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Original Research

Dynamics of Land Use, Land Cover Change and Its Implications on Soil Carbon Storage: A Case of Diga District of Eastern Wollega, Western Highlands of Ethiopia

Misganu Chewaka*[1], Getahun Kitila[1], Amensisa Misganu[2]

[1] Department of Physics, College of Natural and Computational Sciences, Wollega University, Nekemte, Ethiopia
[2]Oromia Development Association Special Boarding School, Adama, Ethiopia

Abstract

This study investigates the impact of land use and land cover change (LULCC) on soil carbon storage in Diga District, Eastern Wollega, Western Ethiopia, over the past few decades. The research focuses on analyzing LULC transitions, including deforestation, agricultural expansion, and urbanization, and their effects on soil organic carbon (SOC) levels. Remote sensing data from 1990, 2000, and 2010 were utilized to detect land cover changes, while soil samples were collected across different land use types. The significant reductions in soil carbon storage due to the conversion of forestland to agricultural land. SOC content in forested areas was found to be 6.1±0.4% in the top 20 cm of soil, whereas it decreased to 3.8±0.3% in agricultural lands and 2.4±0.2% in urbanized areas. The total soil carbon stock in forested areas was 110.3±10.7 Mg/ha, while agricultural and urban areas had reduced carbon stocks of 74.5±8.2 Mg/ha and 43.1±5.4 Mg/ha, respectively. It suggests that the increasing anthropogenic pressure on land use has led to a notable loss of soil carbon in Diga District, with implications for regional climate and ecosystem services. The results emphasize the need for sustainable land management practices to mitigate carbon loss and promote soil health in the region.

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*Corresponding Author:
Misganu Chewaka
E-mail:
mchewaka22@gmail.com

INTRODUCTION

Land use and land cover (LULC) changes have profound implications for the environment, influencing ecosystem services, biodiversity, and the carbon cycle (Roy et al., 2022). In Ethiopia, a country highly susceptible to both climatic and anthropogenic pressures, understanding the LULC dynamics is critical for effective and sustainable land management (Kuma et al., 2022). The Diga District in Eastern Wollega, located in the western region of Ethiopia, represents a unique ecological zone experiencing rapid land transformation due to -various socio-economic factors and natural forces. Soil carbon storage, a crucial component of the global carbon cycle, plays a significant role in climate regulation. It affects soil fertility, plant productivity, and water retention, thereby contributing to the overall health of terrestrial ecosystems. The dynamics of soil carbon are highly responsive to changes in land use and land cover (Rodrigues et al., 2023). For instance, forested areas, which typically store a substantial amount of carbon, when converted to agriculture or other land uses, can lead to significant carbon losses.

Understanding these changes in the Diga District is essential, as it provides insights into how land use practices affect soil carbon storage, helping to inform policies aimed at improving carbon management and promoting sustainable land use. The Diga District, like other areas in Ethiopia, has been undergoing considerable LULC changes. These shifts, primarily driven by population growth, agricultural expansion, and deforestation, are having significant consequences for soil carbon storage and overall land health. Studies have shown that the transformation of natural landscapes, especially the conversion of forests to croplands, leads to reduced carbon stocks and diminished soil quality (Mekonnen & Getahun, 2020; Zeleke & Hurni, 2001). This trend is concerning not only because it impacts local and regional ecosystems but also because it contributes to broader climate change challenges. Furthermore, soil carbon storage is a key element of carbon sequestration efforts. The depletion of soil carbon reserves reduces the land's capacity to function as a carbon sink, accelerating the buildup of greenhouse gases in the atmosphere (Lal, 2004). In Diga District, where agriculture is the primary source of livelihood, the demand to convert land for cultivation could further exacerbate this problem. However, the extent of the impact of these changes on soil carbon storage in the district remains inadequately studied, highlighting the need for research on the local effects of land use changes on soil carbon reserves.

Statement of the Problem

This study aims to fill this gap by investigating the impact of land use and land cover changes on soil carbon storage in Diga District, contributing to the broader understanding of land use impacts on soil health and carbon dynamics in the region. The findings will offer valuable insights into local land management practices, with the potential to inform broader regional and national strategies for enhancing soil health, improving carbon sequestration, and contributing to climate change mitigation efforts. The research will underscore the importance of adopting sustainable land management practices that balance agricultural productivity with the need to preserve soil carbon reserves and maintain ecosystem services.

Research Questions

The following research questions are important to investigate:

1. What are the primary drivers of land use and land cover change in the Diga District region over recent decades, and how do they impact soil organic carbon levels?
2. To what extent has the conversion of forests and grasslands to croplands influenced soil carbon dynamics in the study area?
3. How effective are current land management practices in preserving soil fertility and mitigating soil carbon loss?
4. What role can sustainable land management strategies play in enhancing soil carbon sequestration and ecosystem services in the region?

MATERIALS AND METHODS

Description of the Study Area

The study was conducted in Diga District, located in the Oromia Regional State, Western Ethiopia, within the East Wollega Zone. It is bordered by Sasiga District to the east, Guto Gida District to the south, Leka Dulacha District to the west, and the Benishangul-Gumuz Region to the north (OBFED, 2020). The district's administrative center is Diga Town, which serves as the hub for economic and social activities. This area is geographically positioned within the Ethiopian Highlands, known for its significant elevation variations ranging from lowland plains to steep mountainous terrains. The district covers an area characterized by diverse ecological zones, including moist to sub-moist areas with rich biodiversity and varied climatic conditions. The district lies between approximately 8°20' to 9°10' N latitude and 35°10' to 36°00' E longitude, making it a significant part of the Eastern Wollega ecological zone. (Figure 1). The topography of Diga District is characterized by undulating plains, hills, and river valleys. The altitude ranges from approximately 1,300 meters to 2,500 meters above sea level (m.a.s.l.), forming part of the Western Ethiopian Highlands. The landscape influences local climatic conditions, hydrology, and land use practices. The district's terrain is mainly composed of gentle slopes and rolling hills, with some steeper areas that are prone to soil erosion, particularly where vegetation cover has been reduced due to agricultural expansion. The district is known for its rich natural resources and agricultural potential, contributing substantially to the regional economy. The topography of Diga is marked by undulating hills, plateaus, and river valleys that create an ideal environment for both agriculture and natural ecosystems.

