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Research article

Impact of land use type and altitudinal gradient on topsoil organic carbon and nitrogen stocks in the semi-arid watershed of northern Ethiopia

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ABSTRACT

Understanding the role of soils in the soil organic carbon (SOC) and total nitrogen (TN) cycle is essential, assumed that these parameters are among the key soil quality indicators in a given landscape. Nothing but their status is in a state of continual flux due to land-use, soil management practices, and nature of topographic features. Thus, this study has evaluated the effect of land-use types and altitudinal gradient on SOC and TN concentrations and stocks at a watershed scale in northern Ethiopia. A total of 450 topsoil samples (0–30 cm depth) were collected from four different land-use types (Fig.3) across three elevational categories (Fig.1(b)), and their SOC and TN distributions were studied using descriptive statistics and geostatistical methods. Results revealed significant ($p < 0.05$) differences in SOC and TN concentrations and stocks by land-use type, elevation, and their interactions. The highest SOC stock was recorded at the lower elevation in GL (7.24 Mg C ha^{-1}), followed by PF (4.65 Mg C ha^{-1}) in the middle and GL (4.61 Mg C ha^{-1}) in the upper elevations, respectively. On the other hand, the lowest SOC stock was observed in the BL areas of the upper (2.34 Mg C ha^{-1}) and middle (2.75 Mg C ha^{-1}) elevations. Spatially, the mean SOC stocks of the different land-uses were in the following order: GL > PF > CL > BL in upper elevation, PF > GL > CL > BL in middle elevation, and GL˃CL in lower elevation, respectively. The estimated total SOC and TN stocks of the study watershed were about 46,868.66 ± 7747.38 Mg C and 7,008.02 ± 441.25 Mg N, respectively. The notable difference is attributable to lack of vegetation cover, unsustainable land-use system, and land degradation via water erosion. Hence, these physical landscape disturbances result in disruption of SOC and TN's storage and stability. The SOC and TN stocks have shown a significant ($p < 0.05$) negative correlation with soil bulk density in the study watershed. The study concludes that variations in the land-use along topographic gradients drive the soils' SOC and TN storage. Therefore, land suitability planning, soil and water conservation measures, and reforestation practices are needed and practical worth increasing SOC and TN storage in the watershed.

1. Introduction

The soil is a vital part of the terrestrial ecosystem that contributes to delivering primary ecosystem services (Pereira et al., 2018) and receives increasing attention from the international policy arena (Bouma, 2020). Many researchers have focused on the soil carbon and nitrogen characteristics of different land use and landscape positions worldwide (Xue et al., 2013). Because soil properties exhibit high spatial variability across landscapes, various factors (i.e., climate, parent material, biology, topography, and time) also influence soil development (Guo et al., 2011). To this effect, periodic evaluation of site-specific soil conditions is essential to understand factors that inflict severe soil fertility limitations (Takele et al., 2014). In particular, understanding the spatial distribution of soil organic carbon (SOC) and total nitrogen (TN) at different spatial scales is crucially essential for monitoring soil quality indicators (Hu et al., 2014; Xu et al., 2013). SOC plays a vital role in mitigating global climate change, and alleviates land degradation and enhances crop production and food security (Franzluebbers and Stuedemann, 2009; Lal, 2004; Pan et al., 2004). Soil TN also plays an important role in generating and enhancing soil productivity in terrestrial ecosystems (Pan et al., 2004; Zhang et al., 2016). As dynamic components of terrestrial ecosystems, SOC and TN are characterized by

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high spatial heterogeneity with complex physical, chemical, and biological processes (Lal, 2004).

The soil carbon is a storehouse of several plant nutrients and a vital soil function element and ultimate soil health (Charlie and Mary, 2017; Spaeth and Kenneth, 2020). Essential plant macronutrient (N, P, K, and S), micronutrients (Fe, Cu, and Zn), and other soil nutrient cycles are also closely interconnected with organic carbon and its disposition in the environment (FAO, 2017; Gaskell and Smith, 2007; Spaeth and Kenneth, 2020). SOC plays a crucial role in multiple soil processes, including regulating soil aggregate stability, soil biological activity, soil nutrient cycling and storage, soil water retention capacity, soil erosion control, and providing the food source for edaphic organisms (Amundson et al., 2015; Cherubin et al., 2017; Schjønning et al., 2018). Beyond these essential soil functions, the soilspehere is a critical carbon sink, thus playing a crucial role in mitigating carbon dioxide emissions and global warming (Arias Govín et al., 2020; Hati et al., 2020; Scharlemann et al., 2014). The soil carbon and nitrogen cycle are strongly linked to each other and are fundamental in all soil processes; hence a change in one directly influences the other (Bünemann et al., 2018; Chen et al., 2016). Besides, both SOC and TN are among the basic soil health indicators due to their importance in environmental and agronomic sustainability (FAO, 2019; Somarathna et al., 2016; Yeatman and Yeatman, 2020).

