

Impacts of Land Use /Land Cover Change on Soil Physicochemical Properties and Soil Carbon Stock in Lemo District, Central Ethiopia

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Abstract

This study was to assess the impacts of land use and land cover change (LULCC) on soil physicochemical properties and soil carbon stock at 0-20 cm and 20-40 cm soil depths with three land uses of Forest, Grazing, and Crop lands and three kebeles the Bellesa, Jawa, and Masibira kebeles in Lemo District, Central Ethiopia. The Household survey results indicated that on LULCC trends and driving factors collected through a household survey of 66 purposively selected respondents. The significant increase in mono-cropping (Cropland) between the mid-1990s and 2025s. The result of soil physical and chemical analysis indicated as follows. The soil moisture content was significantly higher in forestland compared to grazing and cropland. Soil texture was predominantly Clay loam and did not differ significantly ($p>0.05$) across land use types. However, PH, CEC, Av.P, OM, OC, and SOC_s exhibited significant differences ($p<0.05$) among land use types at both soil depths. Soil pH was slightly acidic across all land uses, with forestland showing the highest values. Cation exchange capacity (CEC) was high in all land use types, with forestland having higher value at the 0-20 cm depth. Available phosphorus was significantly higher in forestland. Total nitrogen and soil organic carbon (SOC) content followed the order of cropland < grazing land < forestland, with higher concentrations in the topsoil. The soil organic matter (OM) was optimum in forest and grazing lands and low in cropland. Soil organic carbon stock (SOC_s) was also highest under forestland, followed by grazing land, and lowest under cropland. These findings suggest that the conversion of forest and grazing lands to cropland in the study area has negative impacts soil physical and chemical properties. Thus, the current trend shows mono-cropping(cropland) expanding into Forest and Grazing land. Therefore, further research is recommended to support agroforestry and integrated nutrient management to restructure organic matter and prevent soil acidification.

Keywords: Agricultural land expansion, Drought, Global Carbon dynamic, Mono- cropping.

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Introduction

Background of Study

Land systems provide critical ecosystem services, including the conservation of biodiversity, the sequestration and storage of carbon, and the purification and storage of water. Land has a place for the people, where their livelihood is entirely dependent on their environment and the livelihood strategies are limited (Mugagga & Nabaasa, 2022). Land surfaces play a fundamental role in regulating the Earth climate by modulating surface albedo and absorbing solar radiation, which influences global heat distribution (Piao et al., 2020; Smith et al., 2020). Land Use Change is a significant driver of global carbon dynamics, with conversions from forest to agriculture in particular, leading to

substantial C loss from terrestrial ecosystems (Ahmed et al., 2022). Land use and land cover dynamics are persistent, driven by human activities, which in turn generate changes that impact human population (Winkler et al., 2021). The changes in land use and cover can lead to a decline in the availability of various products and services essential for humans, affect agricultural output, and harm the environment. Indeed, land use and land cover change (LULCC) have become a central focus in contemporary strategies for managing natural resources and monitoring environmental transformation (Dadashpoor et al., 2024). An ecosystem is affected by LULCC in two primary ways: through direct impacts on the alteration of aquatic and terrestrial ecosystems an

by contributing to climate change via excessive carbon emissions. The interest in LULCC is driven by its effects on fundamental ecosystem characteristics and processes, including land productivity, biodiversity and climate (Piao *et al.*, 2020). The relationship between LULCC can be understood as the impacts of altered land use and their contribution to global change being significantly mediated by changes (IPCC, 2023). The detrimental effects of land-use and land-cover change (LULCC) on biodiversity and climate, are now recognized as major environmental concerns facing human populations (IPCC, 2023). Land-use change (LUC) significantly influences land cover (LC) can affect land use and soil health (Dadashpoor *et al.*, 2024). This relationship underscores the complexity of managing terrestrial ecosystems under increasing anthropogenic pressure (Winkler *et al.*, 2021). Such land use shifts have contributed to soil degradation and loss soil physical and chemical attributes. The reduction in vegetation cover and disturbance of natural ecosystems has led to soil degradation, accompanied by a decline in soil fertility and concentrations of soil organic carbon (SOC) (Gebremedhin *et al.*, 2021; Boka *et al.*, 2024). Increasing human population, their demands for food and the exploitation of economic resources are key factors driving the degradation of forest cover and biodiversity globally (FAO, 2024). Change in land use from forest to cultivated land can diminish the input of organic residues, resulting in decreased soil fertility, increased rates of erosion, loss of soil organic matter (SOM) and nutrients, and accelerated pace of soil degradation. Research has indicated that soil parameters of SOC, pH, total nitrogen (TN), available phosphorus (Av.P), and clay content are significantly higher in natural forests and protected afforestation areas (Assefa *et al.*, 2025). However, an increase in soil organic matter (SOM) can maintain aggregate stability by enhancing the soil particles, thereby reducing the loss of fine soil components (Tesfaye *et al.*, 2020). Various researchers have extensively investigated the relationship between LULCC and the soil physicochemical properties. Recent studies consistently that transformations from natural ecosystems into agricultural land uses significantly impact soil attributes. SOM and nutrient availability are frequently observed to decline conversions, due to reduced organic residue input and accelerated decomposition from practices like tillage (Worku *et al.*, 2024). This is evident in the shift from forest to cultivated lands, leading to reduced soil fertility. Changes in soil physical properties, including bulk density and porosity, are also reported as compaction from agricultural

machinery and continuous cultivation often leads to increased bulk density and decreased porosity in converted lands, negatively affecting water infiltration and aeration (Gebremedhin *et al.*, 2024). Thus, these studies underscore that LULCC causes a significant degradation of soil physicochemical properties, with direct implications for soil quality, agricultural productivity, and ecosystem health (Li *et al.*, 2024).