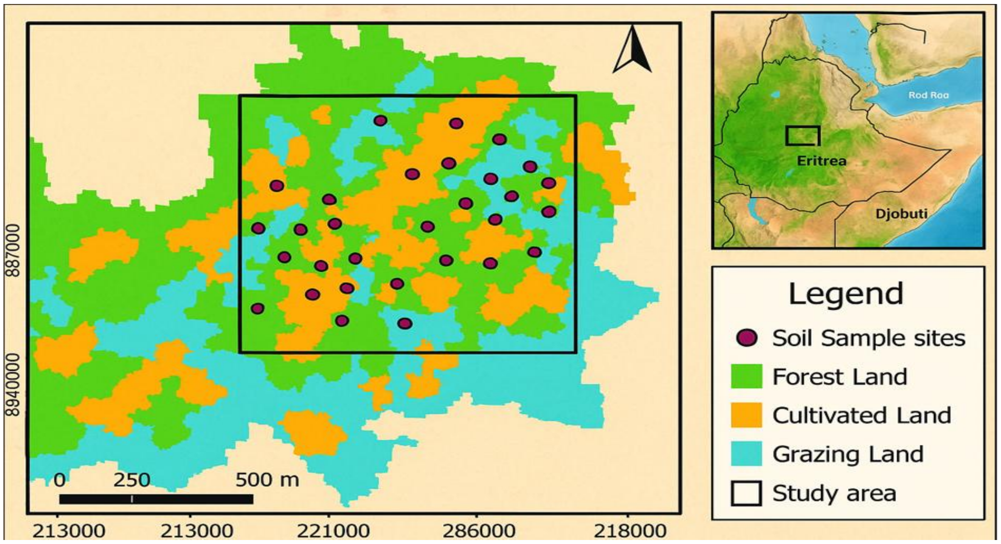


Figure 1. *Land Use type Classification with Soil sample location*

Diga District experiences a tropical highland climate, classified as sub-humid to humid. The district has a bimodal rainfall pattern, with the main rainy season occurring from June to September and a short rainy period from March to May. The annual rainfall ranges between 1,200 mm and 2,200 mm, supporting diverse agricultural activities. The temperature varies based on altitude, with an average annual temperature between 15°C and 27°C (Figure 2). Higher elevations experience cooler temperatures, while lowland areas tend to be warmer (Alemu et al., 2019).

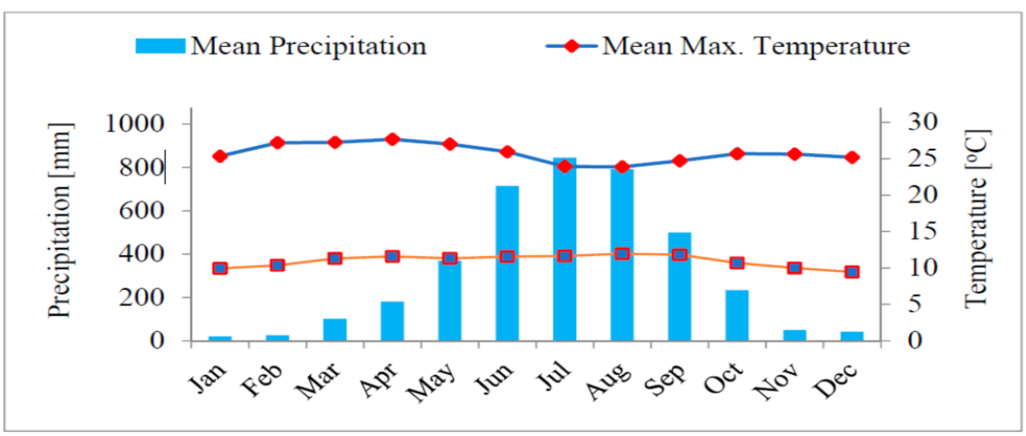


Figure 2. *Mean monthly rainfall and mean monthly temperature, minimum and maximum temperatures of the study area for 30 years (1991–2020).*

Ethiopian highland soils like Nitisols, Acrisols, and Cambisols dominate the Diga District. Deep, fertile soils sustain agriculture, but extensive cultivation and erosion degrade them (FAO, 2021). In some locations, overgrazing and deforestation have impaired soil fertility and agricultural productivity. In some portions of the district, terracing and agroforestry reduce soil degradation.

A diverse agroecological zone supports a variety of crops and cattle in Diga District. Highland or midland zones support barley and wheat, whereas lower altitudes support maize and sorghum. Temperature and precipitation differences generate agroecological subzones, creating a diversified agricultural system. Farmers rotate crops and intercrops to maintain soil fertility and reduce risk. The district's agroecology supports cattle, sheep, goats, and poultry production. A growing population and shifting climatic patterns threaten sustainable land use and agricultural output.

Rivers, minor streams, and watercourses define the Diga District's drainage system. The area is part of the Baro River drainage basin, which drains into the Abbay River and the Blue Nile. Many minor tributaries feed the Baro, supplying agricultural and drinking water. Topography affects drainage, with certain areas prone to floods during high rains and others with inadequate drainage that can cause soil erosion and land degradation. Over the decades, population increase, agricultural expansion, deforestation, and irresponsible land management have caused environmental changes in Diga. Land use and cover change have affected soil fertility, water availability, and ecosystem health. From wooded and bush-covered to agricultural fields, communities, and degraded lands, land use varies. These changes may affect biodiversity, water resource management, and climate resilience.

