6-19-2023

Impact of land use/cover change and slope gradient on soil organic carbon stock in Anjeni watershed, Northwest Ethiopia

Bethel Geremew

Tsegaye Tadesse

Bobe Bedadi

Hero T. Gollany

Kindie Tesfaye

See next page for additional authors

Authors

Bethel Geremew, Tsegaye Tadesse, Bobe Bedadi, Hero T. Gollany, Kindie Tesfaye, and Abebe Aschalew

Environ Monit Assess (2023) 195:971
https://doi.org/10.1007/s10661-023-11537-7

RESEARCH

Impact of land use/cover change and slope gradient on soil organic carbon stock in Anjeni watershed, Northwest Ethiopia

Bethel Geremew · Tsegaye Tadesse · Bobe Bedadi · Hero T. Gollany · Kindie Tesfaye · Abebe Aschalew

Received: 16 November 2022 / Accepted: 19 June 2023

Abstract Today's agri-food systems face the triple challenge of addressing food security, adapting to climate change, and reducing the climate footprint by reducing the emission of greenhouse gases (GHG). In agri-food systems, changes in land use and land cover (LULC) could affect soil physicochemical properties, particularly soil organic carbon (SOC) stock. However, the impact varies depending on the physical, social, and economic conditions of a given region or watershed. Given this, a study was conducted to quantify the impact of LULC and slope gradient on SOC stock and C sequestration rate in the Anjeni watershed, which is a highly populated and intensively cultivated area in Northwest Ethiopia. Seventy-two soil samples were collected from 0–15 and 15–30 cm soil depths representing four land use types and three slope gradients. Soil samples were selected systematically to match the historical records (30 years) for SOC stock comparison. Four land use types were quantified using Landsat imagery analysis. As expected, plantation forest had a significantly ($p < 0.05$) higher SOC (1.94 Mg ha^{-1}) than cultivated land (1.38 Mg ha^{-1}), and gentle slopes (1–15%) had the highest SOC (1.77 Mg ha^{-1}) than steeper slopes (> 30%). However, higher SOC stock (72.03 Mg ha^{-1}) and SOC sequestration rate (3.00 Mg ha^{-1} year^{-1}) were recorded when cultivated land was converted to grassland, while lower SOC stock (8.87 Mg ha^{-1}) and sequestration rate (0.77 Mg ha^{-1} year^{-1}) were recorded when land use changed from cultivation to

---

B. Geremew (✉) · B. Bedadi
Africa Centre of Excellence for Climate-Smart Agriculture and Biodiversity Conservation, Haramaya University, Haramaya, Ethiopia
e-mail: mybethel.y@gmail.com

B. Bedadi
e-mail: bobedadi2009@gmail.com

B. Geremew
College of Agriculture and Natural Resource Sciences, Debre Birhan University, P.O. Box 445, Debre Birhan, Ethiopia

T. Tadesse
National Drought Mitigation Center, University of Nebraska—Lincoln, Lincoln, USA
e-mail: ttadesse2@unl.edu

H. T. Gollany
USDA-Agricultural Research Service, Columbia Plateau Conservation Research Center, Pendleton, OR, USA
e-mail: hero.gollany@usda.gov

K. Tesfaye
International Maize and Wheat Improvement Center (CIMMYT), Addis Ababa, Ethiopia
e-mail: selamita2004@gmail.com

A. Aschalew
College of Agriculture and Environmental Sciences, Bahir Dar University, Bahir Dar, Ethiopia
e-mail: abebe_aschalew@yahoo.com

a plantation forest. The results indicated that LULC changes and slope gradient had a major impact on SOC stock and C sequestration rate over 30 years in a highly populated watershed. It is concluded that in intensively used watersheds, a carefully planned land use that involves the conversion of cultivated land to grassland could lead to an increase in soil C sequestration and contributes to reducing the carbon footprint of agri-food systems.

Keywords Carbon sequestration · Land use · Land cover · Soil carbon stock · Slope gradient

Introduction

Land, as a fundamental natural resource, serves important environmental, economic, and social purposes in the world. More than 95% of the world's food is grown on land. The global food supply is mostly reliant on the availability of productive soils. In part, land use land cover (LULC) change is a key feature and outcome of global environmental change (Song et al., 2018). The term LULC is used for human alteration of Earth's terrestrial surface from one use to the other (Meshesha et al., 2012). The driving factors of LULC changes differ in time and space based on the setting of a specific region (Assefa & Bork, 2014). Population growth is the main driver of LULC change in sub-Saharan Africa (Brandt et al., 2017) besides migration (Muriithi, 2016), and anthropogenic activities (i.e., mining, farmland expansion, urban developments) (Obodai et al., 2019). The presence of a steep slope landscape is another factor for LULC change (Jacob et al., 2016; Lambin et al., 2001; Zhao et al., 2017). The lack of weak regulation of natural resources is also an enabler of LULC change (Lambin et al., 2001). Overall, about 30% of the East African landscape has been converted into cultivated, barren, and urban land uses due to the current human activities (Jacobson et al., 2015).

For decades, Ethiopia has struggled with LULC change, due to rapid population growth along with poor land use planning and regulation (Meshesha et al., 2014). There have been several conservation efforts by the government and non-governmental organizations, though the physicochemical properties of soil have been changing through time. Soils are the largest carbon (C) pool in the terrestrial ecosystem. Global soils contain three to four times as much organic C as plants and twice or three times as much carbon as the atmosphere (Wiesmeier et al., 2019). In the twenty-first century, examining the trend of LULC change and the C stock potential of soil is becoming a precondition to understanding the nexus between LULC change and GHG emission in many disciplines. Such analysis is expected to contribute to the C budget (Hu et al., 2019) and climate change mitigation and adaptation measures at a local scale. Apart from land use impact, recent findings indicate that topographic factors play a significant role in changing the soil C stock potential by affecting soil properties at a watershed level (Sheleme, 2017), and altering the soil C pool (Jin et al., 2006). Topographic factors can, directly and indirectly, affect soil organic carbon (SOC) stocks by affecting soil depth, photosynthesis, nutrient cycle, and management intensity (Jobbagy & Jackson, 2000).

The term SOC refers to C in the soil of organic origin, and it is generally accepted that soil organic matter (SOM) contains approximately 58% SOC (Lal et al., 2015), whereas soil C sequestration is the process by which C physically protected, as in micro-aggregates, or deep within the soil profile and storing of biomass in the soil as organic materials (Lal et al., 2015).

The net flux of CO_2 between the soil and the atmosphere will be significantly affected by a slight relative change in SOC stores (Hartemink et al., 2014). The rate of C mineralization, via which CO_2 returns to the environment, determines the residence period of C in the SOM (Kelliher et al., 2004).

A study at the Kersa sub-watershed of Ethiopia indicated that SOC stock in grazing land use had a higher value in the surface and subsurface soil layers than cultivated and fallow land use (Yared et al., 2018). Similarly, the topsoil layer (0 to 20 cm depth) had higher SOC stock than the deeper layers. Abera and Belachew (2011) at Sinana Dinsho forest revealed the highest SOC (12.95%) under forest land, whereas the cultivated land had the lowest SOC (2.75%) in the 0 to 15 cm depth. Agidew and Singh (2017) at the Teleyayen sub-watershed reported that the highest SOC at the 0 to 15 cm depth was detected in soils under grassland (7.58%), succeeded by fallow lands (4.09%) and the cultivated soils (2.56%).

Wubie and Assen (2020) reported that SOC content was significantly influenced by the change in land cover and slope gradient. The highest values of SOC content were detected on the gentle gradients, while the lowest was noted on the steep slope gradients. During the first few years after converting natural forests to farmland, soil C loss can be very severe (Lal et al., 2015). According to Jakšić et al. (2021), SOC content in forest land decreased with increasing slope, but the difference was not statistically significant. The historic SOC loss over 50 years from rangeland and cropland soils in Ethiopia is estimated to be 230–670 Tg C (Tg = teragram = 1012 g = million metric ton of C) (Girmay et al., 2008). Solomon et al. (2018) in Wujig-Mahgo-Waren forest ecosystems showed that SOC stock in the year 2000 was higher than that in 1985 and 2016 due to the highest coverage of open and dense forests during 2000.

The alarming increase in population over the highlands of Ethiopia is exerting persistent pressure on land resources, which leads to LULC change and the removal of soils on steep slopes (i.e., > 30%) while tilling soil without proper soil management practices put in place (Zeleke & Hurni, 2001). Hence, landscape-based soil studies elucidating the relationship between LULC, slope gradient, and C stock are essential and play a substantial role in climate change mitigation and adaptation.

In the Anjeni watershed, only two studies have been conducted so far related to SOC. The first study was conducted by Amare et al. (2013) to evaluate the feasibility of visible and near-infrared (VNIR) soil spectroscopy for predicting SOC in the highlands of Ethiopia. A second study was conducted by Amare (2018) to assess the long-term impact of sustainable land management practices in the three watersheds (Anjeni, Andit-Tid, and Maybe) which are still being used as soil water conservation sites by the soil conservation research program (SCRP). The above studies were mainly focused on the calibration of VNIR soil spectroscopy and soil C, with less emphasis on the soil C stock change and C sequestration and changes of the various C pools at the watershed level. Thus, this study assessed the current C stock and C sequestration potential of the soil with the historical SOC record of the Anjeni watershed as regular evaluation of the watershed is vital to detect the effect of soil conservation works in the watershed.

Considering the previous studies, it is of paramount importance to have an in-depth evaluation of slope gradient and land use change impact on soil C stock and soil properties to examine the effect of soil conservation work in the watershed. Based on the current dataset, regular assessment of soil C stock, sequestration, and LULC change is crucial for endorsement of the conservation and improvement of soil C stocks. Most importantly, understanding and predicting the dynamics of SOC and the response of soil to the change in land use/cover and slope gradient are important to carry out development activities at the watershed scale. The output will help policymakers, and governmental and non-governmental institutions to stipulate the appropriate soil conservation measures that must be taken immediately if soil C and productivity are to be maintained. Soil water conservation works have been carried out in the Anjeni watershed as it has been exposed to significant losses of natural resources due to unwise exploitation of natural resources, and mismanagement of resources. Therefore, this study was conducted to (1) quantify the impact of slope gradient on SOC stock and selected soil properties in Anjeni watershed, and (2) determine the impact of LULC change on selected soil properties and SOC stock over the period 1997–2021 in Anjeni watershed.

Materials and methods

Study area description

Location

The research was carried out in the Anjeni watershed at 10°40′59 ″N latitude and 37°31′57″E longitude, in the Amhara region, Dembecha district, Northwestern Ethiopia (Fig. 1). The mean elevation of the Anjeni watershed varies from 2100 to 2500 m. The model Anjeni watershed that is soil and water conservation research site was established in March 1984 by SCRP (Soil Conservation Research Project). The watershed is still being used as a soil and water conservation research site by the Amhara Regional Agricultural Research Institute (ARARI). The area of the Anjeni watershed is about 108.3 ha.