Land use changes can accelerate the loss of SOC stocks through erosion or vegetation conversion. Land-use change (LUC) is a primary driver of global carbon (C) dynamics, with the conversion of forest ecosystems to agricultural and settlement lands causing significant terrestrial carbon loss. In the Lemo District of Central Ethiopia, rapid land-use and land-cover changes (LULCC)—characterized by agricultural conversion to random settlements and ongoing upstream deforestation—are fundamentally changing the landscape. While global underscores that shifts trigger immediate soil disturbances and accelerate carbon dioxide (CO₂) emissions from soil horizons (Xiao *et al.*, 2024), the specific magnitude of these impacts on the district natural resources remains poorly quantified. The problem lies in the conversion of natural ecosystems to mono-cropping and urbanized surfaces, which degrades vital soil physicochemical properties such as texture, pH, and nutrient availability. Without site-specific practical data on these modifications, there is a critical knowledge gap that prevents the formulation of sustainable land management strategies custom-made to the Hadiya Zone.

Justification and Research Gaps

Current research across Ethiopia highlights a consistent of soil quality decline land-use transitions. Studies have reported in Southern and Southwest Ethiopia (Miju *et al.*, 2022; Gubila *et al.*, 2024) that cultivated and grazing lands significantly reduce organic carbon and total nitrogen compared to natural or agroforestry systems. Moreover, recent data from the Bubisa Watershed (Lemma & Wakgari, 2022) indicates a precipitous drop in soil carbon stocks of the forest cover is lost. Despite these regional, Lemo District presents a unique socio-economic and topographical context—marked by high population pressure and specific LULC that has not been localized in recent literature. This research is justified by the urgent need to address this by providing high-resolution data on how different land-use types (Forest, Grazing, and Cropland) influence the soil capacity to sequester carbon, this study offers an analytical for local to move beyond

random development toward evidence-based environmental stewardship.

Research Objective and Significance

The significance of this study in its potential to link the gap between local agricultural practices and global climate mitigation goals. Understanding the specific impacts of LULCC on the Lemo District soil carbon reserves is fundamental for maintaining soil health and supporting the long-term livelihoods of the community. Degraded soil properties not only reduce agricultural productivity but also diminish essential ecosystem services and exacerbate the impacts of climate change (FAO, 2024). By identifying which land management practices best preserve soil fertility and carbon stocks, this research will supply the essential localized data currently absent from the regional planning framework. Thus, the findings serve as a baseline for agricultural development institutions to enhance organic carbon sequestration. Therefore,

the objective of this study was to assess the impacts of land use and land cover change (LULCC) on soil physicochemical properties and soil carbon stock at 0-20 cm and 20-40 cm soil depths with three land uses of Forest, Grazing, and Crop lands and three kebeles the Bellesa, Jawa, and Masibira kebeles in Lemo District, Central Ethiopia.

MATERIALS AND METHODS

Description of the Study Area

Location

The study was conducted in the Bellesa, Jawa, and Masibira kebeles within the Lemo District Hadiya Zone, central Ethiopia. The Lemo District is situated in the Hadiya Zone of the Southern Nations, Nationalities, and Peoples' Region. The area is an administrative center for Hosanna town which is found at 237 km from Addis Ababa. It is located at the global grid of 7° 25' 00" to 7° 41' 00" N latitude and 37° 45' 00" to 38° 01' 00" E longitude (LWAO, 2025).