It is observed that more carbon is leaving the soil reservoir (62 Pg) than entering the soil (59–60 Pg) (Battin et al., 2009; Weil and Brady, 2017). Following the Kyoto Protocol, national inventories and carbon stock estimation are needed to identify and stabilize the atmospheric concentration of greenhouse gas concentration (Elbasiouny et al., 2014). Worldwide, soils are estimated to hold 4.5 times greater carbon than the amount in terrestrial biomass (~560 Gt) and 3.3 times greater carbon than the atmospheric stock (~760 Gt) (Fan et al., 2016; Stockmann et al., 2015). Generally, soil carbon is accounting about 62% of the global soil carbon stock (~2500 Gt) (Wang et al., 2014; Xiao, 2015), and current estimates suggest that soils to 1 m depth hold about 74% of the total terrestrial carbon stocks (Batjes, 2016; Scharlemann et al., 2014). Moreover, SOC and TN stocks' stability represents the net balance between inputs and outputs (Tian et al., 2015; Xue and An, 2018). However, these estimates are still highly uncertain because an increase or decrease by a few percent transforms the amount into the relevant magnitude of discrepancy from local to the global scale. The soil cover is currently undergoing rapid evolution due to climate and humans changes (Ciampalini et al., 2012). Accordingly, a small change in these processes will significantly influence soil nutrient conditions, climate variation, land efficiency, and food security (Abegaz et al., 2020). Hence, quantifying the spatial heterogeneity and identifying the major driving forces controlling the SOC and TN dynamics remains a significant research challenge.

In the terrestrial pool, SOC is possibly a more significant sink for atmospheric CO_2 (Abdullahi et al., 2018), and it gives indications on fertility and productivity of soil (Sahoo et al., 2019). Hence, SOC is an essential element for plants and plays a significant role in the global carbon budget and terrestrial ecosystem functions as it affects soil properties and quality (Martin et al., 2010; Zhao et al., 2017). However, its depletion resulting from the complex interactions of natural and anthropogenic factors is mounting with time (Lal, 2009), causing the decline in soil fertility and loss of productivity, which is finally affecting the millions of farm households' livelihood. The necessary components of soil fertility (i.e., SOC and TN stocks) in a given landscape are being affected by land-use change and soil management practices, along with some other environmental factors which are contributing to the spatial variability (Chen et al., 2016; de Oliveira et al., 2015; Kassa et al., 2017). Therefore, land-use types and topography are vital factors determining SOC and TN stock at the global to landscape-level since they influence the input-output balance (Liu et al., 2017; Poeplau and Don, 2013). Remarkably, the SOC in topsoil is supposed to be more prone to land-use change and other perturbations than subsoil (Veldkamp et al., 2003). Numerous studies have also reported a considerable fluctuation in the path of SOC and TN dynamics local to global scale along with land-use changes (Ren et al., 2020; Tesfaye et al., 2018; Twongyirwe et al., 2013) and topography (Chen et al., 2016; Dinku et al., 2014). Therefore, determining land-use change effects and topographic controls of SOC and TN is critical to quantify the regional and global SOC and TN storage (Ajami et al., 2016; Falahatkar et al., 2016).

The world's arable land is shrinking due to land degradation and desertification, while our efforts to ensure commercial land availability make the current scenario even worse (Farooqi et al., 2021). Land use and management influence SOC and other soil properties (Smith et al., 2016). Land-use change affects the global carbon cycle, which drives SOC stock changes (Poeplau et al., 2011; Wiesmeier et al., 2012). According to Houghton (2003), global land-use change since 1850 has released about 156 Pg of soil carbon into the atmosphere. Other studies have also confirmed that land management practices at different scales, from natural ecosystems to managed ecosystems (e.g., forest to agriculture), impact soil quality (Saljnikov et al., 2013). For instance, the conversion of forestlands into croplands decreases SOC concentration and stock by 20–50% (Lal, 2005; Lemenih and Itanna, 2004) and pasturelands to croplands by 59% (FAO, 2007; Guo and Gifford, 2002; Murty et al., 2007). Plantation forests and grassland have significant SOC and TN stocks in the depth of 30 cm due to the stability in land use nature.