Climate

The climate data recorded at Anjeni station from 1984 to 2017 indicates that the study area climate is characterized by a wet sub-humid agro-climate zone. The rainy season starts in mid-April and ends in October. The maximum monthly rainfall is received in July (Fig. 2). The mean

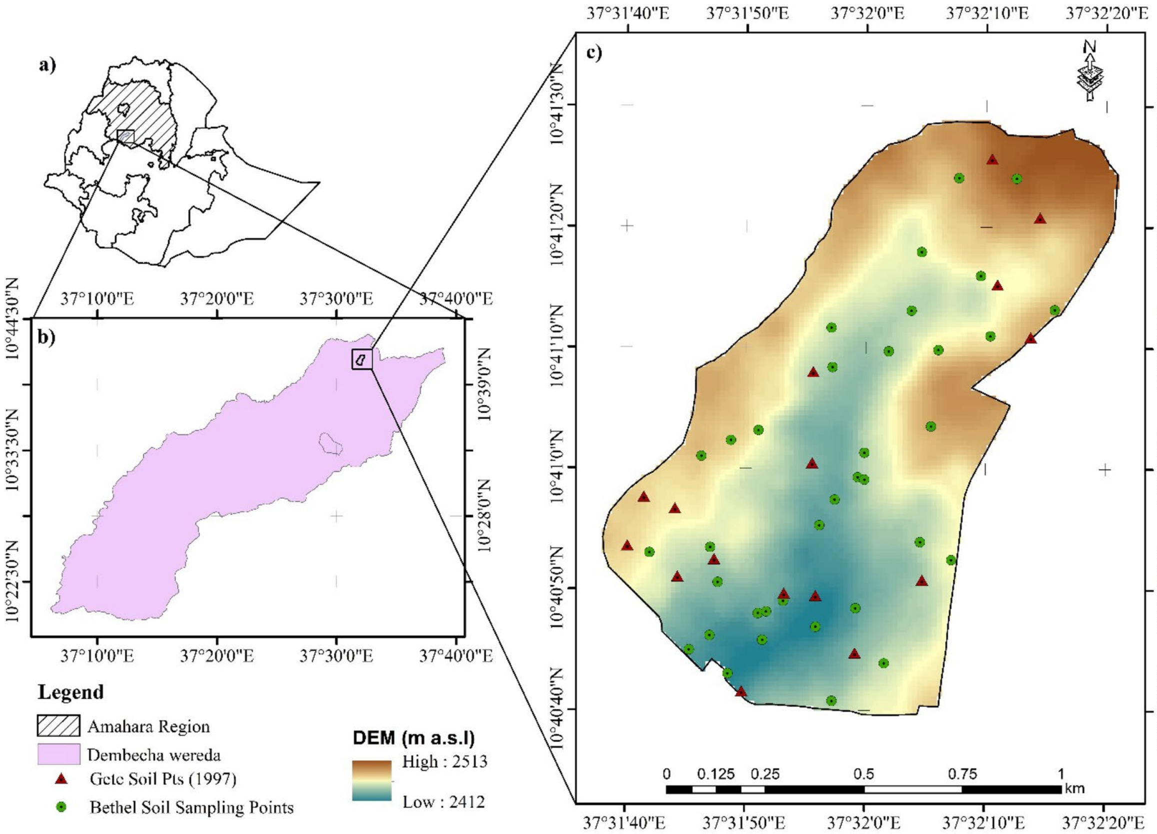

Fig. 1 Location map of Anjeni watershed and soil sampling sites (red triangle Gete sample point and green circle Bethel sample point)

monthly maximum and minimum temperatures are 22 °C and 9 °C, respectively. The main reasons for focusing on this watershed are the benefits of the watershed with a hydro-meteorological monitoring system and the availability of long-term data on rainfall, temperature, and soil characteristics since 1984.

Geology and soils

Based on Kejela (1995), the geology of the Anjeni area consists of the Precambrian basement complex covered by Mesozoic sediments, on top of which lies the trap basalt series. Anjeni area has developed from these basalts and their derivate, the volcanic ashes that occur with them, and mixtures of reworked materials from all these sources. Anjeni's soil is divided into 8 major soil units and 10 subgroups (Alemu et al., 2013). Alisols occupy 41% of the total land area of the catchment area and occupy the depressions of the land unit at the bottom of the valley and the foot of the hill. Medium-deep Nitisols account for 23.8% of the land cover found in the gently sloping convex to straight land units of the catchment area. Regosols and Leptosols (12.4%) occupy the convex-shaped steepest land units. Moderately deep Dystric Cambisols (19%) occupy the hilltop of the catchment and are partly found in the medium steep sloped land units. However, the various land units in the catchment area also contain small amounts of Luvisols, Lixisols, and Acrisols.

Land use and cover (LULC)

The major land use and cover type found in the watershed are mainly cultivated land, grassland, fallow land, and plantation forest (Table 1). Cultivated land accounts for approximately 66% of the total land cover (Alemu et al., 2013).

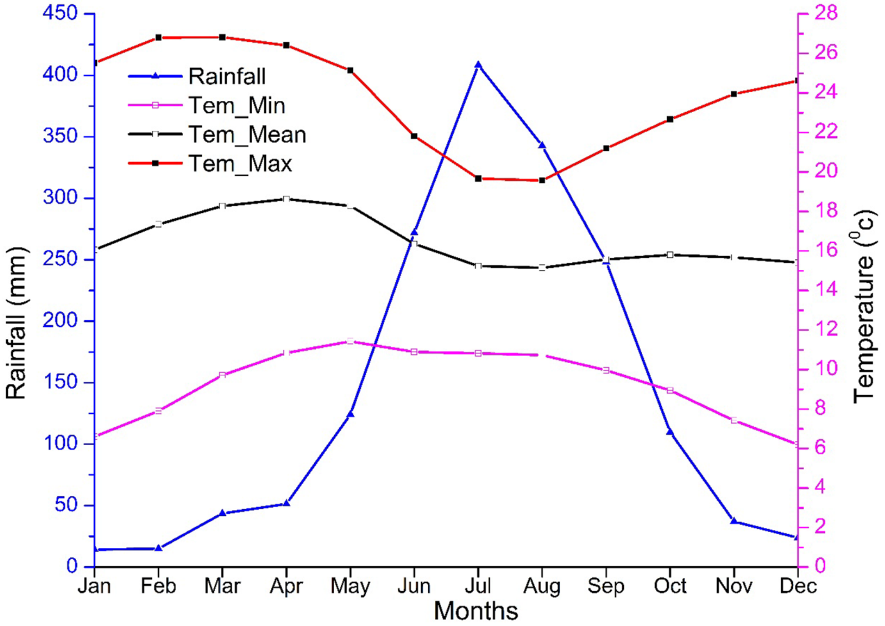

Fig. 2 Average monthly rainfall (mm) and maximum and minimum temperatures (°C) at Anjeni watershed (1984–2017). Climate data obtained from the Water and Land Resource Centre

Demographic and socio-economic settings

The farming system in Anjeni is a mixed type (grain and livestock production) of agriculture and production is rainfed and cereal-dominated (Alemu et al., 2013). Within 38 years, the population density of the Anjeni region increased by 185% from 43.85 per square kilometer in 1957 to 125.26 per square kilometer in 1995 (Zeleke & Hurni, 2001). Heavy population pressure, relatively high annual rainfall, and intensive crop production (mainly teff, barley, wheat, beans, peas, and niger seeds) are causing serious soil erosion damage in the central part of the research unit Kejela (1995).

Sampling and data collection

Dataset for land use land cover analysis

For this study, the three Landsat imageries (Landsat-5, Landsat-7, and Landsat-8) of different bands were downloaded from the United State Geological Survey (USGS) EarthExplorer with no clouds cover and imageries were analyzed using ArcGIS 10.7 to detect land use land cover changes in Anjeni watershed. The acquisition dates (Table 2) of the acquired images were in the dry season of nearby months of December and January to minimize the effects of seasonal variations in vegetation patterns and distribution. The reference

Table 1 Description of LULC classes (Zeleke & Hurni, 2001)

LULC category	Land cover description
Cultivated land (CL)	Areas intended for rainfed and irrigated cultivation
Grassland (GL)	Permanent covered with grass, an area meant for grazing; mostly communal areas
Fallow land (FL)	Dominantly small trees, bushes, shrubs, and sometimes with sparse large trees
Plantation forest (PF)	Areas covered by both natural and planted trees

Table 2 Satellite imagery used for the study

Satellite sensor	Path/row	Acquisition date	Number of bands	Spatial resolution (m)
Landsat-5 TM	169/53	12/01/1984	7	30
Landsat-5 TM	169/53	23/12/1993	7	30
Landsat-7 ETM+	169/53	03/01/2002	8	30
Landsat-7 ETM+	169/53	22/12/2011	8	30
Landsat-8: OLI	169/53	28/01/2021	11	30

data used for the land LULC accuracy assessment was obtained using Global Positioning System (GPS) in the watershed. Besides Google Earth reference data, primary data was collected from Anjeni watershed to moderate the error while we classify LULC and precision assessment.

Landsat imageries downloaded from USGS are geometric and radiometric corrected, but the imageries were preprocessed and prepared properly so that inaccuracy due to atmospheric effects could be accounted for. Band combinations of 2, 3, and 4 were used for the land use land cover analysis (Getahun & Haj, 2015). Pixel-based supervised image classification method was used for this study using a maximum likelihood classifier (algorithm) environment. In the process of supervised classification, pixels that can be easily recognized and represent land use patterns were selected or identified with the help of Google Earth. Training samples for supervised classification were selected knowing the watershed, GPS data, and desired classes of LULC. By prioritizing these classes, we monitored the classification of pixels to which class values were assigned. During image classification, previously collected photographs of the watershed and Google Earth were used as a reference. Finally, for the Anjeni watershed, five classes of LULC identified were fallow land, cultivation land, settlement, grassland, and plantation forest.

Image accuracy assessment The accuracy assessment checks how much a classified image agrees with reference data (assumed true data). Most quantitative methods for assessing classification accuracy use an error matrix constructed from two datasets: remotely sensed map classification and Google Earth reference data. Google Earth provided the reference data. A contingency matrix was used to compare the reference data acquired for each class type to the categorized image (Table 2).

Soil sampling and data

- Historical soil data

The historical SOC, bulk density, and soil depth datasets were obtained from Amhara Regional Agricultural Research Institute (ARARI) from a study conducted by Zeleke and Hurni (2001). First, the historical datasets were compared and matched with the current data (2021). Then, out of the soil pit samples collected by Zeleke and Hurni (2001) in 1997, sixteen pits that matched with current study sample location, slope gradients, and depth (Fig. 1) were taken to examine the soil carbon change. For the historic data, there were minimum of three and maximum four soil pit per land use land cover type. However, unlike slope gradient and soil depth, some land use land covers of the current soil samples were not the same as the historic soil data. Therefore, if change in land use land cover was observed, the change in organic carbon stock and carbon sequestration was quantified separately respective to the changed land use land cover (Table 3).

- Soil sampling and collection

The entire watershed was divided into three slope gradient categories: gentle slope (1–15%), moderate slope (15–30%), and steep slope (>30%). After identifying the major land use cover types in each slope category, soil samples were taken from four land cover types in each of the three slope categories. The soil was sampled from 0–15 and 15–30 cm soil depth according to IPCC recommendations to determine soil carbon stock (IPCC, 2003). Additional undisturbed soil cores were sampled from two depths (0–15 and 15–30 cm) for the determination of bulk density. A systematic sampling method on similar land uses close to the historical sampling points was applied to match historic soil datasets with the

Table 3 Summaries of land use land cover change in the Anjeni watershed from 1984 to 2021

LULC type	Land use land cover (ha)				
	1984	1993	2002	2011	2021
Cultivated land	76.45	86.8	83.72	85.03	78.71
Fallow land	6.54	1.7	2.23	3.75	3.22
Grassland	21.71	12.81	14.47	8.24	7.83
Plantation forest	3.32	6.71	7.6	8.47	13.56
Settlement	0.00	0.00	0.00	2.53	4.70
Total	108.02	108.02	108.02	108.02	108.02
	Land use land cover change (ha) 1984–2021				
	1984–1993	1993–2002	2002–2011	2011–2021	1984–2021
Cultivated land	10.35	−3.08	1.31	−6.32	2.26
Fallow land	−4.84	0.53	1.52	−0.53	−3.32
Grassland	−8.9	1.66	−6.23	−0.41	−13.88
Plantation forest	3.39	0.89	0.87	5.09	10.24
Settlement	0.00	0.00	2.53	2.17	4.70

current sampling points for the soil C stock change analysis. Sixteen new soil samples were collected following the same route of 16 pits that were reported by Gete (2000) and Zeleke and Hurni (2001) in 1997. Approximately 1.0 kg of composite sample was taken from each sampling point and put in plastic bags, secured, and labeled. A total of 72 disturbed soil samples (4 land use cover categories, 2 depths, 3 replicates, and 3 slope gradient categories) were collected. All sampling points were georeferenced by taking the coordinates using a GPS. Soil laboratory analyses were performed at Debre Berhan University and Debre Berhan Agricultural Research Center, Ethiopia.