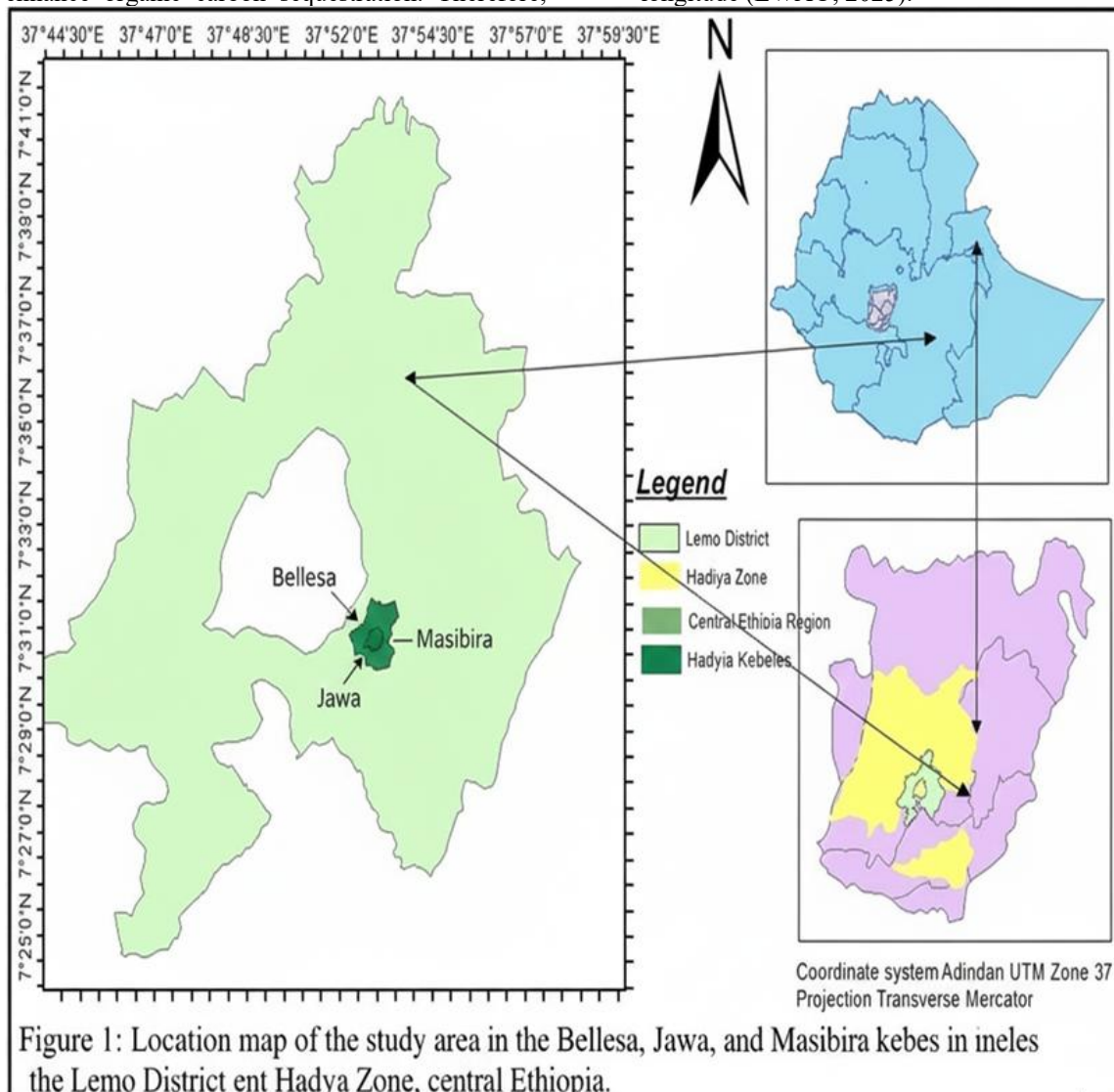


Figure 1: Location map of the study area in the Bellesa, Jawa, and Masibira kebeles in the Lemo District, Hadiya Zone, central Ethiopia.

Topography and Climate

Topographic features the study area is hilly and undulating landscapes with altitude ranges from 1950 to 2400 m.a.s.l (LWOA, 2025). Based on the 30 years (1995-2025) climatic data obtained from National Meteorology Agency (NMA), the mean annual temperature varies between 15 and 22 °C and the mean annual rainfall varies from 800 to 1150 mm with a bimodal distribution pattern. The main rainy season occurs during June to September while the short one, which contributes about one third of the annual rainfall, is in March and April (EMI. 2024). There are Woina-Dega 93% including 33 rural Kebeles, 2 urban kebeles and Dega 7% including 4 kebeles.

Soil type of the study area

The soil type of the study area can be broadly categorized as Nitisols. These soils are deep and have high potential for agricultural production, on which subsistent farmers depend on growing a variety of crops and graze their livestock (LWOA, 2025).

Population

The district is densely populated in two agro-ecological zones and covers an area of 34,695 hectares. The total population of the study area has an estimation of 157,107 (77,662 male and 79,445 female) with population: land ratio of 0.67 ha. This indicated an extreme shortage of land when compared with the population (REF). According to experts of Lemo Woreda, land is not sufficient even for subsistence farming (LWFEDO, 2024).

Farming System

In Lemo District, mixed farming serves as the primary economic engine. This integrated system combines rain-fed crop production with livestock rearing—specifically cattle, sheep, and poultry. The trees and shrubs within the agricultural landscape is a common practice, creating a diverse and resilient farming environment. Enset (Ensete

ventricosum) is the staple food crop. Fruits and tree species (e.g., Avocado- *Persea americana*), vegetables (e.g., Cabbage- *Brassica oleracea*), cereal crops (e.g., Wheat- *Triticum spp.*, Maize- *Zea mays*), root and tuber crops (e.g., Potato- *Solanum tuberosum*, common beet - *Beta vulgaris*) are the most common crops cultivated for household consumption and to some extent income generation (LWANRO, 2024).

Land use/ land cover of study area

Lemo District is characterized by three different land use-land covers including forest, cultivated, and grazing land uses. Cultivated land constitutes about 77.4% of the land use. However, the vegetation covers grazing lands and other lands for building and constructions constitute about 22.6% of the total land coverage. The vegetation coverage is diminishing from time to time at alarming rates because of high population pressure and agricultural land expansion, urbanization and fuel wood consumption (LWANRO, 2024).

Sampling Design for Survey Data Collection

The criteria used for the study site (three kebeles namely Bellesa, Jawe and Masibira) selection were an approximate similarity in tree density, topography, soil type, and climatic zone, presence of forest, grazing land and monocropping system taken as control. The collection of survey data on the trends and drivers of land use land cover dynamics was done using a multi-stage approach. Within the selected kebeles, the households (HH) were selected through purposive random sampling.

The data regarding land use and land cover (LULC) dynamics trends and drivers was assessed using the Kolmogorov-Smirnov test. Respondents were grouped as Male-headed HH and Female-headed HH. Sampling size was determined using Equation as described by Kothari (1985).

$$n = \frac{Z^2 pqN}{d^2(N - 1) + Z^2 pq}$$

$$n = \frac{2548.26}{38.110625} = 66$$

Where, n = required sample size, N = total household (3745), P = probability of success, q= probability of failure, Z = coefficient, d = marginal error (5% and 10%).

The marginal error of 10% was used, then the confidence level of 90%, our probability of access was p = 0.5, failure probability of q = 0.5 as Z 0.25 = 1.65.

Treatments and Experimental Design

A total of six treatment (6) consisting of three land uses such as Forest, Grazing, and Crop land with

two soil depths at 0-20 and 20-40 cm. The soil samples were collected from three kebeles, the Bellesa, Jawa, and Masibira kebeles as replication a total of eighteen treatments (18) were evaluated.

The treatments laid out Completely Randomized Block Design (RCBD) with three replications was employed for soil sample collection across the three land use types. Hence, a 20 x 20 m main sampling plot was established in triplicate for each land use type (Bajigo *et al.*, 2015). Within each main plot, five sampling sub plots.