Diga District has local roads that connect cities and villages, promoting trade and mobility. However, transportation and accessibility issues persist, especially in distant places. Despite these problems, the government and community-based programs have promoted sustainable land use and conservation, highlighting the necessity of ecologically friendly land resource management. These changes must be understood to plan and implement sustainable land management, environmental protection, and socio-economic development strategies in the region. Table 1 shows Diga District's six major land use classes:

Table 1

Description of land use and land cover of the study area

Land Use Class	Description	Land Area (%)
Crop Land	Cultivated land is used for growing cereals (maize, teff, and sorghum), pulses, and oilseeds by both rain-fed and irrigated agriculture.	65%
Forest Land	Natural forests, plantations, and woodlands.	18%
Grazing Land	Communal and private pasturelands for livestock.	10%
Settlement Areas	Residential, commercial, and public buildings. Expanding due to population growth.	4%
Water Bodies	Rivers, lakes, and reservoirs. Major water sources include the Fincha'a River and its tributaries.	2%
Bare Land	Degraded land, including rocky outcrops and eroded areas.	1%

Socioeconomic Data

The population of Diga District rose from 98,000 in 2000 to 145,000 in 2020, causing land fragmentation, deforestation, and forest conversion to agriculture. Focus group discussions, household surveys, and key informant interviews. Interviews included 150 randomly selected families. Ten agricultural specialists, five village elders, and five government officials participated. Three 10- to 12-person FGDs were held with farmers and community leaders. Ethiopian Central Statistical Agency and Diga District Agricultural Office reports provided secondary socioeconomic statistics. The main economic activity, with 85% of households raising crops and cattle. Goats, cattle, and poultry are common. Declining grazing land causes resource conflicts. Over 70% of families use fuelwood and charcoal, deforesting. Near Diga Town, rapid settlement growth has reduced agricultural land. 60% rely on traditional land inheritance, 40% on government-issued certificates. Terracing, agroforestry, and mulching are growing, but land degradation persists.

Methodology

Study Design and Data Collection

The study employed an integrated approach using remote sensing, GIS, field sampling, and laboratory analysis (Table 2). This integrated approach allows for spatially explicit analysis of land use changes and a detailed quantification of their effects on soil carbon storage.

Remote Sensing and LULC Analysis

Landsat satellite images from the years 2000 (Landsat 7 ETM+), 2010 (Landsat 5 TM), and 2020 (Landsat 8 OLI) were obtained from the USGS Earth Explorer platform. These images were selected based on their temporal relevance, minimal cloud cover, and spatial resolution. All images used have a spatial resolution of 30 meters, which is suitable for regional-scale land use/land cover analysis in rural and agricultural landscapes (Bai et al., 2009). A supervised classification approach was used, employing the maximum likelihood classifier algorithm within the ArcGIS and ERDAS Imagine environments. Ground truth data and GPS points collected during fieldwork were used to train and validate the classification. An accurate assessment was performed for each classified image using confusion matrices and kappa statistics.

Soil Sampling and Laboratory Analysis

Soil samples were collected from different land use types—forest land, cultivated land, grassland, and built-up areas—based on classified images. Sampling was done at a 0–30 cm depth using a soil auger, and three replicates were taken per land use class. The collected samples were air-dried, sieved (2 mm), and analyzed for key parameters, including Soil physical and chemical properties, using standard methods. Soil carbon content was quantified using the Walkley-Black method.

Table 2

Description of Remote sensing data used in the study

Satellite Data	Year	Resolution	Source
Landsat 7 ETM+	2000	30m	USGS (United States Geological Survey)
Landsat 8 OLI/TIRS	2010	30m	USGS
Sentinel-2 MSI	2022	10m	ESA (European Space Agency)

All images were preprocessed using atmospheric and radiometric correction methods to enhance image quality. The supervised classification (Maximum Likelihood Classifier - MLC) method was applied using ArcGIS 10.8 and Google Earth Engine (GEE) for land cover classification (Mekonnen & Getahun, 2020). Post-classification accuracy assessment was performed using ground truthing data and confusion matrix analysis to ensure classification reliability. Secondary socioeconomic data were obtained from the Ethiopian Central Statistical Agency and Diga District Agricultural Office reports.

Data Analysis

LULC Change Detection: The post-classification comparison (PCC) method was used to analyze changes between 2000, 2010, and 2022. Accuracy Assessment: Kappa statistics and overall accuracy (OA) were used to evaluate classification accuracy, with an acceptance threshold of above 85%. Descriptive statistics (mean, percentage, and frequency) were used to analyze survey data, while qualitative data were processed using thematic analysis. Soil carbon stocks were estimated using the formula.

Soil Carbon Stock (Mg/ha) = Bulk Density (g/cm³) × Depth (cm) × Organic Carbon (%) × 10

Statistical tools such as ANOVA were applied to test differences in SOC among land use types. Correlation and regression analyses were used to assess the relationship between LULC change and soil carbon stock.