- Soil laboratory analysis and harmonization of historical and current datasets

In the current field-measured soil parameters, bulk density was determined by the core method (Blake & Hartge, 1986). Soil particle size distribution was determined by the Bouyoucos hydrometric method (Bouyoucos, 1962). Soil pH was determined in a 1:2.5 soil:water ratio using a pH meter as described by Thomas (1996). The Walkley and Black wet digestion method was used to estimate the SOC content as described by Nelson and Sommers (1982). Total nitrogen was analyzed using the Kjeldahl digestion distillation and titration method as described by Bremner and Mulvaney (1982). The available phosphorous was analyzed using the Olsen method (Olsen & Dean, 1965). Exchangeable cations (Ca^{2+}, K^+, Mg^{2+}, and Na^+) were determined in a 1.0 M ammonium acetate (NH_4OAc) solution buffered at a pH of 7.0. Exchangeable Ca and Mg were analyzed using an atomic absorption spectrometer, while Na and K were analyzed by a flame photometer (Thomas, 1982). Cation exchangeable capacity (CEC) was estimated from the distillation of ammonium that was displaced by sodium (Chapman, 1965).

Current data had to be harmonized in deriving SOC change between 1997 and 2021. For this process, a data harmonization procedure was followed (Ross et al., 2015). Current soil samples taken from the watershed were from two depths at 0–15 and 15–30 with three replications, but the historical soil samples were from different depths. Soil organic C stock was calculated using the depth-weighted average of the horizons (Xiong et al., 2014). Harmonization is performed by establishing benchmark sites (Hartemink et al., 2014).

Soil organic carbon stock and carbon sequestration rates calculations

Soil organic carbon stock was calculated using the following equation (Henry et al., 2009):

$$\text{SOC Stock (Mg C ha}^{-1} = ((\text{SOC}/100)^* \rho \,^* \, SD)\,^*100 \tag{1}$$

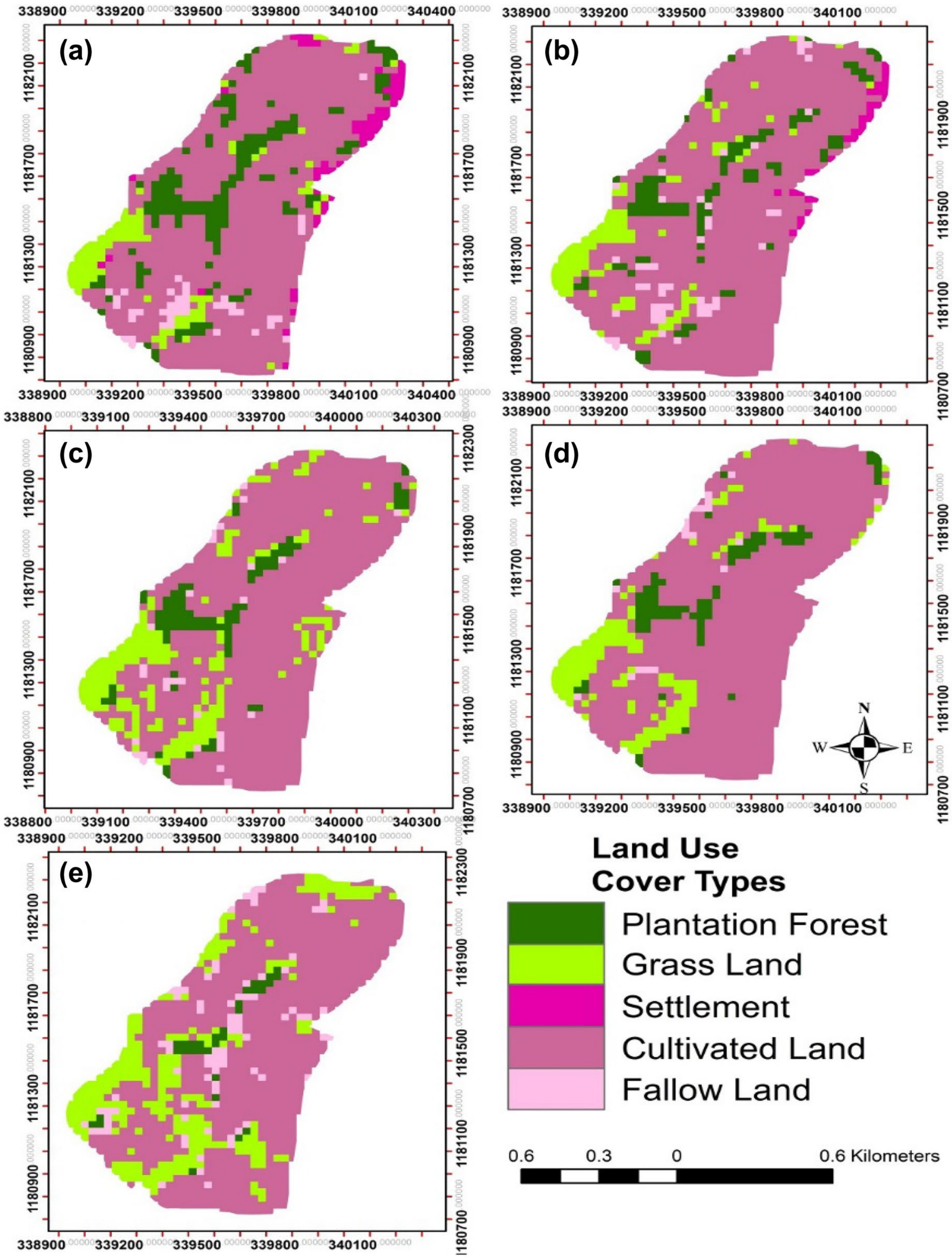

Fig. 3 Land use land cover map of Anjeni watershed: **a** Landsat-8 for 2021, **b** Landsat-7 (ETM+) for 2011, **c** Landsat-7 (ETM+) for 2002, **d** Landsat-5 for 1993, and **e** Landsat-5 for 1984

where ρ is the soil bulk density (g cm^{-3}), SD is the soil depth of the sampling layer (cm), and 100 was used to convert the unit to t C (Mg C ha^{-1}). The SOC sequestration rates were calculated according to the following questions (Ross et al., 2015):

$$\Delta SOC(x_O, NY) = SOC(x_O, YM_C) - SOC(x_O, YM_H) \tag{2}$$

$$SOC_{seq}(x_O) = \frac{\Delta SOC(x_O, NY)}{NY} \tag{3}$$

where H is the past (1997) SOC record, C is the current (2021) SOC record, YM$_C$ is the current measurement year (C), and NY is the number of years between historical and current observations (NY) = YM$_C$ − YM$_H$, SOC is SOC stocks in g^{-2}, SOC$_{seq}$ is the SOC sequestration rate (g m^{-2} year^{-1}) or its equivalent constrained to collocated historical and current sites (x$_0$), and x$_0$ is the geographic coordinate (x and y coordinates) of collocated sites. A positive SOCseq value represents an increase (isolation) in soil carbon, and a negative SOCseq value represents a loss of soil carbon during the period under consideration.

Statistical analysis

Before performing the ANOVA, we used a graphical Q-Q plot test to evaluate whether the data were normally distributed and met ANOVA's assumptions. The physical and chemical properties of the soil obtained were subjected to three-way analysis using SAS 9.2 version. A general linear model (GLM) was used to analyze the effects of land cover changes and gradient changes on dependent variables and their interaction effects. Fisher's least significant difference (LSD) was used to separate means from significant treatment effects ($p \leq 0.05$).

Results and discussion

Land use land cover (LULC) change detection analysis

The LULC change analysis was carried out every 9/10-year interval starting from 1984 to 2021; it was processed in 1984, 1993, 2002, 2011, and 2021. As the LULC change is a slow process and its trend was performed every 10- and/or 9-year intervals (Hassan et al., 2016; Pandi et al., 2022). The LULC change detection analysis indicated that cultivated (agricultural) land was the dominant land cover that covers above 76 hectares (Table 3) during the last 37 years (1984–2021). Grassland was the second dominant land use type in the watershed in the years 1984, 1993, and 2002, excluding the recent years in 2011 and 2021. Plantation forest and settlement areas have increased in recent years especially in 2011 and 2021 (Table 3) as compared to the past years (1984, 1993, and 2002), while grassland has decreased in recent years (2011 and 2021). The extent of settlement in 1984, 1993, and 2002 was not noticeable, but in recent years it has become more visible (Fig. 3). Analysis of the 2021 images revealed that cultivated land occupied the largest area (78.7 ha) followed by plantation (13.6 ha). The increase in settlement areas in the watershed indicated the expansion of population growth. Grassland depletion may be associated with high population demand for various agricultural practices and increased plantations and settlements. The increase in plantation forests in the watershed was due to the development or conservation work over the last 30 or more years as Anjeni is a model watershed in the region.

Overall, plantation forest and settlement land uses showed a constant or positive trend (Table 4). Agricultural land coverage increased in 1984–1993, 2002–2011, and 1984–2021, but the rate of change showed a

Table 4 Rate of land use land cover change at Anjeni watershed since 1984

LULC types	Rate of LULC change ha year – 1				
	1984–1993	1993–2002	2002–2011	2011–2021	1984–2021
Cultivated land	1.15	−0.34	0.14	−0.63	0.06
Fallow	−0.54	0.05	0.16	−0.05	−0.08
Grassland	−0.99	0.18	−0.69	−0.04	−0.37
Plantation forest	0.37	0.09	0.09	0.50	0.27
Settlement	0.00	0	0.28	0.21	0.12

Table 5 Land use land cover change (LULC) transition matrix between 1984 and 1993

	LULC type	LULC 1993				
		Cultivated land	Fallow land	Grass land	Plantation forest	Loss
LULC 1984	Cultivated land	69.8	0.7	2.8	2.8	76.2
	Fallow land	4.5	1.1	0.7	1.2	7.5
	Grassland	12.1	1	8	0.8	21.8
	Plantation forest	0.8	0.1	0	1.8	2.7
	Gain	87.2	2.8	11.6	6.6	108.3
	Net change	11.1	−4.7	−10.2	3.9	
	Net persistence ratio	0.2	−4.3	−1.3	2.1	

declining trend in 1993–2002 and 2011–2021 with an increase in fallow land, grasslands, plantation forest, and settlement, respectively. Between 1984 and 1993, the rate of change in grassland was very slow compared to other years (−0.99 ha/year). The rates of change in plantation forest and settlement areas noticeably increased continuously between 2011 and 2021 with a net rate of change of 0.50 and 0.21 ha/year, respectively. These could be due to the conservation effort and increased population density in the Anjeni watershed. Grasslands decreased throughout the study period, while plantation forests rate increased throughout the study period.