Likewise, several studies in the Ethiopian highlands reported higher SOC and TN stocks in forest lands than grazing lands and croplands (Abegaz et al., 2020; Guteta and Abegaz, 2017; Miheretu and Yimer, 2018). Other studies (Elias, 2017; Gebreselassie et al., 2015; van Beek et al., 2018) also revealed that escalating population growth is forcing clear natural forests and cultivating rugged terrains steep slopes of more than 30%. Elias (2017) has notably reported the depletion of soil nutrients, especially nitrogen (N), sulfur (S), and potassium (K), in the intensive cereal-livestock systems in the Ethiopian highlands. Since antiquity, the Tigrean highlands situation is particularly threatening due to the rugged terrain and unprecedented cereal-based agricultural intensification (Gelaw et al., 2014; van Beek et al., 2018). Generally, the sustained misuse of farmlands such as removal of vegetation cover, traditional and excessive tillage coupled with monocropping and complete removal of crop residues, extreme livestock pressure, use of animal manure as a source of energy for cooking, and cultivation in steep slope and marginal lands has resulted in the depletion of SOC stock typically to less than 2% (Elias, 2017; Girmay et al., 2008; Li et al., 2021; Nyssen et al., 2015; van Beek et al., 2018).

On the other hand, the altitudinal gradient affects SOM concentration by controlling temperature regimes, precipitation, solar radiation, relative humidity, and geologic deposition processes (Tsui et al., 2004). SOC's spatial variability is highly heterogeneous due to topography, landscape complex, and soil thickness (Doetterl et al., 2016; Hu et al., 2014; Lu et al., 2013; Patton et al., 2019; Xin et al., 2016). The current study indicates that SOC and TN accumulation in highland areas are due to diverse environmental conditions such as altitude, slope, and location (Arunrat et al., 2020). Xin et al. (2016) also determined that the altitude influences SOC's spatial pattern in the Chinese Loess Plateau. Other studies also confirmed the increase in SOC with the rise in altitude, which is associated with a reduction in temperature, limiting the degradation in SOC (Leifeld et al., 2005). Other researchers have also described the variables such as climate, soil texture, topography, hydrology, and other primary variables that influence soil carbon stocks' production and decomposition (Hiraishi et al., 2014). Tsozuéa et al. (2019) described the accumulation and stabilization of SOC ascribed to clay concentration, parent material, climate, and vegetation were controlled by the altitudinal gradients contributing to spatial variation in terms of soil physical, chemical, and biological quality.

Recent research findings have explained the role of elevation on SOC. For example, Wang et al. (2019) quantified the relative contribution of biotic and abiotic factors affecting the aboveground litter stock's spatial variation. They reported that the relative influence of abiotic factors (environmental and topographical factors) on the litterfall amount was