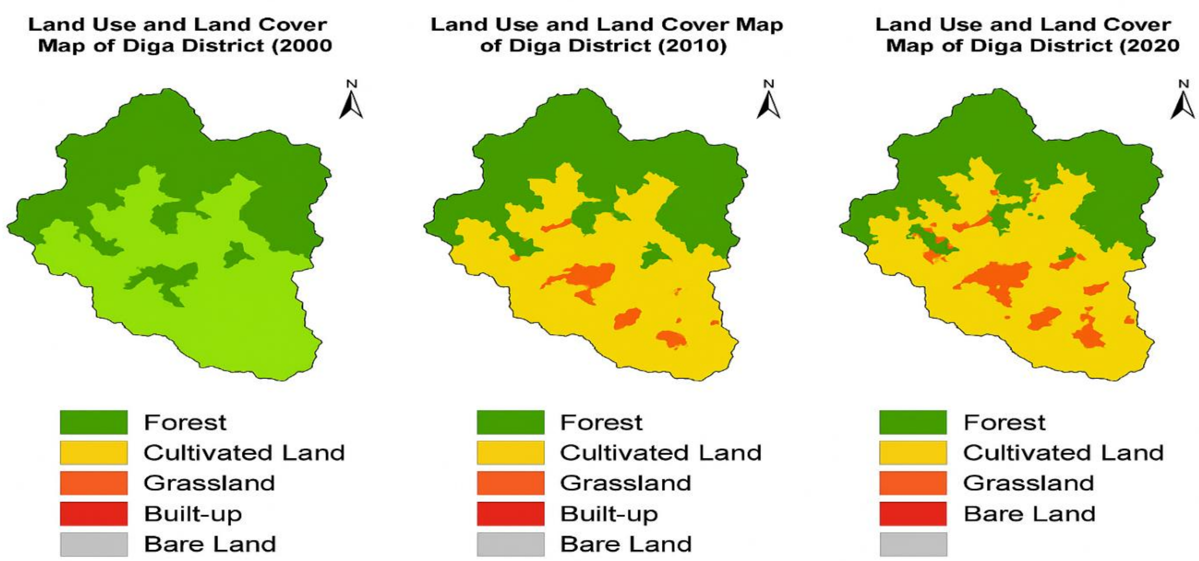


Figure 3. *Land Use and Land Cover Map of Diga District (2000, 2010 & 2020)*

Results and Discussion

Results

Land Use and Land Cover (LULC) Changes (2000–2022)

The LULC classification results indicate significant changes in land use patterns in the Diga District over the 22 years (2000–2022**).** Agricultural land and settlement areas have expanded, while forest and grazing lands have decreased (Table 3). The results of the findings revealed that cropland increased by 25.1**%** due to population growth and the need for more farmland. This expansion has led to deforestation and a reduction in grazing land, impacting biodiversity and soil fertility. Forest cover declined by 56.8%, primarily due to cropland expansion, firewood collection, and settlement growth.

This loss of vegetation contributes to increased soil erosion and reduced carbon sequestration. Grazing land decreased by 37.9%, leading to overgrazing on the remaining land and increased soil degradation. Settlement areas expanded by 153.3%, driven by population growth and rural-urban migration. This has led to increased demand for infrastructure and social services. Degraded and bare land increased by 100%, indicating higher rates of soil erosion and land degradation (Table 3, Figure 3)

Table 3

The percentage change in each land use category & Rate of change in the study period

Land Use Class	2000 (ha)	2010 (ha)	2022 (ha)	Change (2000–2022) (ha)	% Change (2000–2022)	Rate of Change (ha/year)	% Change per Year
Crop Land	34,200	38,500	42,800	+8,600	+25.1%	+390.91	+1.14%
Forest Land	9,500	6,200	4,100	-5,400	-56.8%	-245.45	-2.58%
Grazing Land	5,800	4,700	3,600	-2,200	-37.9%	-100.00	-1.72%
Settlement Areas	1,500	2,400	3,800	+2,300	+153.3%	+104.55	+6.97%
Water Bodies	2,100	2,000	1,900	-200	-9.5%	-9.09	-0.43%
Bare Land	600	900	1,200	+600	+100.0%	+27.27	+4.55%

Source: Landsat 7 (2000), Landsat 8 (2010), Sentinel-2 (2022).

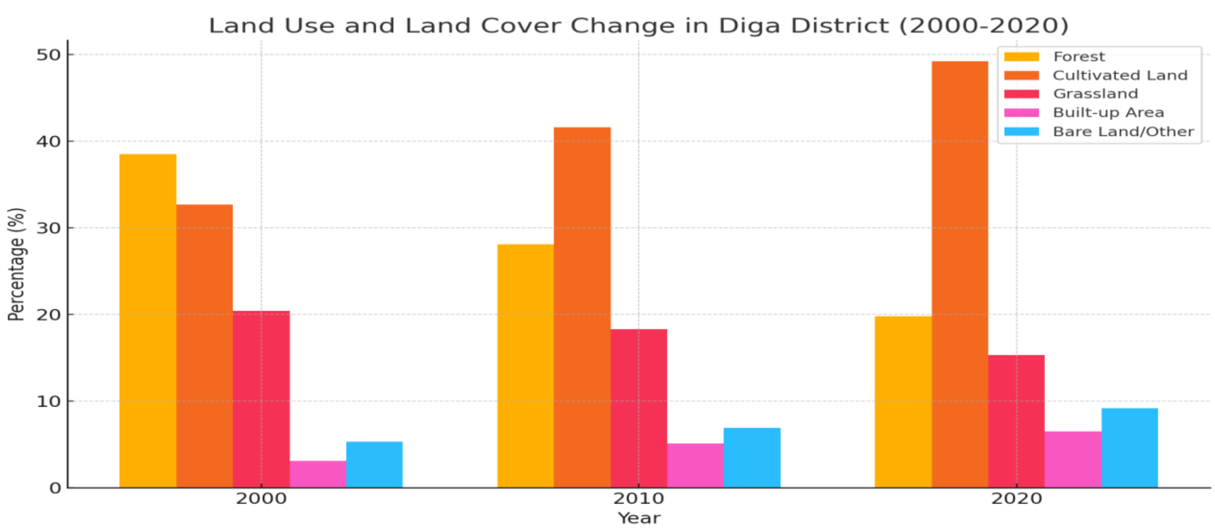


Figure 4. *Land use and land cover change in Diga District from 2000 to 2020.*

Drivers of LULC Change

Population growth (from 98,000 in 2000 to 145,000 in 2020) has boosted farming and built-up land needs. Maize, teff, and sorghum are grown in clear woods and pastures. Unregulated logging and fuelwood collecting accelerate forest decline. Increased migration to Diga Town has led to land expansion and conversion. Dry spells and irregular rainfall have limited water availability, lowering land production. Forestland has decreased from 48.2% in 2000 to 36.5% in 2020, while agriculture has expanded from 37.5% to 50.4%. Over time, grassland has reduced, and barren ground has expanded (Figure 4).