The transition matrix (Tables 5, 6, 7, and 8) showed the transition from one land cover class to another in different years. An area of grassland (21.8 ha) and fallow (7.5 ha) has been converted to cultivated land and plantation forest from 1984 to 1993, resulting in a net increase of 11.1 and 3.9 ha of cultivated land and plantation forest, respectively (Table 5). Between 2002 and 2011, 14.47 hectares of grassland was converted to either cultivated land, fallow land, plantation forests, or settlement (Table 7), resulting in a net increase of 2.50 ha of cultivated land, 1.5 ha of fallow land, 0.8 ha of plantation forest, and 2.4 ha of settlement areas. Between the years 2011–2021, there have been net gains in plantation forests (5.10 ha) and settlement areas (2.10 ha), whereas there were decreases in grassland by 0.40 ha and cultivated land by 6.20 ha and fallow land by −0.50 ha (Table 8). The increase in plantation forest and settlement areas in the years 2002–2011 mainly comes from the decrease in grassland and fallow land cover. Even though cultivated land has an increasing trend in the referenced year it does not show a consistent pattern throughout the year. This could be related to the conservation effort that was taken in the study watershed.

Soil bulk density and particle size distribution

Soil bulk density showed a significant ($p < 0.05$) interaction effect between LU type and slope gradient (Table 9). Cultivated land and steep slopes had higher soil bulk density than plantation forests and gentler slopes. This could be due to silt transportation, high organic matter content, and soil porosity of the soil that moves down toward the gentler slope because of heavy rainfall (Stavi et al., 2008). Thus, steep slopes have a more significant impact on soil composition than surfaces with a slight slant (Hu et al., 2019). According to Landon (2013), the bulk density of clay, clay loam, and

Table 6 Land use land cover change (LULC) transition matrix between 1993 and 2002

	LULC type	LULC 2002				
		Cultivated land	Fallow land	Grass land	Plantation forest	Loss
LULC 1993	Cultivated land	77.2	1.5	6.7	2.1	87.6
	Fallow land	0.6	0.4	0.3	0.3	1.6
	Grassland	2.7	0.1	8.3	0.5	11.5
	Plantation forest	1.6	0.2	0.1	5.8	7.7
	Gain	82.2	2.2	15.4	8.6	108.3
	Net change	−5.3	0.6	3.9	0.9	
	Net persistence ratio	−0.1	1.5	0.5	0.2	

Table 7 Land use land cover change (LULC) transition matrix between 2002 and 2011

		LULC 2011					
	LULC type	Cultivated land	Fallow land	Grassland	Plantation forest	Settlement	Loss
LULC 2002	Cultivated land	73.6	2.2	1.6	2.9	1.9	82.2
	Fallow land	1.2	0.9	0.1	0.3	0	2.5
	Grassland	8.2	0.6	6.9	0.1	0.2	16
	Plantation forest	1.6	0.4	0.2	5.3	0.3	7.7
	Settlement	0	0	0	0	0	0
	Gain	84.7	4	8.8	8.5	2.4	108.3
	Net change	2.5	1.5	−7.2	0.8	2.4	
	Net persistence ratio	0	1.7	−1.1	0.2	2.4	

silt loam soils ranges from 1.00 to 1.60 g cm^{-3}. Therefore, compaction was minimal for surface mineral soils in all the land uses and slope gradients (Table 9). Thus, its effect on crop cultivation and root penetration can be also minimal. Similar results were reported by Selassie et al. (2015) in a study at the Zikre watershed, in the northwestern part of Ethiopia.

The highest mean soil bulk density (ρb) values were recorded for cultivated land (1.30 g cm^{-3}) followed by grassland (1.19 g cm^{-3}) and fallow land (1.18 g cm^{-3}). The lowest mean soil bulk density was observed under plantation forest (1.08 g cm^{-3}). The high soil bulk density values in cultivated land were associated with low OM content (Table 9), and no compaction impact due to conventional tillage. Another study conducted around Bale mountains, south Eastern Ethiopia, also showed that bulk density was high in cultivated land (Warra et al., 2015). In contrast with this study, Yared et al. (2018) reported the highest bulk density value in fallow land than in cultivated land or grassland. The highest bulk density is detected in Gumara watershed grassland as a result of high compaction resulting from intensively grazing animals (Wubie et al., 2016). It is known that deforestation and continuous tillage increase bulk density. The high value of bulk density in cultivated land means that the amount of water in the field is low in the soil. Furthermore, low bulk density in plantation forests indicates less compaction and can retain more water (Kakaire et al., 2016).

In addition, the highest mean soil ρb was exhibited by the steep slope (1.27 g cm^{-3}) followed by the moderate (1.16 gm cm^{-3}) and gentle (1.14gm cm^{-3}) slopes. The high ρb value on steep slope could be due to the removal of fine particles from the steep slope and might lead to a high concentration of coarse particles. Similarly, Wubie and Assen (2020) reported a significantly high soil ρb value at the steep slope in a study at the Gumara watershed in upper Blue Nile. The present result indicated that the slope gradient

Table 8 Land use land cover change (LULC) transition matrix between 2011 and 2021

		LULC 2021					
	LULC type	Cultivated land	Fallow land	Grass land	Plantation forest	Settlement	Loss
LULC 2011	Cultivated land	72.9	2	1.6	6.2	1.8	84.6
	Fallow land	1.5	1.2	0.2	0.8	0.1	3.8
	Grassland	1.6	0.1	5.7	0.6	0.3	8.2
	Plantation forest	2.1	0	0.1	5.9	0.3	8.4
	Settlement	0.3	0	0.1	0	3	3.4
	Gain	78.4	3.2	7.8	13.5	5.4	108.3
	Net change	−6.2	−0.5	−0.4	5.1	2.1	
	Net persistence ratio	−0.1	−0.5	−0.1	0.9	2.1	

Table 9 Mean and standard deviation values of bulk density (g cm^{-3}) and particle size distribution at Anjeni watershed

Factors	Attribute of factors	ρb (g cm^{-3})	Particle size (%)			Textural class
			Clay	Silt	Sand	
Land use type	Cultivated land	1.30 ± 0.20^{a}	63.61 ± 4.88	21.94 ± 5.13	14.44 ± 5.02^{ab}	C
	Fallow land	1.18 ± 0.00^{b}	66.20 ± 7.92	21.33 ± 7.39	12.44 ± 4.93^{b}	C
	Grassland	1.19 ± 0.06^{b}	61.80 ± 6.49	22.72 ± 5.38	16.06 ± 4.90^{a}	C
	Plantation forest	1.08 ± 0.09c	64.67 ± 5.74	21.11 ± 5.91	14.89 ± 5.62^{ab}	C
	p-value	< 0.0001	0.86	0.69	0.04	
Slope gradient	Gentle slope	1.14 ± 0.08	61.20 ± 6.86	24.12 ± 7.76	15.56 ± 6.04	C
	Moderate slope	1.16 ± 0.09	66.22 ± 6.86	21.09 ± 4.83	12.69 ± 5.28	C
	Steep slope	1.27 ± 0.21	65.00 ± 4.34	20.00 ± 3.65	15.00 ± 3.68	C
	p-value	0.676	0.48	0.91	0.06	
Soil depth	0–15	1.18 ± 0.17	63.24 ± 6.40	21.75 ± 5.49	15.59 ± 5.17^{a}	C
	15–30	1.19 ± 0.12	64.94 ± 6.43	21.8 ± 6.43	13.26 ± 4.99^{b}	C
	p-value	0.62	0.29	0.98	0.04	
	LU*SG	0.0005**	47.07 ns	19.62 ns	34.81 ns	
	LU*SD	0.66 ns	93.24**	64.51 ns	58.69**	
	SG*SD	0.37 ns	58.85 ns	16.84 ns	13.02 ns	
	LU*SG*SD	0.66 ns	20.35 ns	41.50 ns	9.97 ns	
	CV %	8.73	8.75	27.27	27.81	
	Error	0.01	31.45	35.28	16.17	

Means ± standard errors. Different letters within a column are significantly different at $p < 0.05$ (Fisher's LSD)

Significantly different * significant at $p = 0.05$ and *ns*, non-significant

LU land use, *SG* slope gradient, *SD* soil depth, *C* clay, *ρb* bulk density

led to a significant variation in the soil bulk density. The soil ρb varies due to the history of land management and land use conversion (Chemistry, 2014).

The bulk density was inversely related with the SOC stock, which implies that the lower SOC typically leads to higher bulk density as SOC has very low density (i.e., weight per unit volume) (Hartemink et al., 2014; Liu et al., 2011; Yuan et al., 2019). The bulk densities at the two soil depths were not significantly ($p > 0.05$) varied in the study area. However, the mean value of soil bulk density (1.19 gm cm^{-3}) was higher in the 15–30 cm soil depth. The higher value of soil bulk density in the subsurface is associated with subsurface layers being more compacted and having less OM, less soil accumulation, and less root penetration than surface layers (Blake & Hartge, 2018).

The soil clay and sand content exhibited a statistically significant ($p < 0.05$) interaction with land use type and soil depth. The high clay content in the fallow land and higher accumulation of clay in the 15–30 cm soil layer could be related to trapping silt and clay. Thus, an increased rate of clay accumulation in subsoil horizons. The second reason may be the contribution of in situ synthesis of secondary clay, or the residual concentration of clay due to coarser particle size (Fite, 2017). The relatively higher sand content in the grassland and accumulation of sand in the upper 0 to 15 cm soil layer confirmed that erosion is a selective process. As a result, clay and silt particles are removed due to high rainfall, and overgrazing in the grassland leaves coarse debris (Wubie & Assen, 2020). The sand fraction showed a significant ($p < 0.05$) variation among the LU types, slope gradients, and soil depths. The overall mean values of clay fractions were high in all land use types and slope gradients. Significantly ($p < 0.05$) higher sand fraction (16%) was under grassland, and the lowest (12%) was recorded under fallow land. A related conclusion was made by Assefa et al. (2020), who found a greater sand fraction in cultivated land and grassland followed by the forest land in the Kabe watershed of Wereilu, Ethiopia.

Statistical analysis of soil particle size distribution and slope gradient revealed no significant ($p > 0.05$) difference. The mean value of clay was > 35%. According to the USDA soil texture triangle, this soil is fine texture soil. Soil particle size varies with land use change and slope gradient; however, it is a slow process and could be related to the management of soil resources and poor soil and water conservation practices (Mekuria et al., 2013).

Soil pH

Soil pH (H_2O) showed significant interaction ($p < 0.05$) with land use types and slope gradient (Table 5). A higher value of pH in grassland use and a moderate slope could be related to the high buffering capacity of organic matter and the less leaching of basic cations. However, there were no significant differences in the variation of soil pH with land use and slope gradient in the Anjeni watershed. The highest pH value was recorded in the grassland (5.49) and the lowest in the plantation forest land use type (5.18). These results were in agreement with Alemu (2015) for the highlands of Ethiopia which explained the relatively low pH value of plantation forest soil due to the uptake of basic cations in tree biomass and the acidic nature of the decomposed litter of the tree species. The pH value in the study area was rated acidic to slightly acidic (Tadesse et al., 1991). The pH value in the Anjeni watershed is associated with heavy rainfall, acidic parent material, and organic matter decay.

Considering the slope gradient, a significantly ($p < 0.5$) higher pH value was recorded at the steep slope (5.32) and the lowest (5.22) was recorded at the gentle slope. In contrast with our results, Wubie and Assen (2020) reported a high pH value in gentle slopes compared to steep slopes due to the accumulation of base cations. Generally, soil pH is a good indicator of soil health because soil pH affects nutrient availability (Medinets et al., 2015).