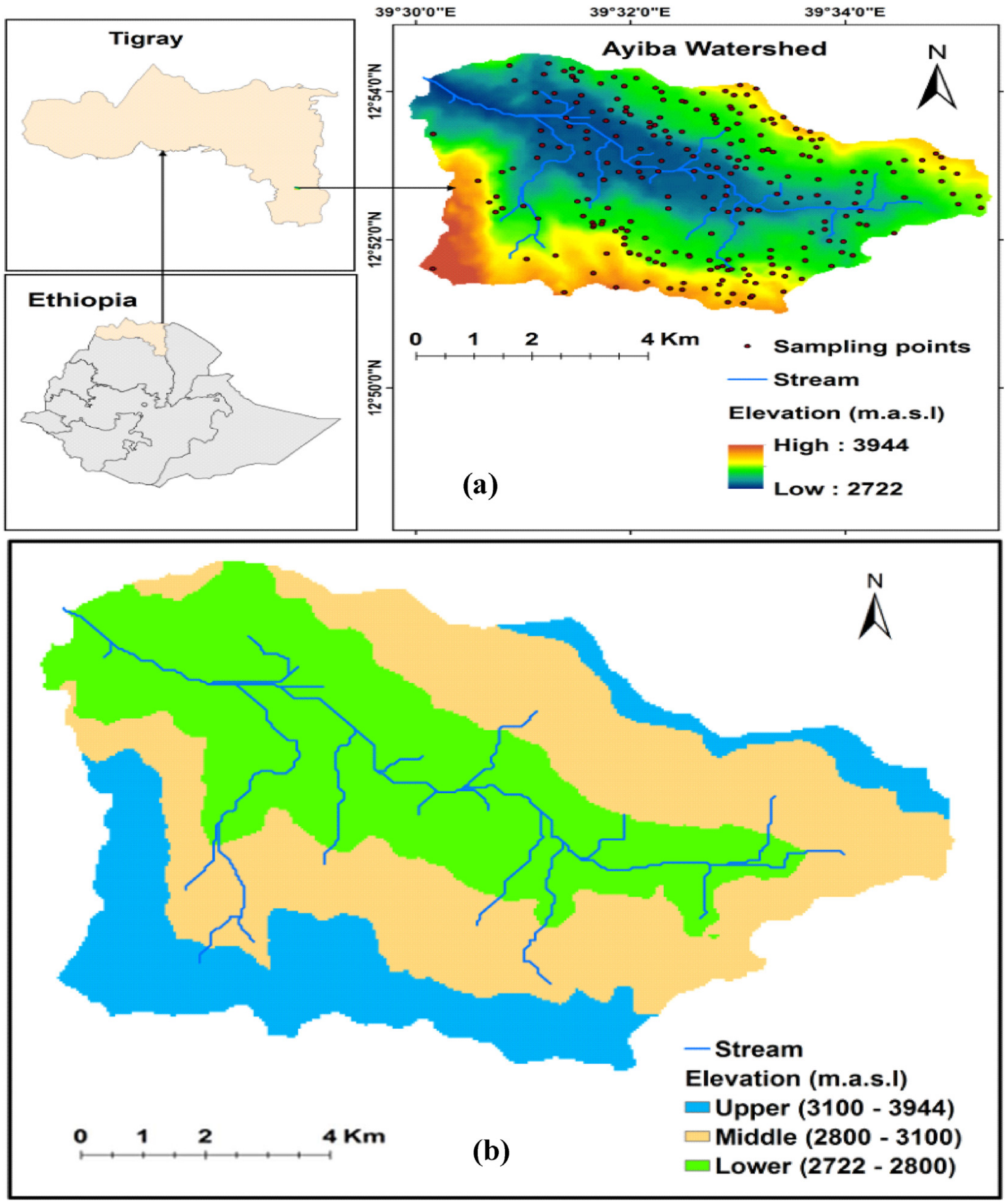


Figure 1. Map of the study watershed showing (a) location and distribution of soil sampling points and (b) classified elevational gradients (Seifu et al., 2020).

enormous (71.4%). Qiao et al. (2019) reported that carbon use efficiency could reduce quicker in the cold regions than in warm areas, as the rate of climate warming is faster at high than low latitudes. Besides, in north China's hilly and mountainous areas, topography was reported as an essential driving factor for SOC and TN distribution (Zhang et al., 2018). Zhang et al. (2008) also noted that the terrain has large effects on SOC estimates in rugged regions. Moreover, the lower landscape has higher SOC and other soil nutrients due to the impact of erosion. The slope is a vital soil erosion factor as soil erosion intensity increases as the slope increases (Seifu et al., 2020; Xin et al., 2016). As topography plays a crucial role in spatial soil erosion distribution, so, this is why the terrain morphology is relevant to soil erosion modeling (Ciampalini et al., 2012). In the long term, topography can alter soil properties that control soil biogeochemical processes (Suriyavirun et al., 2019).

Securing food and livelihood is inseparably linked to the exploitation of natural resources in Ethiopia (Baye, 2017; Nigussie et al., 2018), where more than 80% of the population is living in rural areas and depend on subsistence small scale agriculture (Beyene, 2015; CSA, 2015). The highland regions are the most productive parts of the country and comprise about 45% of the country's area (Teshome et al., 2013). However, this area is highly characterized by rugged topographic settings, prone to land degradation mainly by water erosion coupled with anthropogenic agents. In this regard, the study was proceeding forward with the general hypothesis that the continuous increase of the human population contributes to exploitative and inappropriate land use and management practices, resulting in increased forest cover removal. Consequently, lower topsoil carbon and nitrogen stocks are expected with lower woody biomass above ground and lower litter inputs. Given these all-aforementioned justifications, this study was set out to assess the effect of land-use types and landscape positions on SOC and TN stocks at a watershed scale. In Ethiopia and around the study region, few literature works have compared the effect of land-use type and topography on the spatial distribution of soil properties to the best of our knowledge. Besides, the reports on altitudinal stratified quantification of

Table 1. Watershed physical landscape characterization.

(a) Description of some physical landscape characteristics of the Ayiba watershed.