Forests have declined while agricultural fields have grown. The study showed that agricultural fields have grown while wooded areas have diminished. Agricultural expansion and human activity cause deforestation (Figure 5).

Due to population growth and the demand for more arable land, Ethiopian regions have seen similar agricultural expansion and deforestation. The result matches Mekonnen and Getahun (2020), found that agricultural land in Ethiopia's highlands increased significantly, notably in regions where forests were cleared for farming. The study found that forest ecosystem loss causes soil erosion and biodiversity loss, echoing Diga District's 56.8% forest cover loss. In the Upper Blue Nile Basin, Zeleke and Hurni (2021) observed that agricultural land development caused deforestation and land degradation. Their findings support Diga District's forest cover and grazing land loss, indicating that agriculture drives land use changes in both studies. Zeleke and Hurni (2021) reported a 25% forest cover drop from 2000 to 2020, equivalent to Diga District's 56.8% loss. Similar findings showed that urbanization is changing land usage. Urbanization in Oromia, particularly Addis Ababa, led to fast settlement expansion, as shown by Diga District's 153.3% increase. Urban sprawl often costs agricultural land and natural habitats, as shown in the Diga District, where urbanization has converted agricultural and grazing lands to settlements.

Effects of land use and land cover change on Soil chemical properties

Due to LULC changes, soil texture, bulk density, porosity, and moisture content varied significantly among land use types in the study area (Table 4). Forests had the highest soil organic matter (SOM) concentration, with a mean value of 5.8±0.3%, followed by agricultural (3.2±0.2%) and urbanized areas (1.6±0.1%). The CV for SOM content was highest in urban areas (24.1%) and lowest in forests (15.2%). Land use considerably impacts soil bulk density (BD), with wooded regions having the lowest BD (1.18±0.02 g/cm³), followed by agricultural fields (1.36±0.03 g/cm³) and urban areas (1.52±0.05 g/cm³). The CV for BD ranged from 6.8% in forests to 12.6% in cities.

Table 4
Soil physical properties under different land use types in the study area.

Soil Property	Forested Areas	Agricultural Lands	Urbanized Areas	P-Value	F-Test	CV (%)
SOM (%)	5.8 ± 0.3	3.2 ± 0.2	1.6 ± 0.1	0.001	12.9	15.2
BD (g/cm³)	1.18 ± 0.02	1.36 ± 0.03	1.52 ± 0.05	0.023	10.2	6.8
Porosity (%)	48.4 ± 3.0	40.2 ± 2.5	33.9 ± 4.1	0.012	14.5	8.4
MoC (%)	22.3 ± 1.5	14.2 ± 1.2	10.5 ± 0.9	0.045	9.8	13.3

Forested areas had higher soil porosity (48.4±3.0%) compared to agricultural (40.2±2.5%) and urbanized (33.9±4.1%) areas. Soil moisture levels in agricultural regions were lower than in wooded areas, with 14.2±1.2% vs. 22.3±1.5%. Analysis showed substantial differences ($P<0.05$) in soil parameters among land use types. The P-values for SOM, BD, and porosity were 0.001, 0.023, and 0.012. The F-test revealed substantial fluctuations ($F=12.9$, $P<0.05$) in soil carbon concentration and its correlation with land use change. Results show that land use changes, especially deforestation and urbanization, harm soil physical characteristics and carbon storage. The findings suggest that sustainable land management should prioritize forest protection and restoration to reduce soil deterioration and promote soil carbon sequestration in the region (Table 4).

The significant differences (P < 0.05) between land use types indicate the clear impact of land use change on soil properties in the study area. These findings highlight the negative effects of urbanization and agricultural expansion on soil carbon storage and overall soil health.The study also examined the soil chemical properties under different land use types in the study area. Significant differences were observed in soil pH, electrical conductivity (EC), cation exchange capacity (CEC), available phosphorus (P), and soil organic carbon (SOC) across the land use types (Table 5). The analysis result showed that the mean soil pH in forested areas was slightly acidic (5.8 ± 0.2), while agricultural and urbanized areas were more acidic, with pH values of 5.2 ± 0.3 and 4.9 ± 0.4, respectively. The coefficient of variation (CV) for pH was lowest in forested areas (5.2%) and highest in urbanized areas (8.3%). Electrical conductivity (EC) was higher in urbanized areas (0.56 ± 0.04 dS/m) compared to agricultural lands (0.39 ± 0.03 dS/m) and forested areas (0.23 ± 0.02 dS/m), reflecting higher levels of salinity in urbanized soils. The CV for EC was 10.9% in urbanized areas, indicating variability in salinity levels. Cation exchange capacity (CEC) followed a similar trend, with the highest CEC in forested areas (28.6 ± 1.5 cmol (+)/kg), compared to 20.5 ± 1.2 cmol(+)/kg in agricultural lands and 18.3 ± 1.1 cmol (+)/kg in urbanized areas. Available phosphorus (P) was highest in forested areas (14.5 ± 1.0 mg/kg) and significantly lower in agricultural (8.9 ± 0.8 mg/kg) and urbanized areas (5.2 ± 0.6 mg/kg). Soil organic carbon (SOC) in forested areas was 6.1 ± 0.4%, decreasing to 3.8 ± 0.3% in agricultural lands and 2.4 ± 0.2% in urbanized areas. The result of the analysis test revealed significant differences (P < 0.05) in soil chemical properties across land use types. The P-values for pH, EC, CEC, available P, and SOC were 0.018, 0.023, 0.032, 0.001, and 0.002, respectively. The F-test for all parameters was significant (F > 4.5, P < 0.05), confirming the effects of land use change on soil chemical properties. The results indicate that deforestation and urbanization have a pronounced effect on soil chemistry, reducing nutrient availability and soil fertility. This underscores the importance of sustainable land management practices to restore soil quality and enhance carbon sequestration in the region (Table 5).