Statistically significant ($p < 0.05$) variation in soil pH (KCl) was detected due to the land use types and slope gradient (Table 10). Accordingly, the highest pH value (4.16) was recorded under the grassland, while the lowest (3.88) was under fallow land. Similarly, the highest pH value (4.16) was found on the steep slope as compared to the gentle (4.05) and moderate (3.82) slopes. This is most likely due to erosion on steep slopes and exposure of subsoil. Subsoils typically have higher pH due to accumulation (illuviation) of basic cations.

Soil organic carbon, total nitrogen, and available phosphorus

Soil organic carbon content was significantly ($p < 0.05$) different due to the land use type and slope gradient (Table 10). A higher value of SOC in plantation forests and gentler slopes could be associated with land use and slope (topography) since they are some of the soil's forming factors (Bizuhoraho et al., 2018). The SOC variability in this watershed study could be due to the interaction of these two factors and the perpetual removal of organic nutrients from the steeper slopes. The land use and slope gradient are factors in controlling SOC.

Plantation forests had the highest SOC (1.94%) relative to the other land use types, and the lowest SOC was observed for cultivated land (1.38%). The significantly higher SOC in plantation forests may be due to the litterfall on the soil surface and high biomass production, which resulted in high biological activity in the soil and on the soil surface (Lal et al., 2015).

Decreased SOC content in cultivated land is often associated with residue removal and lack of crop rotation (Boix-Fayos et al., 2009) and rapid decomposition and mineralization of SOM (Ritchie, 2014). Continuous cultivation negatively affects the soil moisture and aeration resulting in the oxidation of SOM and reduction in SOC through harvesting of plants and plant residue input.

The SOC content was relatively higher in the gentle slope (1.77%) than in the steep slope gradient (1.49%). Various factors may contribute to the relatively high SOC content in the gentle slope gradient of the watershed. This may be due to prolonged fallow periods and differences in geomorphological erosion processes compared to steep slopes, which likely had higher soil erosion. Betemariyam et al. (2020) reported similar results for Jimma in the southwestern part of Ethiopia. Therefore, the soil and water conservation on the steeper slopes of the Anjeni watershed might have contributed to the SOC increase in the area. Also, a statistically significant ($p < 0.05$) higher SOC value (1.69%) was recorded for the top 0–15 cm soil depth compared to the 15–30 cm depth.

Total nitrogen exhibits a statistically significant ($p < 0.05$) interaction between land use and slope gradient. The higher amount of TN in the plantation forest could be due to the presence of nitrogen-fixing plants. The second reason could be the high organic matter, a major source of TN in the plantation forest.

Table 10 Mean and standard error values of pH (H_2O and KCl), soil organic carbon (SOC), total N (%), average P for different land use types, slope gradient, and soil depth at Anjeni watershed

Factors	Attribute of factors	pH		SOC (%)	TN (%)	Av. P (%)
		H_2O	KCl			
Land use type	Cultivated land	5.19 ± 0.36	3.93 ± 0.25b	1.38 ± 0.39c	0.16 ± 0.04c	10.40 ± 2.21a
	Fallow land	5.30 ± 0.31	3.88 ± 0.74b	1.51 ± 0.32bc	0.17 ± 0.04bc	08.92 ± 2.08b
	Grassland	5.49 ± 0.16	4.21 ± 0.11a	1.63 ± 0.28b	0.19 ± 0.05ab	07.31 ± 1.42c
	Plantation forest	5.18 ± 0.13	4.03 ± 0.11ab	1.94 ± 0.57a	0.22 ± 0.11a	07.45 ± 1.71c
	p-value	0.41	0.05	< 0.0001	0.0003	< 0.0001
Slope gradient	Gentle slope	5.22 ± 0.28	4.05 ± 0.16	1.77 ± 0.58	0.21 ± 0.09	7.94 ± 1.24
	Moderate slope	5.34 ± 0.27	3.82 ± 0.65	1.57 ± 0.32	0.16 ± 0.04	9.75 ± 2.46
	Steep slope	5.32 ± 0.30	4.16 ± 0.16	1.49 ± 0.34	0.17 ± 0.05	7.95 ± 2.42
	p-value	0.13	0.38	0.55	0.54	0.45
Soil depth (cm)	0–15	5.28 ± 0.30	4.06 ± 0.17	1.69 ± 0.44 a	0.19 ± 0.07	8.61 ± 2.35
	15–30	5.29 ± 0.27	3.96 ± 0.56	1.53 ± 0.44b	0.17 ± 0.06	8.42 ± 2.14
	p-value	0.73	0.38	0.02	0.09	0.47
	LU*SG	0.21**	0.22 ns	0.69**	0.02**	3.44 ns
	LU*SD	0.04 ns	0.13 ns	0.01 ns	0.003 ns	3.44 ns
	SG*SD	0.08 ns	0.18 ns	0.09 ns	0.00 ns	2.57 ns
	LU*SG*SD	0.01 ns	0.12 ns	0.06 ns	0.00 ns	1.78 ns
	CV %	4.39	9.11	19.03	24.1	19.35
	Error	0.05	0.13	0.09	0	2.72

Means ± standard error with different letters within a column are significantly different ($p < 0.05$) (Fisher's LSD)

SOC soil organic carbon, *TN* total nitrogen, *Av. P* available phosphorus

The highest TN was recorded for plantation forest (0.22%) followed by grassland (0.19%), fallow (0.17%), and cultivated land uses (0.16%). The low TN in the cultivated land often is associated with the limited application and/or use of nitrogen inputs and removal of plant and animal residue. This study finding is in agreement with Abera and Belachew (2011) indicating the lower value of TN was recorded in arable land uses at different soil depths. This study result was in line with Wubie and Assen's (2020) study in the Gumara watershed of the upper Blue Nile. The considerably higher amount of TN in the plantation forest resulted from nutrient recycling.

The TN content in the Anjeni watershed was rated as high according to Landon (2013). The mean TN in the soil declined substantially from 0.21% in the gentler slope to 0.17% in the steeper slope of the watershed. The lower TN value in the steep slope areas could be associated with the accumulation of eroded deposits. A similar result was reported by Yared et al. (2018) in a study conducted in Eastern Ethiopia. The depth of the soil and TN content do not show any significant ($p > 0.05$) difference in the study watershed. Loss of N in the soil occurs by volatilization, leaching, or decrease in an OM when forest or grassland cover is changed into other LULC types (Zhu et al., 2019).

Available phosphorus did not exhibit a significant ($p > 0.05$) interaction between the slope gradient and land use types (Table 10). The amount of available phosphorous was significantly ($p < 0.05$) affected by LU and SG. A relatively high amount of available phosphorous was found in cultivated land (10.4%) and the lowest available phosphorous (7.3%) was recorded for grassland. The result was in line with the Wubie and Assen (2020) findings, which showed that lower phosphorus was found in the grassland. The level of available phosphorous in the watershed is generally rated as high (Landon, 2013). The relatively high amount of phosphorous in the cultivated land could be associated with manure and inorganic fertilizers' application. This finding is in agreement with the previous study by Jakšić et al. (2021) in Ghana who reported the highest amount of available phosphorus in the arable land. On the other hand, the significantly highest amount of available phosphorous was recorded in the moderate slope (9.75) compared to the steep slope (7.95) and gentle slope (7.94) positions of the watershed. This implies that there was the removal of available phosphorous on steep slopes and deposition on the moderate and gentle slope of the watershed.

Cation exchange capacity and exchangeable bases

Cation exchange capacity (CEC) did not exhibit a significant ($p > 0.05$) interaction effect between land use and slope gradient (Table 11). The mean value of CEC ranged from 42.62 to 37.86 cmolc(+)/kg in cultivated and fallow land respectively. Higher CEC was found in cultivated, plantation, and grasslands compared to fallow land.

The significantly higher CEC of cultivated land could be associated with the variation in clay type at the study site. Because of the type of clay mineralogy, soils with substantially lower clay content may have higher CEC (Landon, 2013). The contribution of SOM to CEC varies between 25 and 90% (Trivedi et al., 2018). Cation exchange capacity primarily varies according to the type of clay and SOM; soil OM has both cation and anion exchange capacity (Nesic et al., 2015).

The CEC results can sometimes also be used as a rough guide to the types of clay minerals present (Landon, 2013). Additionally, the dominant soil type in the Anjeni area is ALISOLS (AL) which consists of strongly acidic soils with accumulated high-activity clays in their subsoils. According to Landon (2013), soil CEC in all the land uses and slope gradient was in the range of high to very high for surface mineral soils (Table 11).

Except for potassium (K^+), the interaction between land uses and slope gradient was statistically non-significant ($p > 0.05$) for all measured soil chemical parameters. The relatively high value of K in the grassland use type and gentler slope could be associated with the high organic matter content of grassland as a result of the fast growth and decomposition of the grass plant.

A significant ($p < 0.05$) difference in Ca^+ and Mg^+ was found between the land use types. The plantation forest had the highest exchangeable Ca^+ (6.01 $cmol_c(+)/kg$), whereas the grassland soils had the lowest (3.43 $cmol_c(+)/kg$). The low Ca^+ content of grassland (3.43 $cmol_c(+)/kg$) is most likely associated with cattle grazing leading to decreases in the source of soil organic matter, facilitates litter decomposition, and increases leaching which reduces soil organic matter. A similar result was reported by Alemu (2015) in a study conducted in the highlands of Ethiopia.

Statistically significant ($p < 0.05$) variation is measured in K^+, Ca^+, and Na^+, among the slope gradient. Higher K^+, Ca^+, and Na^+ were found at gentler slopes than at moderate slopes. This could be associated with the amount of rainfall at the study area, the crop cover, and the leaching of basic cations.

Significant ($p < 0.05$) differences in K^+ with the soil depth were recorded. This difference could be due to the fertilizer application and decomposed plant material. The geology and soil types are often the primary sources of K variation. If soil is amended with copious amounts of compost, plant decays contribute to available potassium levels (White & Brown, 2010).

Soil organic carbon stock

The interaction effect between land use type, SOC stock, and slope gradient was statistically significant ($p < 0.05$). The SOC stock was relatively higher in grasslands (29.86 Mg ha^{-1}) followed by plantation forest (28.26 Mg ha^{-1}), fallow land (25.68 Mg ha^{-1}), and cultivated land use (21.15 Mg ha^{-1}) (Table 12). A higher value of SOC stock in the grassland could be associated with these land use systems having high annual biomass dynamics. Because plant productivity is restricted by precipitation in grasslands, carbon stocks are highest in areas in which rainfall is the greatest (Ontl et al., 2020). Similarly, grassland C stocks decrease with increasing annual temperatures due to higher biological activity and decomposition of SOM at higher temperatures. Therefore, grassland C stores are sensitive to management and vulnerable to soil organic carbon loss (Ontl et al., 2020).

The SOC stock changes with slope gradient were not statistically significant ($p > 0.05$). However, it was generally higher at gentle slope (27.84 Mg ha^{-1}) as compared to steep slope (26.76 Mg ha^{-1}) and moderate slope (23.97 Mg ha^{-1}) areas. The result indicated statistically significant ($p < 0.05$) change in SOC stock with the soil depths. This finding is consistent with that of Amanuel et al. (2018) at the Birr watershed in upper Blue Nile basin, Ethiopia. The relatively high value of SOC stock (28.37 Mg ha^{-1}) that was measured in the top 0–15 cm depth is in line with that of Anokye et al. (2021), where SOC stock significantly decreased with soil depth.