Soil Sampling and Preparation

During sampling, dead plants furrow, footpaths, areas near trees and compost pits were excluded to minimize spatial variability in soil properties, composite soil samples were collected at two distinct phases of the study. Initial samples were gathered prior to the application of organic soil amendments to establish a baseline for the soil physical and chemical status. Following the experimental period, a second set of samples was collected immediately after crop harvest to evaluate the impact of the treatments on soil fertility and nutrient depletion. Soil samples were collected from the surface (0–20 cm) and sub-surface (20–40 cm) layers using an auger.

The samples were taken randomly at five different points using the zig-zag method to form each of the one composite soil samples before treatment application. Each collected sample was immediately placed in a labeled plastic bag and transported to the Wachemo university Soil Laboratory.

Upon the samples were sent to soil laboratory then air-dried at room temperature. Following the air-drying period, the samples were crushed to break up aggregates and sieved through a 2 mm mesh to remove coarse fragments. For soil organic carbon (SOC) and total nitrogen (TN) analyses of the soil samples were further ground and sieved (mesh size 0.5 mm). The processed samples were stored in clean plastic bags, ready for physicochemical analysis, specifically soil texture, pH, cation exchange capacity (CEC), available phosphorus (Av.P), and organic carbon (OC).

Analysis of Soil psychochemical Properties

The moisture content of soil was determined as described by Hess (1972). The hydrometer method was used to determine soil particle size distribution (Bouyoucos, 1962). Soil bulk density (BD) was determined from undisturbed soil core (2.5 cm radius and 5.0 cm height) of dry solids in each bulk volume of soil samples as described by Jamison *et al.* (1950). The soil pH (H₂O) was determined in the suspension of 1:2.5 soil: water and soil (Chopra and Kanwar, 1976). The Soil organic C was analyzed following the method of Walkley and Black (1934). The estimation of Soil Organic Matter (SOM) from measured Soil Organic Carbon is standardly performed by multiplying the carbon concentration by a factor of 1.724. The CEC of the

soil was determined from the NH₄⁺ saturated samples that were subsequently replaced by K from a percolated KCl solution (Chapman, 1965).

Soil Organic Carbon (SOC) stock is calculated as the product of the carbon concentration, soil bulk density, and the thickness of the soil layer, adjusted for the presence of coarse fragments and standardized to a per-hectare basis (Demessie *et al.*, 2011).

$$SOC \text{ (stock)} = C_{conc} \times BD \times T \times (1 - CF_{coarse}) \times 10 \dots \dots \dots \text{Equation.1}$$

Where SOC_s = Soil organic carbon stock C_{conc} = Carbon concentration (kg mg⁻¹) BD = Bulk density (mg/m⁻³), CF = Correction factor (1 – (Gravel % + Stone %) /100) T = Depth or thickness (m).

Analysis of Land Use/Land Cover (LULC) dynamics

The analysis of Land Use/Land Cover (LULC) dynamics was conducted through a rigorous, multi-stage remote sensing and Geographic Information System (GIS) workflow. LULC dynamics were examined using Landsat 8 and Landsat 9 Operational Land Imager (OLI) imagery, selected for their appropriate spatial resolution and temporal availability to ensure a consistent comparison of land cover changes within the Lemo District. Prior to classification, these satellite scenes underwent standardized pre-processing across various time steps.

A Supervised Classification method was then implemented using the Maximum Likelihood Algorithm within ArcGIS/ERDAS Imagine software, chosen for its proven robustness in classifying pixels based on the probability of their association with a specific LULC class. Representative training areas for the three primary LULC types—forest land, grazing land, and cropland—were selected based on ground-truth points gathered during field surveys and supplemented by high-resolution historical imagery from Google Earth. Finally, to validate the classification, a confusion matrix was generated to calculate the Accuracy and Kappa Coefficient. An accuracy threshold exceeding 85% was strictly maintained to ensure the reliability of the spatial data before proceeding with the subsequent change detection analysis.

Statistical Data Analysis

The data were collected on the trends and drivers of land use and land cover dynamics, as well as the soil physicochemical parameters. Analysis of variance (ANOVA) was performed for statistical data analysis using the general linear model

procedures using Tukey's Honestly Significant Difference (HSD) test (Kuhfeld, 2005). Descriptive statistics were computed using SPSS version 26 to analyze the different land use treatments.

RESULTS AND DISCUSSION

Trends of land use/ land cover dynamics

Household survey results indicated that the households generally perceived a decrease in forest and grazing land over time. Conversely, there was a perceived increasing trend in cropland since 1995, with a more pronounced increase observed between 2015 and 2025 (Table 1). This transformation was attributed to a combination of bio-physical, socio-economic, cultural, and institutional factors. The expansion of cropland at the expense of forest and grazing land in the study area was driven by the economic benefits it provides to the local community, alongside various biophysical, socioeconomic, political, cultural, and institutional factors, as well as the demand for agricultural land. The findings of this study align with research conducted by Masham *et al.* (2021) in the Damota Area, Abate (2011) in the Wollo highlands, and Masha *et al.* (2023) in the Adama district, all of which reported an expansion of croplands at the expense of forests, grazing lands, and other land use types.

Similar findings were reported by Belayneh *et al.* (2020), who noted that significant population

growth has led to a high rate of land use and land cover changes. Furthermore, the study by Hishe *et al.* (2020) indicated that an alarming increase in population intensified the rate of LULCC due to keen demand for agricultural land and productions of charcoal and wood materials.

Recent studies in the Southern and Central Highlands indicate that the rate of conversion to agricultural land has accelerated due to heightened demographic pressure and the lack of alternative livelihood strategies (Bekere *et al.*, 2023; Assefa *et al.*, 2025). These transitions are no longer limited to the northern regions but are now pervasive across the Hadiya Zone and the Southern Ethiopian Rift Valley, where remaining forest fragments are rapidly being converted into intensive tuber-based farming systems (Gubila *et al.*, 2024; Worku *et al.*, 2024). In contrast, a study by Bekele and Demessie (2023) indicated an increase in forest cover at the expense of cropland. However, the sampled households in the current study areas perceived an increase in cropland at the expense of forest and grazing land from 1995 to the present. The trend of forest and grazing land conversions to cropland showed an increasing pattern from 1995 to 2025s (Table 1), thus, indicating an expansion of cropland into forest and grazing land in the Lemo District.