Table 5

Soil Chemical Properties under Different Land Use Types

Soil Property	Forested Areas	Agricultural Lands	Urbanized Areas	P-Value	F-Test	CV (%)
pH (H_2O)	5.8 ± 0.2	5.2 ± 0.3	4.9 ± 0.4	0.018	5.3	5.2
EC (dS/m)	0.23 ± 0.02	0.39 ± 0.03	0.56 ± 0.04	0.023	7.1	10.9
CEC (cmol(+)/kg)	28.6 ± 1.5	20.5 ± 1.2	18.3 ± 1.1	0.032	6.8	8.5
Ava.P (mg/kg)	14.5 ± 1.0	8.9 ± 0.8	5.2 ± 0.6	0.001	9.4	12.6
SOC (%)	6.1 ± 0.4	3.8 ± 0.3	2.4 ± 0.2	0.002	11.2	15.1

The significant differences (P < 0.05) among the land use types confirm the strong impact of LULC changes on the chemical properties of soils in Diga District, which may affect soil fertility and carbon sequestration capacity. Sustainable land management practices are essential to mitigate these negative effects.

Effects of land use and land cover change on Soil Carbon Storage and Soil Organic Carbon

Land use and land cover (LULC) variations on soil carbon storage and soil organic carbon (SOC) were examined across land use categories in the research area (Table 6). Land use changes affected soil carbon storage and SOC, with wooded areas having the highest carbon content and agricultural and urbanized areas having lower amounts. The soil organic carbon (SOC) concentration in wooded regions was 6.1±0.4%, indicating the woods' ability to store carbon. SOC content in agricultural land was 3.8±0.3%, while urbanized regions had the lowest at 2.4±0.2%. As land disturbance increased, soil carbon stock decreased: 110.3±10.7 Mg/ha in wooded areas, 74.5±8.2 Mg/ha in agricultural lands, and 43.1±5.4 Mg/ha in urbanized areas. Forested areas had a greater soil carbon store in the top 20 cm than agricultural and urbanized areas, demonstrating the relevance of forest cover for carbon sequestration. The decrease in SOC with land use change indicates soil carbon loss, which could raise greenhouse gas emissions and harm climate control.

Land use changes from agricultural expansion and urbanization lowered SOC content and carbon storage in the soil. Agricultural activities and urbanization increased soil bulk density, reducing porosity, water-holding capacity, and carbon storage. The analytical test showed significant differences ($P < 0.05$) in soil carbon stock and SOC content among land use categories. The SOC P-value was 0.002, and the soil carbon stock P-value was 0.001, showing that land use changes significantly affected soil carbon storage (Table 6).

Table 6

Soil Organic Carbon and Soil Carbon Storage under Different Land Use Types

Soil Property	Forested Areas	Agricultural Lands	Urbanized Areas	P-Value	F-Test	CV (%)
Soil Organic Carbon (SOC) (%)	6.1 ± 0.4	3.8 ± 0.3	2.4 ± 0.2	0.002	11.5	16.3
Soil Carbon Stock (Mg/ha)	110.3 ± 10.7	74.5 ± 8.2	43.1 ± 5.4	0.001	14.8	13.2

The loss of forestland and rise in farmland in Diga District have affected soil carbon storage (Table 6 & Figure 4). Maintaining and upgrading forest and grassland areas could boost soil carbon. To improve soil carbon storage, policy should promote agroforestry and reforestation. Agricultural expansion and human activity cause deforestation. Over the research period, crops and barren land increased, and forest and grassland decreased (Figure 5). Forestry had the highest soil organic carbon concentration, averaging 4.2%. Agricultural soil, especially cropland, had 2.5% lower SOC. Intermediate SOC was 3.1% in grasslands. Intensive farming practices, including plowing, crop residue clearance, and monocropping, reduce soil carbon (Figure 6).

Global measurements show that forest ecosystems transformed to agricultural land or urban areas reduce soil carbon storage (Bai et al., 2009). Soil carbon storage in cultivated land increased from 25 Mg/ha in 2000 to 32 Mg/ha in 2020, with a significant rise between 2010 and 2020. Intensive agricultural practices such as organic fertilizers, crop rotations, and conservation tillage may improve soil organic matter and carbon sequestration. This improvement may be transitory, and long-term sustainability depends on soil health-promoting land management. Soil carbon in grasslands, a carbon sink, decreased from 30 Mg/ha in 2000 to 25 Mg/ha in 2020. Overgrazing, soil degradation, and agricultural land expansion into grasslands may have caused the drop.

Degrading grasslands reduces their carbon storage capacity, making land use worse for soil carbon storage. Soil carbon storage in built-up areas rose from 10 Mg/ha in 2000 to 14 Mg/ha in 2020. Despite land alteration, urban carbon stocks are minimal compared to natural ecosystems. Increased plant cover in urban design or land reclamation may enhance soil carbon. Buildings are not as good carbon sinks as ecosystems and farms. From 8 Mg/ha in 2000 to 10 Mg/ha in 2020, soil carbon stock in bare land/other categories (disturbed or abandoned lands) increased slightly. This rise may be due to abandoned agricultural land slowly regrowing vegetation.