Table 11 Mean and standard error values of CEC, K$^+$, Ca$^+$, and Na$^+$ in different land use types, slope gradient, and soil depth at Anjeni watershed

Factors	Attribute of factors		Exchangeable bases (meq/100 g)			
		CEC	K$^+$	Ca$^+$	Na$^+$	Mg$^+$
Land use type	Cultivated land	42.62 ± 5.65a	0.49 ± 0.12ab	4.28 ± 1.21b	1.25 ± 0.74a	3.25 ± 2.12a
	Fallow land	37.86 ± 4.93a	0.44 ± 0.07b	4.19 ± 1.59b	0.79 ± 0.56b	3.17 ± 1.82a
	Grassland	41.65 ± 9.87a	0.53 ± 0.21a	3.43 ± 1.69b	1.09 ± 0.75b	3.23 ± 1.19a
	Plantation forest	42.21 ± 4.84a	0.52 ± 0.14a	6.01 ± 1.76a	0.80 ± 0.67b	1.75 ± 0.89b
	p-value	0.17	0.19	< 0.0001	0.16	0.01
Slope gradient	Gentle slope	41.42 ± 5.28	0.57 ± 0.14	4.10 ± 1.59	1.39 ± 0.72	3.26 ± 1.65
	Moderate slope	40.44 ± 7.58	0.47 ± 0.11	5.11 ± 1.65	0.83 ± 0.63	2.29 ± 1.18
	Steep slope	41.36 ± 7.59	0.43 ± 0.14	4.26 ± 2.07	0.92 ± 0.60	2.63 ± 1.22
	p-value	0.86	0.48	0.77	0.43	0.06
Soil depth (cm)	0–15	41.09 ± 7.19	0.53 ± 0.15 a	4.59 ± 1.72	1.05 ± 0.69	2.59 ± 1.36
	15–30	41.08 ± 6.44	0.46 ± 0.13b	4.36 ± 1.92	1.06 ± 0.71	2.91 ± 1.48
	p-value	0.91	0.01	0.28	0.52	0.80
	LU*SG	38.39 ns	0.09**	3.14 ns	0.73 ns	0.85 ns
	LU*SD	114.5 ns	0.01 ns	1.11 ns	0.07 ns	0.34 ns
	SG*SD	16.53 ns	0.00 ns	2.26 ns	0.26 ns	0.66 ns
	LU*SG*SD	11.12 ns	0.01 ns	3.19 ns	0.29 ns	0.92 ns
	CV %	17.3	18.9	31.9	59.3	50.3
	Error	48.6	0.01	2.05	0.39	1.91

Means and standard errors with different letters within a column are significantly different ($p < 0.05$) (Fisher's LSD)

CEC cation exchange capacity, *Ca*$^+$ calcium, *Na*$^+$ sodium, *Mg*$^+$ magnesium

Soil organic carbon stock change from 1997 to 2021

Comparisons of the current SOC stock measured with the historical datasets revealed significant SOC stock change in 1997 and 2021 (Table 13). A considerably higher SOC stock was recorded in 2021. In the historical data (1997), the highest SOC stock (71.7 Mg ha^{-1}) was recorded in grassland while the lowest (33.52 Mg ha^{-1}) was measured in the fallow land. Likewise, in the current (2021) land use, the highest SOC stock was 121.59 Mg ha^{-1}, measured in the grassland, followed by plantation forest (103.47 Mg ha^{-1}). The study result is in line with Ibrahim et al. (2021) that the soil in grassland is rich in organic matter content due to high biomass return.

The highest value of SOC stock change was obtained from the conversion of fallow land to grassland (77.61 Mg ha^{-1}) followed by a land use conversion from cultivated land to grassland (72.03 Mg ha^{-1}). However, in comparison with historical data, the current data showed a high SOC stock increase in all land uses. These could be due to the continuous conservation effort taken by the farmers and responsible government bodies. Even though there was a decreasing trend in the grassland coverage from 21.71 to 7.83 ha in the past two-plus decades, still the SOC stock of grasslands was very high.

A recent study on SOC stock and land use change reported that the decline of SOC stock by 30 to 80% was recorded when forest and grassland use changed to cultivated land (Poeplau et al., 2015). In contrast with these losses, land use intensification, especially the conversion of cropland to grassland or forests, often leads to SOC gain (Wiesmeier et al., 2019) which is in line with this study. Overall, from our study, grasslands have a great potential for SOC storage followed by plantation forests, and conservation efforts of the grasslands and plantation forests are very important. Similar studies reached the same conclusion (Wiesmeier et al., 2019).

Land use change is the most dynamic factor in SOC stock changes (Wiesmeier et al., 2019). In the last decades, the Anjeni watershed has gone through extensive LULC change. The results of this study

Table 12 Soil organic carbon stock (Mg ha^{-1}) of different land use types and slope gradient

Factors	Attribute of factors	SOC stock (Mg ha^{-1})
Land use type	Cultivated land	21.15 ± 9.83
	Fallow land	25.68 ± 8.78
	Grassland	29.86 ± 9.15
	Plantation forest	28.26 ± 10.65
	p-value	0.03
Slope gradient	Gentle slope	27.84 ± 12.23
	Moderate slope	23.95 ± 07.73
	Steep slope	26.76 ± 09.29
	p-value	0.39
Soil depth	0–15	28.37 ± 11.09
	15–30	23.99 ± 08.23
	p-value	0.04
	LU*SG	0.01
	LU*SD	0.62
	SG*SD	0.29
	LU*SG*SD	0.34
	CV %	31.80
	Error	69.62

indicate that LULC changes between 1997 and 2021 have led to net SOC gain (Table 13). Though the dominant land use type in the watershed was cultivated land, there was an expansion of plantation forests due to the conservation efforts. Soil organic C sequestration during the current (2021) period revealed that there was a net C gain in all the converted and the unconverted land uses. Over the last 24 years, changes from fallow land to grassland have led to an increase of SOC sequestration by 3.23-ton ha^{-1} year^{-1}. Parallel to this, only a small amount of SOC sequestration was observed from the conversion of cultivated land to plantation forest, which seems unusual. This might be due to lower soil bulk density and young forest stand (Padbhushan et al., 2022). The small change in SOC stock when converting cultivated land into plantation forest can be attributed to several factors like the initial soil condition, management practice, vegetation type, soil depth, and climate and environmental factors (Yuan et al., 2021).

It is important to note that these factors are not exhaustive and that site-specific conditions and management practices can play a significant role in determining the impact of converting cultivated land into plantation forest on SOC stock. Long-term monitoring and careful assessment are necessary to accurately evaluate SOC changes in response to land use conversions.

Based on the analysis of this study, the grassland and plantation forests have acted as a net sink for atmospheric carbon over the past 24 years in the Anjeni watershed. Over the past 24 years, plantation forest coverage has increased from 3.32 ha in 1997 to 15.56 ha (Table 4), which leads to a net gain in carbon. A relatively small change in SOC stocks can have a significant impact on the net flux of GHG between the soil and the biosphere (Singh & Benbi, 2018).

Table 13 Comparison of the historical soil organic carbon SOC stock (1997) with the current (2021) stock

Land cover type changes	Historic (1997) SOC stock (Mg ha^{-1})	Current (2021) SOC stock (Mg ha^{-1})	SOC stock change	SOC Seq. (Mg ha^{-1} year^{-1})
Grassland to plantation forest	71.7	98.21	26.51	1.11
Cultivated land to grassland	49.56	121.59	72.03	3.00
Cultivated land to plantation forest	69.31	78.18	8.87	0.37
Cultivated land to fallow land	64.11	91.05	26.94	1.12
Fallow land to cultivated land	56.45	86.84	30.40	1.27
Plantation to grassland	34.18	78.23	44.05	1.84
Grassland to plantation forest	61.79	103.47	41.67	1.74
Fallow land to grassland	33.52	111.12	77.61	3.23
Grassland to grassland	37.58	51.60	14.01	0.58
Cultivated land to cultivated land	43.84	61.24	17.40	0.72
Plantation forest to plantation forest	68.97	101.10	32.13	1.34

Conclusions

The positive implication of soil carbon stock potential and SOC sequestration is not only to improve soil water holding capacity, soil health, fertility, and overall productivity of soils, but also to combat climate change via mitigation. Implementing climate-smart soil water conservation practices that enhance SOC stock potential is a sustainable method of managing farmlands. However, such practices as crop rotation, zero tillage, fallow management, crop cover, and crop selection can be time-consuming, expensive, and laborious for smallholder farms. Smallholder farms in this area require incentive to implement several activities that increase SOC sequestration. Implicating such practices for small farmland can be risky to commit to without an immediate financial benefit as smallholder farmers want to get benefits seasonally. However, in the long run, this can establish a more resilient soil that lets farmers produce more and combat the growing effects of climate change.

Thus, this study illustrates the impact of LULC change and slope gradient on the soil properties of the Anjeni watershed and compares the historical carbon stock with the current and potential for the soil organic carbon (SOC) stock of the watershed. The LULC changes and slope gradient had a major impact on the soil's physical and chemical properties and the SOC stock of the watershed. The response of most soil parameters to the difference in LULC and slope gradient was negative. Most soil parameters showed significant changes with land use and slope gradient. Furthermore, the differences in slope gradient and LULC not only affect the soil's physical and chemical properties but also affected the spatial distribution and relative SOC stocks. This study only focused on the smaller area of the Anjeni watershed which only covers 108.3 ha of land. Further research is recommended that covers a larger area to extensively examine the combined impact of LULC and slope gradient on the SOC stock and soil properties.

The findings on the interaction of LULC change and slope gradient have further implications for the future C stock potential of the soil and SOC sequestration under changing climate, and decline in soil productivity problem in Ethiopia. The soil and water conservation effort in the watershed has significant benefit and bearing for improving the soil properties of the area as well as the livelihood of the local communities. Thus, increasing the SOC stock could reduce the accumulation of atmospheric carbon dioxide while also improving the productivity of the land.

Acknowledgements The first author thanks Haramaya University Africa Center of Excellence for Climate Smart Agriculture and Biodiversity Conservation (ACE Climate SABC), Debre Berhan University, CGIAR's research program on Climate Change, Agriculture and Food Security (CCAFS), and the Global Research Alliance on Agricultural Greenhouse Gases (GRA) through their CLIFF-GRADS program for the financial support. The authors also thank Dr. Woubet Alemu, for providing us with the necessary data, Dr. Fikrey Tesfay for the continuous supervision and support during data collection and laboratory analysis, Debre Berhan Agricultural Research Center, and Anjeni area farmers for the laboratory work and support during data collection respectively.

Author contribution Bethel Geremew: data curation, conceptualization, methodology, writing — original draft, formal analysis and investigation visualization. Tsegaye Tadesse: data curation, writing — review and editing and supervision. Bobe Bedadi: data curation, writing — review and editing, project administration, resources and supervision. Hero T. Gollany: writing — review and editing, resources and supervision. Kindie Tesfaye: data curation, writing — review and editing and supervision. Abebe Aschalew: writing — reviewing and editing and supervision.

Funding This laboratory work is supported by CGIAR's research program on Climate Change, Agriculture and Food Security (CCAFS), Africa Centre of Excellence for Climate-Smart Agriculture and Biodiversity Conservation, Haramaya University, Haramaya, Ethiopia and the Global Research Alliance on Agricultural Greenhouse Gases (GRA) through their CLIFF-GRADS program.

Availability of data and materials The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval The authors declare that the manuscript is original and has not been published in any journal.

Consent to participate The authors have participated in the preparation and submission of this paper for a publication in *Environmental Monitoring and Assessment*.