Altitude (m.a.s.l)	Land use types	Slope*		Erosion*		Major landform*	Major Soil type**
		% class	Description	Category	Degree		
Upper (3100–3944)	Bare land	30-60, >60	Steep to very steep	WS	Severe	High gradient mountain	Leptosols, Regosols, and Vertisols
	Cultivated land			WR	Moderate	Medium gradient hill	
	Grassland			WS	Slight	Medium gradient mountain	
	Plantation land			WR	Severe	Medium gradient hill	
Middle (2800–3100)	Bare land	10–30	Strongly sloping to moderately steep	WS	Severe	Medium gradient hill	Leptosols and Vertisols
	Cultivated land			WR	Moderate	Medium gradient hill	
	Grassland			WS	Slight	Medium gradient hill	
	Plantation land			WR	Moderate	Medium gradient hill	
Lower (2722–2800)	Cultivated land	2–10	sloping to gently sloping	WA	Slight	Valley floor	Cambisols, Fluvisols and Vertisols
	Grassland			WA	Slight	Valley floor	

(b) Characteristics of the major land-use studied across the three elevations transect.

Land use types	Area		Number of samples			Major crops and vegetation
	ha	%	Upper	Middle	Lower	
Bare land	778.23	18.99	45	45	-	Very Isolated bushes (unidentified)
Cultivated land*	1860.93	45.40	45	45	45	wheat, barley, Teff, pea, maize, and sorghum
Grassland	949.23	23.16	45	45	45	Bermuda, Rhodes, couch, and natal grasses
Plantation forest	510.75	12.46	45	45	-	eucalyptus, coniferous, and olive trees
subtotal	-	-	180	180	90	
Overall Total	4099.14	100	450			

* Cultivated land:

- Irrigation: cereal crop (maize), vegetables (Onion, Tomato, and Pepper), and fruits (e.g., apple) are cultivated with traditional irrigation at the middle and lower segment of the watershed during the off-season. Sometimes spate irrigation that relies on flood water is also practiced as supplementary irrigation by diverting runoff water to crop fields.
- Tillage type: traditional tillage using an ard (symmetric breaking type) plow locally called the "*Mahresha*" pulled by a pair of oxen is a common practice of land preparation in Ethiopia.
- Fertilization: Urea (46% N) and Diammonium phosphate (DAP: 18% N, 46% P_2O_5) at a blanket rate of 100 kg/ha^{-1} has been the conventional practice. More recently however, the compound fertilizer of NPSZnB (17 N–34 P2O5 + 7S + 2.2Zn + 0.67B) has been introduced for the area (ATA, 2014).

Commonly cultivated Crops: Wheat (*Triticum aestivum* L.), Barley (*Hordeum vulgare* L.), Teff (*Eragrostis tef.* (Zucc.) Trotter), Pea (*Pisum sativum* L.), Linseed (*Linum usitatissimum* L.), Lentil (*Lens culinaris* Medik), Maize (*Zea mays* L.), Sorghum (*Sorghum bicolor* L.)

Teff is a small cereal crop unique to Ethiopia; it is a common ingredient and staple of bread staff called "*Enjera*.

Common Grasses grown: Bermuda grass (*Cynodon dactylon* L.), Rhodes grass (*Chloris gayana* L.), East African couchgrass (*Digitaria abyssinica* L.), and Natal grass (*Melinis repens* L.)

Common Trees: Eucalyptus tree (*Eucalyptus globulus* L.) and coniferous tree (*Juniperus procera* L.), and African Olive tree (*Olea africana* L.)

m.a.s.l: meter above sea level, WR: Rill erosion, WS: Sheet erosion, WA: Water and wind erosion * Description is based on FAO (2006), and ** major soil type is based on Elias (2016).