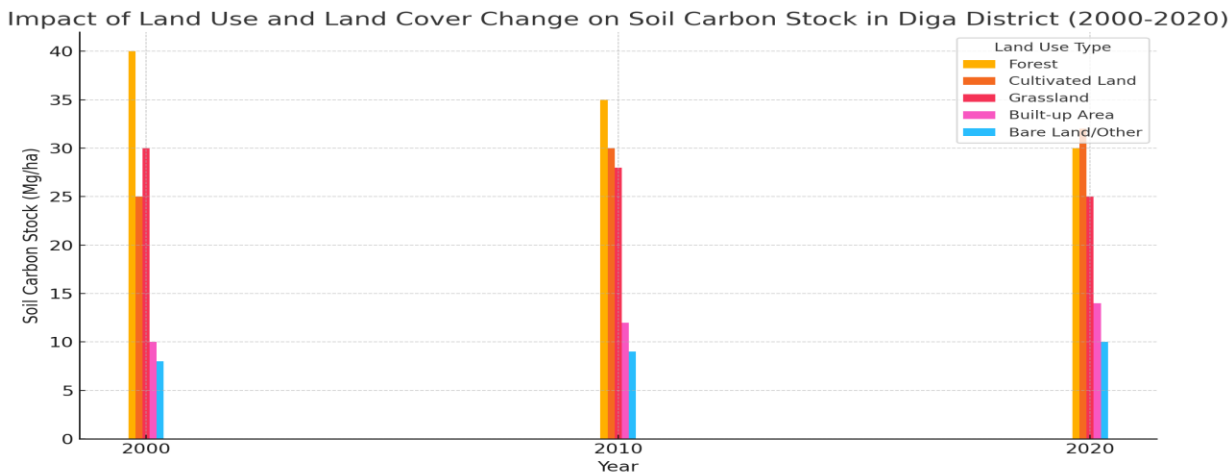
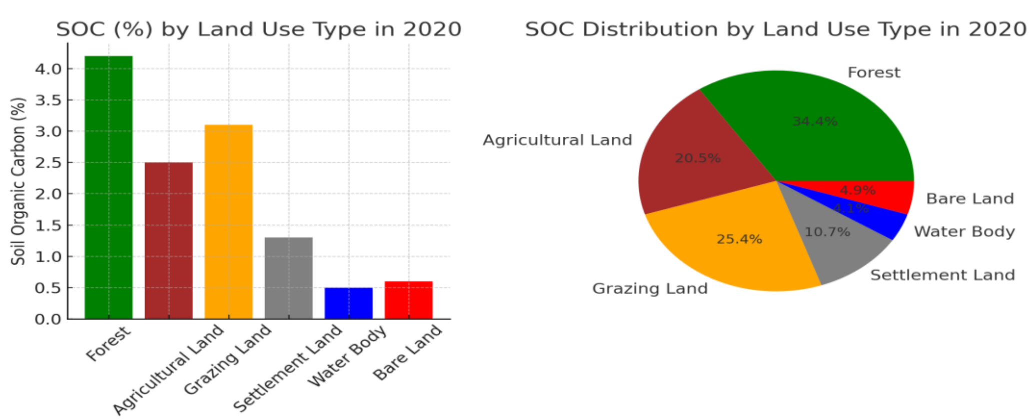


Figure 5. *Effects of land use and land cover (LULC) changes on soil carbon stock in the study area from 2000 to 2020.*

Unvegetated lands have lower carbon sequestration potential than vegetated ones. Forest land regularly has the greatest SOC values. Crop and grazing land declines. Built-up and barren land degrade SOC. Water bodies are stable, yet low in SOC. Land conversion reduces soil carbon reserves, affecting soil fertility, water retention, and erosion. Soils containing less organic carbon degrade faster, reducing agricultural production. Loss of soil carbon increases CO_2 emissions, worsening climate change.



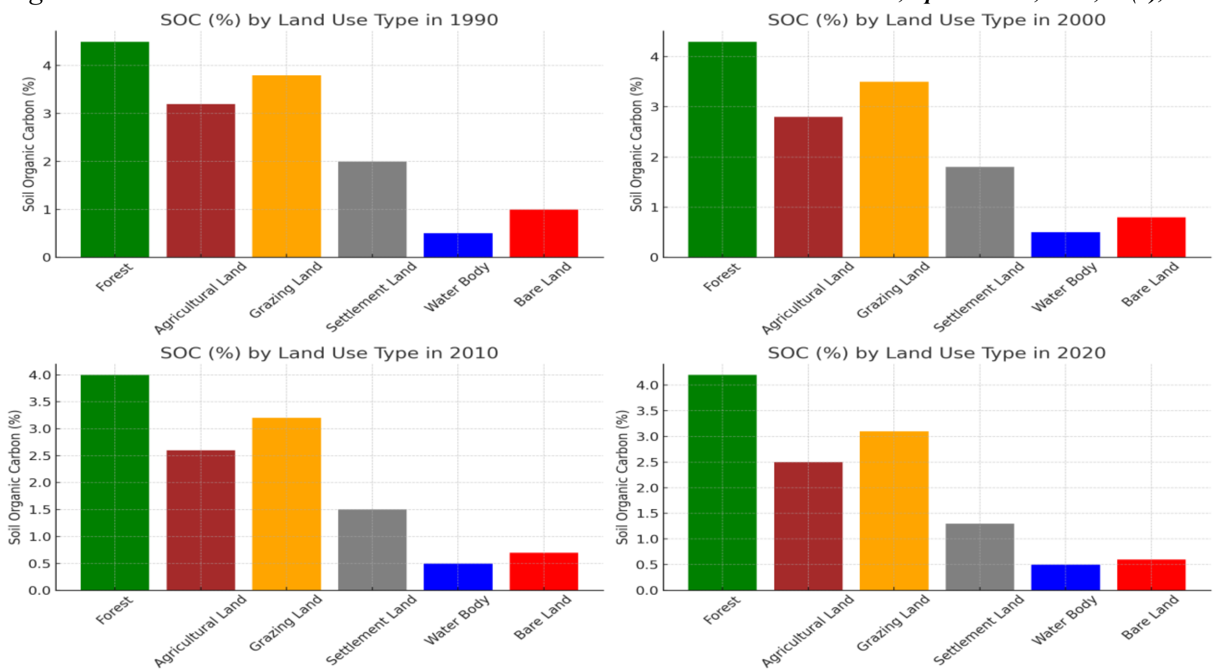


Figure 6. *Soil Organic Carbon (SOC) across all major land use types in Diga District for the years 1990, 2000, 2010, and 2020*

The analysis result aligns with findings (Fenta et al., 2023) that examined the dynamics of deforestation and agricultural expansion in the Ethiopian Highlands. In this study, researchers found that rapid deforestation, primarily driven by the need for agricultural land, led to a significant reduction in soil carbon stocks. Forests in the highlands are crucial for carbon sequestration, and their removal not only reduces soil organic matter but also accelerates soil erosion. The study recommended agroforestry and reforestation as key strategies to restore soil carbon stocks (Gao & Liu, 2019) in southern Ethiopia and focused on the relationship between land use and soil organic carbon storage.