Consent for publication The authors declare their consent to publication of the manuscript in "*Environmental Monitoring and Assessment*" journal.

Competing interests The authors declare no competing interests.

References

Abera, Y., & Belachew, T. (2011). Effects of landuse on soil organic carbon and nitrogen in soils of bale, Southeastern Ethiopia. *Tropical and Subtropical Agroecosystems, 14*, 229–235.

Agidew, A. meta A., & Singh, K. N. (2017). The implications of land use and land cover changes for rural household food insecurity in the Northeastern highlands of Ethiopia: The case of the Teleyayen sub-watershed. *Agric. Food Secur., 6*, 1–15. https://doi.org/10.1186/s40066-017-0134-4

Alemu, B. (2015). The Effect of Land Use Land Cover Change on Land Degradation in the Highlands of Ethiopia. ISSN 2224–3216 (Paper) ISSN 2225–0948 (Online). *Journal of Environment and Earth Science, 5*(1), 1–13. www.iiste.org

Alemu, W. G., Amare, T., Yitaferu, B., Selassie, Y. G., Wolfgramm, B., & Hurni, H. (2013). Impacts of Soil and Water Conservation on Land Suitability to Crops: The Case of Anjeni Watershed, Northwest Ethiopia. *Journal of Agricultural Science, 5*, 95–109. https://doi.org/10.5539/jas.v5n2p95

Amanuel, W., Yimer, F., & Karltun, E. (2018). Soil organic carbon variation in relation to land use changes: The case of Birr watershed, upper Blue Nile River Basin, Ethiopia. *Journal of Ecology and Environmen, 42*. https://doi.org/10.1186/s41610-018-0076-1

Amare, T. (2018). Impact of Sustainable Land Management Practices on Soil Organic Carbon Content of Three Watersheds in Ethiopia. *Ethiopian Journal of Natural Resources, 17*, 61–83.

Amare, T., Hergarten, C., Hurni, H., Wolfgramm, B., Yitaferu, B., & Selassie, Y. G. (2013). Prediction of Soil Organic Carbon for Ethiopian Highlands Using Soil Spectroscopy. *ISRN Soil Science, 2013*, 1–11. https://doi.org/10.1155/2013/720589

Anokye, J., Logah, V., & Opoku, A. (2021). Soil carbon stock and emission: estimates from three land-use systems in Ghana. *Ecological Processes, 10*. https://doi.org/10.1186/s13717-020-00279-w

Assefa and Bork. (2014). Deforestation and Forest Management in Southern Ethiopia: Investigations in the Chencha and Arbaminch Areas 284–299. https://doi.org/10.1007/s00267-013-0182-x

Assefa, F., Elias, E., Soromessa, T., & Ayele, G. T. (2020). Effect of Changes in Land-Use Management Practices on Soil Physicochemical Properties in Kabe Watershed, Ethiopia. *Air, Soil and Water Research, 13*. https://doi.org/10.1177/1178622120939587

Betemariyam, M., Negash, M., & Worku, A. (2020). Comparative Analysis of Carbon Stocks in Home Garden and Adjacent Coffee Based Agroforestry Systems in Ethiopia. *Small-Scale, 19*, 319–334. https://doi.org/10.1007/s11842-020-09439-4

Bizuhoraho, T., Kayiranga, A., Manirakiza, N., & Mourad, K. A. (2018). The Effect of Land Use Systems on Soil Properties; A case study from Rwanda. *Sustainable Agriculture Research, 7*, 30. https://doi.org/10.5539/sar.v7n2p30

Blake, G. R., & Hartge, K. H. (2018). Bulk density. *Methods of Soil Analysis: Part 1 Physical and Mineralogical Methods, 9*, 363–375. https://doi.org/10.2136/sssabookser5.1.2ed.c13

Blake, G. R. R., & Hartge, K. H. H. (1986). Bulk Density, in: Klute, A. (Ed.), Methods of Soil Analysis, Part 1. Physical and Mineralogical Methods, SSSA Book Series SV - 5.1. ASA, SSSA, Madison, USA, pp. 363–375. https://doi.org/10.2136/sssabookser5.1.2ed.c13

Boix-Fayos, C., de Vente, J., Albaladejo, J., & Martínez-Mena, M. (2009). Soil carbon erosion and stock as affected by land use changes at the catchment scale in Mediterranean ecosystems. *Agriculture, Ecosystems & Environment, 133*, 75–85. https://doi.org/10.1016/j.agee.2009.05.013

Bouyoucos, G. J. (1962). Hydrometer Method Improved for Making Particle Size Analyses of Soils1. *Agronomy Journal, 54*, 464–465. https://doi.org/10.2134/agronj1962.00021962005400050028x

Brandt, M., Rasmussen, K., Peñuelas, J., Tian, F., Schurgers, G., Verger, A., Mertz, O., Palmer, J. R. B., & Fensholt, R. (2017). Human population growth offsets climate-driven increase in woody vegetation in sub-Saharan Africa. *Nature Ecology & Evolution, 1*, 4–9. https://doi.org/10.1038/s41559-017-0081

Bremner, J. M., & Mulvaney, C. S. (1982). Nitrogen-Total, in: Page, A.L., Miller, R.H., Keeney, D.R. (Eds.), Methods of Soil Analysis, Part 2. Chemical and Microbiological Properties. ASA, SSSA, Madison, Wisconsin USA, pp. 595–624. https://doi.org/10.2136/sssabookser5.3.c37

Chapman, H. D. (1965). Cation Exchange Capacity. In: Page, A.L., Miller, R.H., Keeney, D.R. (Eds.), Methods of Soil Analysis. Part 2.: Chemical and Microbiological Properties. ASA, SSSA, Madison, USA, pp. 891–901. https://doi.org/10.2134/agronmonogr9.2.c6

Chemistry, S. (2014). Introduction to Soil Chemistry. *Introduction to Soil Chemistry*. https://doi.org/10.1002/9781118773383

Fite, T. (2017). Influence of Different Land Use Types and Soil Depths on Selected Soil Properties Related to Soil Fertility in Warandhab Area, Horo Guduru Wallaga Zone, Oromiya, Ethiopia. *International Journal of Environmental Sciences & Natural Resources, 4*. https://doi.org/10.19080/ijesnr.2017.04.555634

Getahun, Y. S., & Haj, V. L. (2015). Assessing the Impacts of Land Use-Cover Change on Hydrology of Melka Kuntrie Subbasin in Ethiopia, Using a Conceptual Hydrological Model. *Journal of Waste Water and Treatment Analysis, 6*. https://doi.org/10.4172/2157-7587.1000210

Gete, Z. (2000). *Landscape Dynamics and Soil Erosion Process Modelling in the North Western Ethiopia highlands*. Univesity of Berne, Switzerland.

Girmay, G., Singh, B. R., Mitiku, H., Borresen, T., & Lal, R. (2008). Carbon stocks in Ethiopian soils in relation to land use and soil management. *Land Degradation & Development, 19*, 351–367. https://doi.org/10.1002/ldr.844

Hartemink, A., McSweeney, K. (Eds.), & Soil Carbon. (2014). Progress in soil science. Springer, Cham. https://doi.org/10.1007/978-3-319-04084-4_48

Hassan, Z., Shabbir, R., Ahmad, S. S., Malik, A. H., Aziz, N., Butt, A., & Erum, S. (2016). Dynamics of land use and land cover change (LULCC) using geospatial techniques: a case study of Islamabad Pakistan. Springerplus 5. https://doi.org/10.1186/s40064-016-2414-z

Henry, M., Valentini, R., & Bernoux, M. (2009). Soil carbon stocks in ecoregions of Africa. *Biogeosciences Discuss., 6*, 797–823. https://doi.org/10.5194/bgd-6-797-2009

Hu, Y., Zhen, L., & Zhuang, D. (2019). Assessment of Land-Use and Land- Cover Change in Guangxi, China. *Scientific Reports*, 1–13. https://doi.org/10.1038/s41598-019-38487-w

Ibrahim, T., Tesfay, F., & Geremew, B. (2021). Spatio-Temporal Dynamic of Land Use and Land Cover in Andit Tid Watershed, Wet Frost/Afro-Alpine Highland of Ethiopia. *Edelweiss Applied Science and Technology, 5*, 33–38. https://doi.org/10.33805/2576-8484.192

IPCC. (2003). Intergovernmental Panel on Climate Change Special Report; Land Use, Land-Use Change and Forestry. Institute for Global Environmental Strategies (IGES) for the IPCC ©, Kanagawa Japan.

Jacob, M., Romeyns, L., Frankl, A., Asfaha, T., Beeckman, H., & Nyssen, J. (2016). Land use and cover dynamics since 1964 in the afro-alpine vegetation belt: Lib Amba mountain in north Ethiopia 653, 641–653.

Jacobson, A., Dhanota, J., Godfrey, J., Jacobson, H., Rossman, Z., Stanish, A., Walker, H., & Riggio, J. (2015). A novel approach to mapping land conversion using Google Earth with an application to East Africa. *Environmental Modelling and Software, 72*, 1–9. https://doi.org/10.1016/j.envsoft.2015.06.011

Jakšić, S., Ninkov, J., Milić, S., Vasin, J., Živanov, M., Jakšić, D., & Komlen, V. (2021). Influence of slope gradient and aspect on soil organic carbon content in the region of Niš, Serbia. *Sustainability, 13*. https://doi.org/10.3390/su13158332

Jin, Z., Charlock, T., & Rutledge, K. (2006). A parameterization of spectral and broadband ocean surface albedo. In: 12th Conference on Cloud Physics, and 12th Conference on Atmospheric Radiation. pp. 6493–6499. https://doi.org/10.1029/96JC00629.K.

Jobbagy, E. G., & Jackson, R. B. (2000). The Vertical Distribution of Soil Organic Carbon and Its Relation to Climate and Vegetation. *Ecological Applications, 10*, 423. https://doi.org/10.2307/2641104

Kakaire, J., Makokha, G. L., Mwanjalolo, M., Mensah, A. K., & Menya, E. (2016). Effects of Mulching on Soil Hydro-Physical Properties in Kibaale Sub-catchment, South Central Uganda. *Applied Ecology and Environmental Sciences, 3*, 127–135. https://doi.org/10.12691/aees-3-5-1

Kejela, K. (1995).The soils of the Anjeni Area – Gojam Research Unit, EthiopiaResearch Report 27. Soil Conservation Research Project, Centre for Development and Environment, University of Berne.