Table 1: Trends in land use/ land cover changes in the study area from 1995 to 2025

| | | <i>Kebeles</i> | | | | |
|--------------|---|---------------------|------------------|----------------------|--------------|----------------|
| | | Belleza Area(ha) | Jawe Area(ha) | Masibira Area(ha) | Frequency(f) | Percentage (%) |
| Since 1995's | Forest land | 1.07 | 0.44 | 0.0 | 9 | 13.63 |
| Since 2005's | Either Forest or Grazing to Crop land | 0.6 | 0.8 | 1.2 | 13 | 19.69 |
| Since 2015's | Either Forest or Grazing to Crop land | 1.3 | 1.41 | 1.9 | 16 | 24.24 |
| Since 2025's | Either Forest or Grazing to Crop land | 6.2 | 4.31 | 3.6 | 28 | 42.24 |
| Total | | | | | 66 | 100 |

Effect of Land Uses on Soil Physical Properties

Soil Bulk Density

The analysis of variance indicated a statistically significant ($p \leq 0.05$) effect of different land use types and soil depths on bulk density (BD) (Table 2). The present study revealed the following BD values at a depth of 0-20 cm: forest land (1.07 g cm^{-3}), grazing land (1.32 g cm^{-3}), and cropland (1.33 g cm^{-3}). At the 20-40 cm depth, the corresponding values were forest land (1.16 g cm^{-3}), grazing land (1.28 g cm^{-3}), and cropland (1.31 g cm^{-3}) (Table 2). Consequently, the soil bulk

density in the study area was classified as moderate ($< 1.4 \text{ g cm}^{-3}$). This could be attributed to the greater accumulation of organic matter and litter fall in forest and grazing lands compared to cropland. This finding aligns with Schoonover and Crim (2015), who reported that the presence of organic matter in soil improves its bulk density, structure, texture, and porosity. According to Tamiru and Amsalu (2019), optimal plant growth requires a bulk density below 1.4 g cm^{-3} .

Table 2: Soil Bulk Density under different land use types at 0-20cm and 20-40cm soil depths.

| Land uses | Depth (cm) | BD (gcm^{-3}) |
|--------------|------------|--------------------------|
| Forest land | 0-20 | 1.16 ^c |
| | 20-40 | 1.24 ^c |
| Grazing land | 0-20 | 1.32 ^{ab} |
| | 20-40 | 1.28 ^b |
| Crop land | 0-20 | 1.07 ^d |
| | 20-40 | 1.33 ^a |
| Mean | | 1.24 |
| LSD (0.05) | | 0.05 |
| CV (%) | | 2.38 |

Means with the different letters are statistically different at 5% level.

Soil Moisture

The soil moisture content was significantly influenced ($p \leq 0.05$) under forest land compared to grazing and cropland at both soil depths (Table 3). Specifically, soil moisture content (SMC) at the 0-20 cm depth was 28.8% under forest land, 24.4% under grazing land, and 20.2% under cropland. At the 20-40 cm depth, the SMC was 29.1% under forest land, 25.6% under grazing land, and 21.1% under cropland (Table 3). This higher moisture content in forest land could be attributed to high amount of organic matter, and the agro-ecological characteristics, which is known for receiving optimal rainfall the significantly higher moisture content in forest land and the lowest in cultivated land suggests that vegetation cover in forests reduces evaporation, allowing water to remain in the soil. This is consistent with similar findings of Wako and Kitila (2021).

Soil texture

There were no significant differences ($p > 0.05$) in soil texture among the forest, grazing, and croplands at either soil depth. Thus, the soil texture under these land-use types was classified as clay loam.

Effects of Land Use on Soil Chemical Properties

Soil pH

As presented in Table 4, soil pH values analysis of variance (ANOVA) indicated that these variations were significantly influenced ($P \leq 0.05$) by both land use types and soil depths. The soil pH values at the 0–20 cm depth were 6.14, 6.09, and 6.04 for forest, grazing, and cropland, respectively. At the 20–40 cm depth, these values were 6.13 for forest land, 6.07 for grazing land, and 5.98 for cropland, respectively. According to the classification by Tekalign (1991), the soil pH across all treatments falls within the slightly acidic range.

The highest soil pH was consistently recorded in forest land, while the lowest was observed in cropland at both depths. The higher pH in forest land can be attributed to higher organic matter content. Organic matter serves as a buffer and can trap basic cations, thereby reduce H^+ concentration and increase soil pH (Xiao *et al.*, 2024).

Table 3: Soil moisture content and soil texture under different land use types at 0-20cm and 20-40cm soil depths.

| Treatments | MC | Soil Texture (0-20cm) | | | Textural classes |
|--------------|-------------------|--------------------------|-----------------|-----------------|------------------|
| | | % Sand | % Clay | % Silt | |
| Forest Land | 48.8 ^a | 46 ^a | 32 ^a | 22 ^a | Clay loam |
| Grazing Land | 25.4 ^c | 36 ^a | 40 ^a | 24 ^a | Clay loam |
| Crop Land | 25.8 ^b | 32 ^a | 38 ^a | 30 ^a | Clay loam |
| Mean | 25.6 | | | | |
| CV (%) | 12.38 | | | | |
| LSD (5%) | 2.9 | ns | ns | ns | |
| Treatments | % MC | (Soil Texture (20-40cm)) | | | Textural classes |
| | | % Sand | % Clay | % Silt | |
| Forest Land | 49.0 ^a | 32 ^a | 28 ^a | 40 ^a | Clay loam |
| Grazing Land | 26.0 ^b | 36 ^a | 38 ^a | 26 ^a | Clay loam |
| Crop Land | 25.0 ^c | 34 ^a | 36 ^a | 30 ^a | Clay loam |
| Mean | 33.3 | | | | |
| CV (%) | 6.47 | | | | |
| SD (5%) | 2.9 | ns | ns | ns | |

Means with the same letter are not statistically different at 5% level; ns, means not significant.