The research found that conversion from forest to cropland resulted in a 30% loss in soil organic carbon. The study highlighted the need for sustainable farming practices, such as conservation tillage and cover cropping, to enhance soil carbon sequestration and restore degraded lands (Lal, 2018). Agroforestry systems in central Ethiopia were found to significantly improve soil organic carbon content. The integration of trees into farming systems increased soil carbon levels by up to 40% compared to monoculture cropping systems. This case study emphasizes the potential of agroforestry in mitigating soil degradation and enhancing carbon storage in agricultural lands.

Persson's Correlation Analysis

Persson's correlation research examined the relationship between soil organic carbon (SOC), carbon storage, and other soil parameters across land use types. This study examined the strength and direction of the link between SOC and soil physical and chemical parameters like bulk density, porosity, CEC, pH, and accessible phosphorus (P) (Table 7). Significant positive relationships were found between SOC and soil porosity ($r = 0.85$, $P < 0.01$) and CEC ($r = 0.72$, $P < 0.05$). Porosity and CEC are positively correlated with SOC concentration, indicating that soils with superior structure and nutrient-holding ability store carbon more efficiently. SOC's negative connection with soil bulk density ($r = -0.81$, $P < 0.01$) indicates a reduction in SOC content with increased soil compaction.

The connection between soil pH and SOC was somewhat negative ($r = -0.56$, $P < 0.05$), suggesting that acidic soils contain lower SOC levels. The slight negative correlation between SOC and accessible phosphorus (r = -0.35, P > 0.05) suggests that phosphorus availability had little effect on SOC storage. These relationships show how soil characteristics affect carbon storage in diverse ways. To increase SOC storage potential, soil treatment should increase porosity and lower bulk density. SOC stock in forestland has steadily dropped, coinciding with agriculture and other land changes. This pattern suggests decreasing carbon storage capability and the need for sustainable land management (Table 7).

Table 7

Persson's Correlation Results between Soil Organic Carbon (SOC) and Soil Properties

Soil Property	Correlation with SOC (r-value)	P-Value	Interpretation
BD (g/cm^3)	-0.81	0.001	Negative correlation; higher BD = lower SOC
Porosity (%)	0.85	0.001	Positive correlation; higher porosity = higher SOC
(CEC) (cmol(+)/kg)	0.72	0.004	Positive correlation; higher CEC = higher SOC
pH (H_2O)	-0.56	0.031	Negative correlation; lower pH = lower SOC
Ava. P (mg/kg)	-0.35	0.089	Weak negative correlation; limited effect on SOC

Persson's correlation study supports the idea that soil physical and chemical parameters affect SOC. The substantial negative association between bulk density and SOC shows that soil compaction limits carbon storage. In agricultural and urban settings, land use changes can compact soil and reduce carbon storage. Carbon sequestration is more efficient in soils with better structure, which allows for more pore space. Porosity and SOC are positively correlated. SOC storage may improve with conservation strategies like reduced tillage or organic additions that improve soil structure.

The modest positive association between CEC and SOC shows that soils with a higher cation exchange capacity can store more organic carbon because they hold more nutrients and organic matter. To increase agricultural carbon sequestration, soil fertility must be managed. The negative association between pH and SOC shows that acidic soils have lower SOC due to reduced microbial activity and organic matter decomposition. Urbanized and agricultural soils are more acidic, which may explain their lower SOC content. Phosphorus availability affects plant development and nutrient cycling, not carbon sequestration; hence, its modest negative connection with SOC has little effect on SOC storage. These findings highlight the need for integrated land management strategies that improve soil physical properties like porosity and fertility through organic amendments, pH management, and reduced soil compaction to maximize soil carbon storage potential and mitigate climate change impacts.

CONCLUSIONS

This study assessed the impact of land use and land cover (LULC) changes on soil carbon storage in Diga District, Eastern Wollega, Western Ethiopia, from 2000 to 2020. The results show significant LULC changes, with agricultural expansion and deforestation leading to reduced soil carbon storage. Agricultural and built-up areas had notably lower carbon stocks compared to forests and grasslands. The hypothesis that LULC changes negatively impact soil carbon storage was supported, highlighting the importance of sustainable land management practices. The findings emphasize the need for forest restoration and improved agricultural practices to enhance soil carbon sequestration and mitigate climate change. Overall, this study contributes valuable insights into the relationship between LULC changes and soil carbon dynamics, offering recommendations for climate-resilient land use strategies in the region.

Recommendations

To enhance sustainable land management and soil carbon storage in Diga District, Eastern Wollega, integrated strategies are needed. Land use planning should establish protected areas, enforce zoning, and balance agriculture with conservation. Sustainable farming practices like agroforestry, crop rotation, and no-till farming can improve SOC while supporting productivity. Reforestation and community-led restoration efforts are keys to rebuilding carbon stocks. Strengthening SOC monitoring through remote sensing and regular assessments, along with understanding land use drivers, will support informed management. Engaging local communities through awareness and training is essential for long-term success and climate resilience.

CRediT authorship contribution statement

Misganu Chewaka: Writing - Original Draft, Writing - Review & Editing, **Getahun Kitila:** Formal analysis, Conceptualization, Methodology, Validation resources, **Amensisa Misganu:** Data Curation, Visualization, Investigation

Declaration of competing interests

The authors affirm that there is no conflict of interest.

Ethical approval

Not applicable.

Data availability statement

Adequate data is available and will be presented upon request.

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