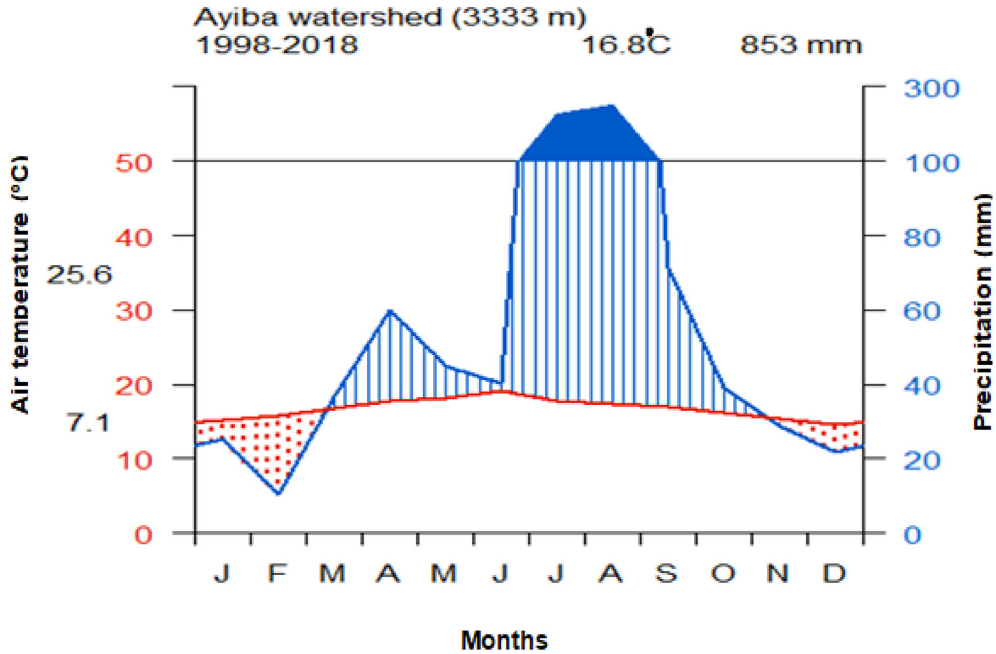


Figure 2. Climatic diagram of Ayiba watershed for 1998–2018 (Seifu et al., 2020).

SOC and TN stocks in the region seem to be inadequate. Therefore, this study aimed to: i) determine the influence of land-use type and altitudinal gradient on the distribution of SOC and TN concentration and stocks in Ayiba watershed, and; ii) map the spatial distribution of SOC and TN concentrations by Kriging interpolation technique to provide a basis for an environmentally sound management plan. Finally, this paper's findings is expected to benefit environmental researchers, producers, land managers, policymakers, and other relevant stakeholders for decision making in sustainable land management planning strategy.

2. Materials and methods

2.1. Description of the study watershed

Ayiba watershed (Figure 1) is part of the Denakil River basin located within the geographical bounds of 12°51′18″-12°54′36″N and 39° 29′ 24″-39° 35′ 24″ E covering an area of about 4099.14 ha (Figure 1a). Elevation ranges from 2722 to 3944 m above sea level (m.a.s.l.) with mountainous landscape and steep slope terrain at upper and middle slopes (Figure 1b). The landform is dominated by high mountainous relief hills and starkly dissected plateaus with steep slopes (>30% gradient) accompanied by valley bottoms and river gorges (Amanuel

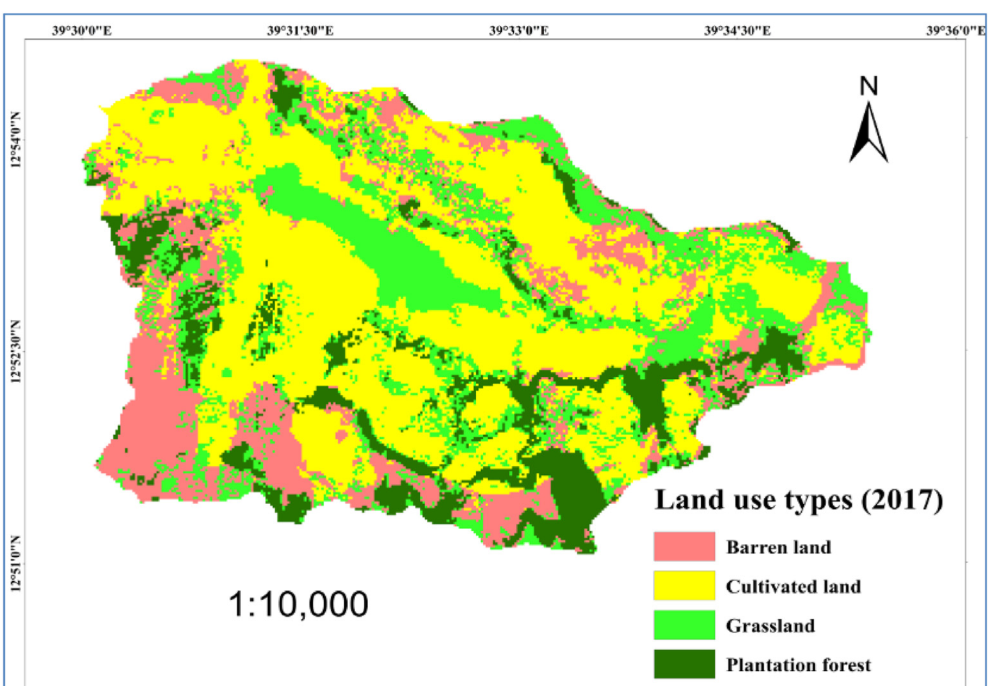


Figure 3. Land-use map of Ayiba watershed, northern Ethiopia (Seifu et al., 2020).