These findings align with studies in Northern Ethiopia by Asmare *et al.* (2023), which similarly reported that forest soils maintain higher pH levels than intensively cultivated lands. Conversely, the lower pH in cropland is likely due to the intensive removal of basic cations during crop harvests, the leaching of nitrates, and the application of acid-forming inorganic fertilizers that release hydrogen ions (H⁺) into the soil solution.

The soil pH decreases with depth trend across all land uses is driven by the leaching of exchangeable basic cations such as calcium (Ca²⁺), magnesium (Mg²⁺), and potassium (K⁺). In high-rainfall

regions, these basic ions are washed from the topsoil into deeper layers; however, they often leach entirely beyond the root zone (40 cm), leaving the subsoil saturated with hydrogen (H⁺) and aluminum (Al³⁺) ions that lower the pH (Regasa *et al.*, 2024). The higher organic matter content in the topsoil (0–20 cm) provides a superior buffering capacity compared to the subsoil. Organic matter acts as a reservoir for basic cations and reduces the activity of acidic ions. As organic matter naturally declines with depth, this buffering effect weakens, making the lower soil layers more susceptible to acidification (Gebreselassie *et al.*, 2023).

Table 4: Soil pH under different land use types at 0-20cm and 20-40cm soil depths.

| Treatments | pH | |
|--------------|-----------------------|------------------------|
| | (0-20) cm soil depths | (20-40) cm soil depths |
| Forest Land | 6.14 ^a | 6.13 ^a |
| Grazing Land | 6.09 ^{ab} | 6.07 ^b |
| Crop Land | 6.04 ^b | 5.98 ^c |
| Mean | 6.09 | 6.07 |
| CV (%) | 12.44 | 14.5 |
| LSD (5%) | 0.05 | 0.03 |

Means with the different letters are statistically different at 5% level.

Cation Exchange Capacity

The analysis of variance indicated that cation exchange capacity (CEC) was significantly influenced ($P \leq 0.05$) by land use types and both soil depths at 0-20 cm and 20-40cm (Table 5). The study revealed that forest land exhibited the highest CEC values at both soil depths which accordingly followed by grazing and crop land (Table 5). Based on the classification by Landon (1991), the Cation Exchange Capacity (CEC) across all land use types with soil depths is rated as high. The higher CEC values in the surface and sub-surface soils at the

forest land are likely attributed to the substantial presence of organic matter in the soils, a key factor in enhancing a soil's capacity to retain cations (Regasa *et al.*, 2024). Thus, land-use systems of forests and grazing lands accumulate higher levels of organic matter compared to continuously cultivated croplands. This accumulation contributes to greater CEC values, as organic matter provides a high density of negatively charged exchange sites (Asmare *et al.*, 2023).

Table 5: The CEC under different land use types at 0-20cm and 20-40cm soil depths.

| Treatments | CEC ($Cmolc\ kg^{-1}$) | |
|--------------|--------------------------|------------------------|
| | (0-20) cm soil depths | (20-40) cm soil depths |
| Forest Land | 33.01 ^a | 31.3 ^a |
| Grazing Land | 31.6 ^b | 30.43 ^{ab} |
| Crop Land | 30.5 ^{ab} | 27.7 ^b |
| Mean | 31.70 | 29.81 |
| CV (%) | 13.7 | 12.42 |
| LSD (5%) | 1.48 | 2.1 |

Means with the different letters are statistically different at 5% level.

Soil Available Phosphorus

The available phosphorus (Av.P) varied significantly ($P \leq 0.05$) across different land-use types and soil depths (Table 6). According to the classification by Landon (1991), which categorizes Av.P levels between 5 and 15 mg/kg as medium and 15 to 25 mg/kg as high, the soil Av.P in the study area ranged from medium to high. Specifically, forest land exhibited high Av.P levels at both depths, while grazing and cropland values were rated within the medium range. Forest land consistently showed the highest Av.P concentration, followed by grazing land, with the lowest values recorded in cropland at both soil depths. This significant variation is primarily attributed to the higher accumulation of soil organic matter (SOM) in forest and grazing lands. During the decomposition of organic matter, organic acids are released that can be complex with iron (Fe^{+2}) and aluminum (Al^{+3}), thereby reducing phosphorus fixation and increasing its availability in the soil solution (Regasa *et al.*, 2024).

The lower Av.P levels in cropland likely result from a combination of factors: the continuous removal of phosphorus through crop harvests, a lack of organic residue return, and the potential fixation of phosphorus into unavailable forms due to the slightly lower pH observed in these soils. The slight decrease in Av.P with depth across all land uses further suggests that phosphorus availability is strongly tied to the distribution of organic matter and biological activity, which are most concentrated in the surface layer (Tiruneh *et al.*, 2021). As OM input increases, soil microorganisms decompose it, releasing more nutrients, including phosphorus. Phosphorus availability is closely associated with the amount of OM in the soil, as OM serves as a primary nutrient source (Alemayehu, 2020). These findings align with the results of Assefa *et al.* (2025) and Horamo (2024), who also reported greater total phosphorus concentrations in forest land compared to cropland at both soil depths.