Kelliher, F. M., Ross, D. J., Law, B. E., Baldocchi, D. D., & Rodda, N. J. (2004). Limitations to carbon mineralization in litter and mineral soil of young and old ponderosa pine forests. *Forest Ecology and Management, 191*, 201–213. https://doi.org/10.1016/j.foreco.2003.12.005

Lal, R., Negassa, W., & Lorenz, K. (2015). Carbon sequestration in soil. *Current Opinion in Environment Sustainability, 15*, 79–86. https://doi.org/10.1016/j.cosust.2015.09.002

Lambin, E. F., Turner, B. L., Geist, H. J., Agbola, S. B., Angelsen, A., Bruce, J. W., Coomes, O. T., Dirzo, R., Fischer, G., Folke, C., George, P. S., Homewood, K., Imbernon, J., Leemans, R., Li, X., Moran, E. F., Mortimore, M., Ramakrishnan, P. S., Richards, J. F., … Xu, J. (2001). The causes of land-use and land-cover change: Moving beyond the myths. *Global Environmental Change, 11*, 261–269. https://doi.org/10.1016/S0959-3780(01)00007-3

Landon, J. R. (2013). Booker Tropical Soil Manual. *Routledge*. https://doi.org/10.4324/9781315846842

Liu, Z., Shao, M., & Wang, Y. (2011). Effect of environmental factors on regional soil organic carbon stocks across the Loess Plateau region, China. *Agriculture, Ecosystems & Environment*, *142*, 184–194. https://doi.org/10.1016/j.agee.2011.05.002

Medinets, S., Skiba, U., Rennenberg, H., & Butterbach-Bahl, K. (2015). A review of soil NO transformation: Associated processes and possible physiological significance on organisms. *Soil Biology & Biochemistry, 80*, 92–117. https://doi.org/10.1016/j.soilbio.2014.09.025

Mekuria, W., Getnet, K., Noble, A., Hoanh, C. T., McCartney, M., & Langan, S. (2013). Economic valuation of organic and clay-based soil amendments in small-scale agriculture in Lao PDR.*Field Crops Research, 149*, 379–389. https://doi.org/10.1016/j.fcr.2013.05.026

Meshesha, D. T., Tsunekawa, A., Tsubo, M., Ali, S. A., & Haregeweyn, N. (2014). Land-use change and its socio-environmental impact in Eastern Ethiopia's highland. *Regional Environmental Change, 14*, 757–768. https://doi.org/10.1007/s10113-013-0535-2

Meshesha, D. T., Tsunekawa, A., & Tsubo, M. (2012). Continuing land degradation: cause–effect in Ethiopia's Central Rift Valley. *143*, 130–143.

Muriithi, F. K. (2016). Author' s Accepted Manuscript commercial horticulture *Applications: Remote Sensing Applications: Society and Environment*. https://doi.org/10.1016/j.rsase.2016.01.002

Nelson, D. W., & Sommers, L. E. (1982). Total Carbon, Organic Carbon, and Organic Matter. In: Page, A.L., Miller, R.H., Keeney, D.R. (Eds.), Methods of Soil Analysis, Part 2. Chemical and Microbiological Propertie. ASA, SSSA, Madison, USA, pp. 593–579. https://doi.org/10.2134/agronmonogr9.2.2ed.c29

Nesic, L., Vasin, J., Belic, M., Ciric, V., Gligorijevic, J., Milunovic, K., & Sekulic, P. (2015). The colloid fraction and cation-exchange capacity in the soils of Vojvodina, Serbia. *Journal Ratarstvo i Povrtarstvo, 52*, 18–23. https://doi.org/10.5937/ratpov52-7720

Obodai, J., Amaning, K., Nii, S., & Lumor, M. (2019). Remote Sensing Applications : Society and Environment Land use / land cover dynamics using landsat data in a gold mining basin-the. *Remote Sensing Applications: Society and Environment, 13*, 247–256. https://doi.org/10.1016/j.rsase.2018.10.007

Olsen, S. R., & Dean, L. A. (1965). Phosphorus. In: Page, A.L., Miller, R.H., Keeney, D.R. (Eds.), Methods of Soil Analysis, Part 2. Chemical and Microbiological Propertie. ASA, SSSA, Madison, WI, pp. 1035–1049. https://doi.org/10.2134/agronmonogr9.2.c32

Ontl, T. A., Janowiak, M. K., Swanston, C. W., Daley, J., Handler, S., Cornett, M., Hagenbuch, S., Handrick, C., McCarthy, L., & Patch, N. (2020). Forest management for carbon sequestration and climate adaptation. *Journal of Forestry, 118*, 86–101. https://doi.org/10.1093/jofore/fvz062

Padbhushan, R., Kumar, U., Sharma, S., Rana, D. S., Kumar, R., Kohli, A., Kumari, P., Parmar, B., Kaviraj, M., Sinha, A. K., Annapurna, K., & Gupta, V. V. S. R. (2022). Impact of Land-Use Changes on Soil Properties and Carbon Pools in India: A Meta-analysis. *Frontiers in Environmental Science, 9*, 1–15. https://doi.org/10.3389/fenvs.2021.794866

Pandi, D., Kothandaraman, S., Kasiviswanathan, K. S., & Kuppusamy, M. (2022). A catchment scale assessment of water balance components: A case study of Chittar catchment in South India. *Environmental Science and Pollution Research, 29*, 72384–72396. https://doi.org/10.1007/s11356-022-19032-1

Poeplau, C., Kätterer, T., Bolinder, M. A., Börjesson, G., Berti, A., & Lugato, E. (2015). Low stabilization of aboveground crop residue carbon in sandy soils of Swedish long-term experiments. *Geoderma, 237*, 246–255. https://doi.org/10.1016/j.geoderma.2014.09.010

Ritchie, M. E. (2014). Plant compensation to grazing and soil carbon dynamics in a tropical grassland. *PeerJ, 2014*. https://doi.org/10.7717/peerj.233

Ross, Ribeiro, E., Batjes, N. H., Leenaars, J. G. B., van Oostrum, A., de Jesus, J. M., et al (2015). Towards the standardization and harmonization of world soil data. Proced. Man. ISRIC World Soil Inf. Serv. (WoSIS version 2.0). 1–111.

Selassie, Y. G., Anemut, F., & Addisu, S. (2015). The effects of land use types, management practices and slope classes on selected soil physico-chemical properties in Zikre watershed, North-Western Ethiopia. *Environmental Systems Research, 4*, 0–6. https://doi.org/10.1186/s40068-015-0027-0

Sheleme, B. (2017). Topographic positions and land use impacted soil properties along Humbo Larena-Ofa Sere toposequence, Southern Ethiopia. *Journal of Soil Science and Environmental Management, 8*, 135–147. https://doi.org/10.5897/jssem2017.0643

Singh, P., & Benbi, D. K. (2018). Soil organic carbon pool changes in relation to slope position and land-use in Indian lower Himalayas. *Catena, 166*, 171–180. https://doi.org/10.1016/j.catena.2018.04.006

Solomon, N., Hishe, H., Annang, T., Pabi, O., Asante, I. K., & Birhane, E. (2018). Forest Cover Change, Key Drivers and Community Perception in Wujig Mahgo Waren Forest of Northern Ethiopia. *Land, 7*, 32. https://doi.org/10.3390/land7010032

Song, X. P., Hansen, M. C., Stehman, S. V., Potapov, P. V., Tyukavina, A., Vermote, E. F., & Townshend, J. R. (2018). Global land change from 1982 to 2016. *Nature, 560*, 639–643. https://doi.org/10.1038/s41586-018-0411-9

Stavi, I., Ungar, E. D., Lavee, H., & Sarah, P. (2008). Grazing-induced spatial variability of soil bulk density and content of moisture, organic carbon and calcium carbonate in a semi-arid rangeland. *Catena, 75*, 288–296. https://doi.org/10.1016/j.catena.2008.07.007

Tadesse, T., Haque, T., & Aduayi, E. A. (1991) Soil, plant, water, fertilizer, animal manure and compost analysis manual. ILCA PSD Working Document, B13, International Livestock Center for Africa, Addis Ababa, Ethiopia.

Thomas, G. W. (1982). Exchangeable Cations. In: Page, A.L., Miller, R.H., Keeney, D.R. (Eds.), Methods of Soil Analysis. Part 2. Chemical and Microbiological Properties. ASA, SSSA, Madison, USA, pp. 159–165. https://doi.org/10.1007/978-3-540-31211-6_22

Thomas, G. W. (1996). Soil pH and Soil Acidity. In: Methods Soil Anal Part 3—Chemical Methodss-SSSA Book Series No. 5. Soil Science Society of America and American Society of Agronomy, Madison, WI, pp. 475–490. https://doi.org/10.2136/sssabookser5.3.c16

Trivedi, P., Singh, B. P., & Singh, B. K. (2018). *Soil carbon: Introduction, importance, status, threat, and mitigation*. Modulators, Mechanisms and Modeling. Elsevier Inc. https://doi.org/10.1016/B978-0-12-812766-7.00001-9

Warra, H. H., Ahmed, M. A., & Nicolau, M. D. (2015). Impact of land cover changes and topography on soil quality in the Kasso catchment, Bale Mountains of southeastern Ethiopia. *Singapore Journal of Tropical Geography, 36*, 357–375. https://doi.org/10.1111/sjtg.12124

White, P. J., & Brown, P. H. (2010). Plant nutrition for sustainable development and global health. *Annals of Botany, 105*, 1073–1080. https://doi.org/10.1093/aob/mcq085

Wiesmeier, M., Urbanski, L., Hobley, E., Lang, B., von Lützow, M., Marin-Spiotta, E., van Wesemael, B., Rabot, E., Ließ, M., Garcia-Franco, N., Wollschläger, U., Vogel, H. J., & Kögel-Knabner, I. (2019). Soil organic carbon storage as a key function of soils - A review of drivers and indicators at various scales. *Geoderma, 333*, 149–162. https://doi.org/10.1016/j.geoderma.2018.07.026

Wubie, M. A., & Assen, M. (2020). Effects of land cover changes and slope gradient on soil quality in the Gumara watershed, Lake Tana basin of North-West Ethiopia. *Modeling Earth Systems and Environment, 6*, 85–97. https://doi.org/10.1007/s40808-019-00660-5

Wubie, M. A., Assen, M., & Nicolau, M. D. (2016). Patterns, causes and consequences of land use/cover dynamics in the Gumara watershed of lake Tana basin, Northwestern Ethiopia. *Environmental Systems Research, 5*, 1–12. https://doi.org/10.1186/s40068-016-0058-1

Xiong, X., Grunwald, S., Myers, D. B., Ross, C. W., Harris, W. G., & Comerford, N. B. (2014). Science of the Total Environment Interaction effects of climate and land use / land cover change on soil organic carbon sequestration. *Science of the Total Environment, 493*, 974–982. https://doi.org/10.1016/j.scitotenv.2014.06.088

Yared, M., Kibebew, K., Bobe, B., & Muktar, M. (2018). Soil organic carbon stock under different land use types in Kersa Sub Watershed, Eastern Ethiopia. *African Journal of Agricultural Research, 13*, 1248–1256. https://doi.org/10.5897/ajar2018.13190

Yuan, Z., Jin, X., Guan, Q., & Meshack, A. O. (2021). Converting cropland to plantation decreases soil organic carbon stock and liable fractions in the fertile alluvial plain of eastern China. *Geoderma Regional, 24*, e00356. https://doi.org/10.1016/j.geodrs.2021.e00356

Yuan, Z. Q., Fang, C., Zhang, R., Li, F. M., Javaid, M. M., & Janssens, I. A. (2019). Topographic influences on soil properties and aboveground biomass in lucerne-rich vegetation in a semi-arid environment. *Geoderma, 344*, 137–143. https://doi.org/10.1016/j.geoderma.2019.03.003

Zeleke, G., & Hurni, H. (2001). Implications of land use and land cover dynamics for mountain resource degradation in the Northwestern Ethiopian highlands. *Mountain Research and Development, 21*, 184–191. https://doi.org/10.1659/0276-4741(2001)021[0184:IOLUAL]2.0.CO;2

Zhao, J., Yang, Y., Zhao, Q., & Zhao, Z. (2017). Effects of ecological restoration projects on changes in land cover: A case study on the Loess Plateau in China. *Science and Reports, 7*, 1–12. https://doi.org/10.1038/srep44496

Zhu, M., Feng, Q., Qin, Y., Cao, J., Zhang, M., Liu, W., Deo, R. C., Zhang, C., Li, R., & Li, B. (2019). The role of topography in shaping the spatial patterns of soil organic carbon. *Catena, 176*, 296–305. https://doi.org/10.1016/j.catena.2019.01.029