et al., 2015; Elias, 2016). Detailed physical landscape characterization of the watershed based on land use and elevation class is presented in Table 1(a). The watershed has V-shape with high mountaintops in southward and northward directions, medium peak at the eastward direction, and the lowest peak (outlet) at the westward direction. Leptosols and Regosols are dominant in the steep slope landscapes, and Cambisols cover the valleys of sloping land-medium gradient areas while the valley bottoms are covered by Vertisols and Fluvisols (Amanuel et al., 2015). All the soils are derived from alkali basalts of trap series volcanic parent materials and its derivative unconsolidated sedimentary alluvial materials (Elias, 2016).

The area is generally characterized as tepid-semi-arid climatic conditions with extended 9–10 months of dry periods and 50–60 days of the rainy season (Elias, 2016). According to the 20 years weather data obtained from four nearby weather stations (Bora, Maychew, Wedisemero, and Korem), the mean monthly rainfall is 72.88 mm with a total annual rainfall of 853 mm (Figure 2). The area experiences a bimodal precipitation pattern, with the bulk of the rains falling during the primary rainy season (June to September), while the small spring rains between February and May derived predominantly from the Indian Ocean (Elias, 2016; Embaye, 2009). The mean minimum and maximum monthly temperatures of the area are 7.1 and 25.6 °C, respectively, with a mean average temperature of 16.8 °C (Figure 2).

2.2. Land use and farming system

The dominant land-use practices in the watershed are characterized by a highland-cereal livestock mixed farming system with eucalyptus plantations (integral system) (Elias, 2016), but cropping remains the mainstay of the livelihood economy. Tef-wheat-pea is the common crop rotation practice in the area, and some other landscape, agronomic and vegetation cover description based on land use and the altitudinal gradient is presented beneath in Table 1. Therefore, the mainland use classes include crop fields, grassland, plantation forests, and degraded barren lands. The crop fields are distributed on the bottom and middle slopes, grassland occurs mainly on toeslopes and irregularly on the upper and hill slopes, plantation forest are present mostly on the mountain and sparingly around churches and homesteads, barren lands are scattered on the steep hill slopes. Further assessment is done to identify and classify the current land-use types described in Table 2, and readers can refer to Seifu et al. (2020), our previously published article for detailed land use classification activities. The borderline of the watershed was demarcated using the Soil and Water Assessment Tool (ArcSWAT software), and the land-use map (Figure 3) of the study watershed was produced in ArcGIS (10.5) software environment.

2.3. Soil sampling and laboratory analysis

2.3.1. Soil sampling procedure and preparation

SOC and TN concentrations and stocks were assessed under four different land-use types (Figure 3, Table 2) across three altitudinal classes (Figure 1b). For the purpose of this study, the elevation transect was divided into three discrete parts according to altitudinal gradient as (i) the upper part (3100–3944 m), (ii) the middle part (2800–3100 m), and (iii) the lower part (2722–2800 m), respectively (Figure 1b). The upper stream of the landscape consists of steep slopes (>30%) and mountainous topography with dissected side slopes with tepid moist and cold climatic regimes. The upper stream landscape is largely deforested and converted to crop, barren and grazing lands. The middle part is characterized by moderate relief hills with slopes ranging between 15-30% and tepid climatic conditions. Cultivated land and homesteads are the dominant land cover of the middle and lower landscapes. The lower part consists of the main relief dominant by undulating plains and rolling hills with a slope range of 2–15% (FAO, 2006).

A systematic stratified sampling procedure was used to distribute sampling throughout the watershed under careful consideration of topography and spatial pattern of land use. A geographical positioning system (GPS) was used to identify the site's longitude, latitude, and elevation. A hand-driven auger (100 cm^3) was used for soil sampling. Three plots (10 m × 10 m) were established with 15 subplots in each sampling land-use type. The soils from 15 subplots were combined to make a composite sample for each sampled land use. Therefore, a total of 450 topsoil samples from three replicated plots of each land-use type across elevational class were collected (Table 1(b)) and composited into 30 samples (each triplicated) following the coning and quartering method (Maiti, 2003). For BD, 30 undisturbed core soil samples (triplicated cores per land-use across elevation) were collected by the cylindrical core method (Anderson and Ingram, 1993). The samples were weighed at the time of sampling, and after were oven-dried at 105 °C until the samples retained constant weight, the cooled dry natural soil core samples were weighed at constant room temperature (25 °C), and BD (g cm^{-3}) was calculated as follows (eq. 1):

$$BD = \frac{M_2 - M_1}{V} \tag{1}$$

Table 2. Description of land-use types in Ayiba watershed, northern Ethiopia (Seifu et al., 2020).