Table 6: Available phosphorus under different land use types at 0-20cm and 20-40cm soil depths.

| Treatments | Avail. P(mg/kg) | |
|--------------|-----------------------|------------------------|
| | (0-20) cm soil depths | (20-40) cm soil depths |
| Forest Land | 18.56 ^a | 16.61 ^a |
| Grazing Land | 15.50 ^b | 14.04 ^b |
| Crop Land | 10.80 ^c | 9.69 ^c |
| Mean | 14.9 | 13.3 |
| CV (%) | 8.87 | 9.88 |
| LSD (5%) | 1.62 | 2.28 |

Means with the different letters are statistically different at 5% level.

Total nitrogen

The results presented in Table 7 indicated a significant ($p \leq 0.05$) difference in total nitrogen (TN) content among the various land use types and soil depths. As shown in Table 7, the mean soil TN concentrations for the 0–20 cm and 20–40 cm depths were 0.33% and 0.26% in forest land, 0.12% and 0.10% in grazing land, and 0.19% and 0.15% in cultivated land. According to the classification by Landon (1991), the TN content in the study area ranges from medium to high. In the study area, TN content increased in the order of cultivated < grazing < forest lands. This finding aligns with the reports of Wako *et al.* (2021), who observed that average TN increased from cultivated to grazing and forest land soils, and also decreased with increasing soil depth from the surface to subsurface layers. Land use changes from forest

land to cultivated land resulted in a TN decline, and a further decrease was observed with increasing soil depth. This is consistent with the findings of Gubila *et al.* (2024), which showed higher TN levels in soils with high organic matter content. The cultivated soils exhibited significantly lower TN at all depths compared to grasslands and forest lands, suggesting that continuous cultivation leads to a reduction in the soil TN content. The minimal change in TN under cultivated land compared to forestland and grazing land suggests that fertilizer applications may not have fully compensated for the TN loss due to harvest removal, leaching, and humus decomposition associated with cultivation (Assefa *et al.*, 2025). The continuous practice of cultivation could have also accelerated organic carbon oxidation and the subsequent loss of nitrogen in cultivated fields, resulting in the lowest nitrogen contents.

Table 7: Total Nitrogen (TN) under different land use types at 0-20cm and 20-40cm soil depths.

| Treatments | (Total N %) | |
|--------------|-----------------------|------------------------|
| | (0-20) cm soil depths | (20-40) cm soil depths |
| Forest Land | 0.33a | 0.26b |
| Grazing Land | 0.12e | 0.10f |
| Crop Land | 0.19c | 0.15d |
| Mean | 0.19 | 0.17 |
| CV (%) | 12.21 | 11.41 |
| LSD (5%) | 3.21 | 2.28 |

Means with the different letters are statistically different at 5% level.

Soil Organic Carbon

Land-use types exhibited a significant difference ($p \leq 0.05$) in organic carbon (OC) content across both soil depths (Table 8). Based on the classification by Landon (1991), the OC content in the present study was high under forest land and optimum under grazing and cropland at both soil depths. The forest land consistently maintained higher soil OC concentrations in both the upper (0–

20 cm) and lower (20–40 cm) layers compared to the grazing and croplands (Table 8). This increase is attributed to the substantial return of biomass through leaf litter, bark, and root turnover, which are characteristic of mature forest ecosystems. These findings align with similar agreement Taye *et al.* (2023), who reported that undisturbed forest structures promote high carbon sequestration. The lower OC levels in the cropland are direct result of land-use conversion. As demonstrated by Xiao *et al.* (2024), transitioning from forest cover to

cultivated land reduces litter input and increases soil disturbance through tillage. This acceleration in organic matter decomposition, combined with

higher erosion rates and the lack of crop residue return, leads to a significant loss of soil organic matter and overall soil degradation.

Table 8: Organic carbon under different land use types at 0-20cm and 20-40cm soil depths.

| Treatments | Organic C (%) | |
|--------------|-----------------------|------------------------|
| | (0-20) cm soil depths | (20-40) cm soil depths |
| Forest Land | 3.44 ^a | 3.26 ^a |
| Grazing Land | 2.18 ^b | 1.88 ^c |
| Crop Land | 1.65 ^c | 1.39 ^d |
| Mea | 2.3 | 2.3 |
| CV (%) | 17.25 | 15.84 |
| LSD (5%) | 0.44 | 0.24 |

Means with the different letters are statistically different at 5% level.

Soil Organic Matter

The land use types showed a significant difference ($p \leq 0.05$) in OM content at both soil depths (0- 20 cm and 20-40 cm) (Table 9). The result revealed the following organic matter (OM) content: under forest land (4.04%), grazing land (3.82%), and cropland (2.80%) at the 0-20cm soil depth, and under forest land (4.03%), grazing land (3.13%), and cropland (2.74%) at the 20-40 cm soil depth (Table 9). According to the classification by Abuye et al. (2021), who soil OM as low (2– 3%), optimum (3–7%), and high (7–8%), the OM

content in forest and grazing land in the present study ranged within the optimum level for both soil depths, while it was low under cropland across all treatments. This higher OM content in forest land could be attributed to the greater amount of residues produced by the forest vegetation, including leaves, branches, bark, and especially roots, which remain in the soil. This finding aligns with the observations made by Lemma & Wakgari, 2022. (2010), who found considerably higher soil OM content in forest land and noted that forest cover does not significantly affect OM content across different soil depths.

Table 9: Organic matter under different land use types at 0-20cm and 20-40cm soil depths.

| Treatments | Organic matter (%) | |
|--------------|-----------------------|------------------------|
| | (0-20) cm soil depths | (20-40) cm soil depths |
| Forest Land | 4.04 ^a | 4.03 ^a |
| Grazing Land | 3.82 ^{ab} | 3.13 ^{abc} |
| Crop Land | 2.80 ^{bc} | 2.74 ^c |
| CV (%) | 17.25 | 17.25 |
| LSD (5%) | 0.76 | 1.07 |

Means with the different letters are statistically different at 5% level.

