declaration of Competing Interest

The author declares that there is no conflict of interest.

Ethical approval

Not Applicable

Data Availability

The data used in this study are available upon request.

Acknowledgments

The author is thankful to the Department of Physics, Wollega University, Ethiopia, for providing the necessary support to accomplish this study.

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