Soil Organic Carbon Stock (SOCs)

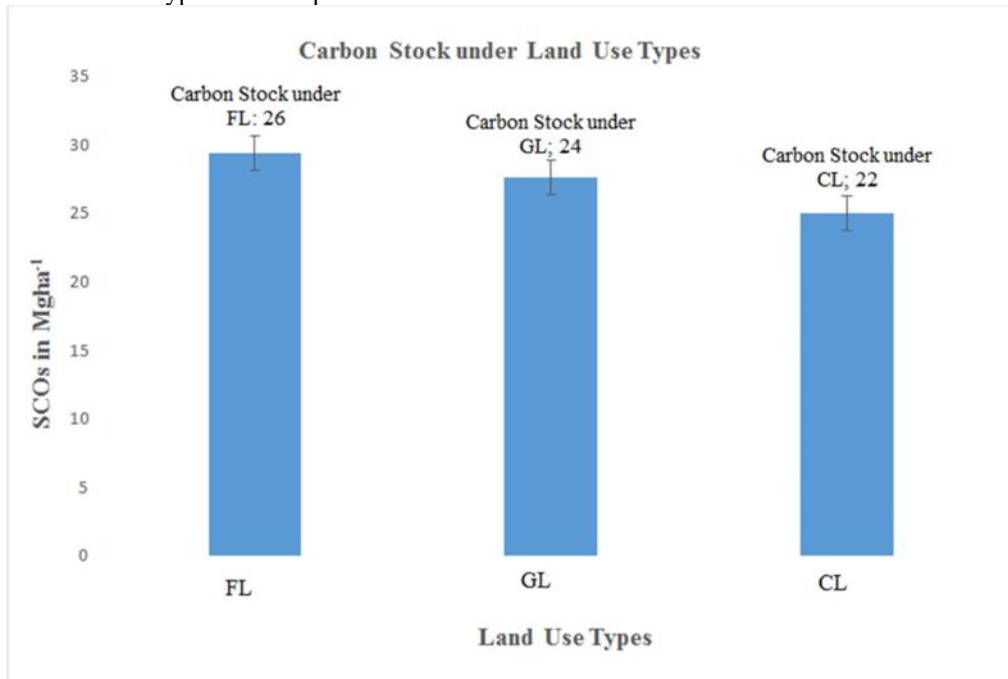
The result indicated that soil organic carbon stock (SOCS) was the highest under forest land (26 Mg ha⁻¹), followed by grazing (24 Mg ha⁻¹), and crop lands (22 Mg ha⁻¹) (Figure-2). This suggests that forest ecosystems are significantly more effective

at sequestering organic carbon than grazing lands, while continuously cultivated croplands represent the least efficient land use for carbon. The difference may be attributed to the greater capacity of forest land to produce litter above ground compared to grazing and crops. This result is consistent with the study by Tiwari et al. (2017),

which demonstrated that afforestation of abandoned agricultural land with multipurpose tree species enhances the SOCS through a continuous supply of organic matter to the soil.

Similarly, the study by Alemayehu (2024) showed that the means of SOC in the land use types were significantly different ($P < 0.05$) and shrub lands reported the highest mean total of 31.26 Mg C ha⁻¹ which was significantly higher than grazing land (13.54 Mg C ha⁻¹) and bare land (12.85 Mg C ha⁻¹). Similarly, the mean SOC and TN stocks in the surface layers were significantly higher than the sub-surface layers, indicating for the stocks decreased as depth increased. These results suggest that land-use types exert a profound influence on

soil physicochemical properties and their carbon sequestration potential. Consequently, the strategic management of these landscapes is essential for promoting sustainable land management (SLM). Maintaining forest cover and improving the management of grazing and croplands—through practices such as agroforestry and reduced tillage—can enhance SOC and TN stocks (Bezuayehu *et al.*, 2024). Improving these soil reservoirs not only restores land productivity but also serves as a critical mechanism to mitigate the negative effects of climate change by sequestering atmospheric CO₂ and reducing greenhouse gas emissions (Gebreselassie *et al.*, 2023).



Where:- FL= Forest Land use, GL=Grazing Land use, CL=Crop Land use

Figure 2 Carbon stock under different land use types

Conclusions and Recommendations

The study reveals that the Lemo District has undergone a dramatic transformation over the last three decades, with cropland coverage surging from 13.3% in the 1990s to 19.1% by the mid-2000s, reaching 25% by the mid-2010s, and further expanding to 42.6% by the mid-2020s. The sustained expansion of cropland over the last 30 years is primarily attributed to heightened demographic pressure and the subsequent demand for agricultural land and wood-based fuels. This rapid expansion is primarily driven by demographic pressure, overgrazing, and recurrent droughts, leading to the conversion of ecologically

vital forests and grazing lands into monoculture systems. Soil analysis reveals that forest lands maintain significantly lower bulk density and higher moisture content compared to grazing land and cropland, with significant differences observed among all land use types at both soil depths (0-20 and 20-40 cm). Soil textural class showed no significant difference across the land use types at either soil depth. In contrast to the degraded state of cultivated areas, forest land maintained significantly higher levels of cation exchange capacity (CEC), organic matter (OM), available phosphorus (Av.P), total nitrogen (TN), and soil organic carbon stocks (SOCS) across both soil depths (0–20 and 20–40 cm). While the soil parameters suggest inherent fertility, the ongoing conversion of ecologically and economically valuable forests and grazing lands into monoculture

cropland poses a severe risk to long-term sustainability. This study underscores that while the region's clay-loamy soils and favorable climate currently support food production, the rapid depletion of organic matter and nutrient reservoirs in croplands is unsustainable. Based on the finding, we recommend supporting agroforestry and integrated nutrient management to restructure organic matter and prevent soil acidification. Local extension services should encourage conservation agriculture through reduced tillage and mulching to restore soil structure and nutrient levels.

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