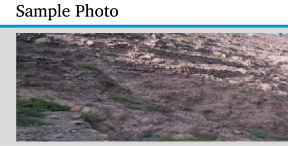
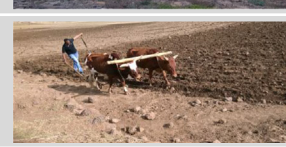
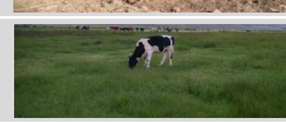
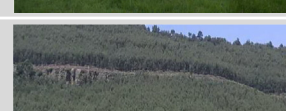
Land-use types (LU)	Description	Sample Photo
Barren land (BL)	Marginal land where no cultivation is practiced with no or minimal vegetation cover characterized by a very shallow and rocky surface of the land	
Cultivated land (CL)	Area used for subsistence rainfed annual crop production and sparingly traditional irrigational farming in offseason and rural settlements associated with cultivated fields. The main crop types are wheat, Barley, and Pulse crops.	
Grassland (GL)	Land-used for both communal grazing and the cut-and-carry system is mainly found between cultivating lands and floodplains.	
Plantation forest (PF)	Areas covered by densely planted trees that form nearly close canopies. This category included plantation forests, mainly eucalyptus and junipers.	

Photo credit: First Author (WS), February 2017.

Where: BD: dry soil bulk density, M_1: the weight of core (g), M_2: the weight of core + oven-dried soil (g), and V: volume of the core (cm^3).

At each sampling point, the surface litter was scraped, and vegetation cover was removed before collecting samples which were taken at 10 m before and after the border of each adjacent land-use type and ~150 m away from the outer ridge to avoid edge effects. Sampling points with a considerable difference were excluded to minimize variability. The samples were air-dried (to reduce oxidation of soil carbon), ground, sieved to remove gravel fraction (>2 mm), weighed, and prepared as required for laboratory analysis. After sieving, the samples were analyzed for SOM, SOC, and TN concentrations and stocks using standard protocols and procedures as outlined in Van Reeuwijk (2006). Laboratory work was done at Tigray Soil Laboratory Centre, Mekelle, Ethiopia, and at Plant Nutrition Laboratory, College of Environmental Science Resources, Zhejiang University, China.

2.3.2. Determination of SOC and TN stocks

Estimation of SOC and TN stocks requires estimates of the carbon and nitrogen concentration, BD, stone concentration, and depth of a respective soil layer (Poeplau et al., 2016). In this study, the loss-on-ignition (LOI) method was used to determine SOM concentration (Heiri et al., 2001). A programmable muffle furnace (capable of 1000 °C) and ceramic crucible (30 ml) were used to ash samples. Equivalent volumes of 5 ± 0.001 g air-dry soil (<2 mm) fraction were placed into crucibles, oven-dried at 105 °C to constant weight to remove its moisture, cooled in a desiccator, and weighed. The samples were then ashed at 400 °C in the

Table 3. Descriptive and analysis of variance statistics of the selected soil properties in the Ayiba watershed (n = 30).

(a) Descriptive statistics

LU	Descriptive	Soil parameters						EC	Soil parameters					
		BD	SOM	SOC	TN	SOCs	TNs		BD	SOM	SOC	TN	SOCs	TNs
BL	Mean	1.37	1.07	0.62	0.13	2.55	0.54	L	1.04	3.32	1.92	0.20	5.87	0.61
	Median	1.38	1.09	0.63	0.13	2.57	0.53		1.02	3.36	1.95	0.20	5.92	0.60
	Variance	0.00	0.02	0.01	0.00	0.10	0.03		0.01	1.03	0.35	0.00	2.10	0.01
	SD	0.07	0.14	0.08	0.04	0.31	0.17		0.07	1.01	0.59	0.04	1.45	0.12
	Minimum	1.28	0.86	0.50	0.08	2.00	0.35		0.96	2.26	1.31	0.15	4.42	0.47
	Maximum	1.45	1.26	0.73	0.19	2.89	0.81		1.16	4.35	2.52	0.27	7.26	0.80
	Skewness	-0.19	-0.28	-0.28	0.13	-1.05	0.55		0.96	-0.02	-0.02	0.94	-0.01	0.81
	Kurtosis	-1.82	-0.53	-0.67	-1.87	1.54	-0.73		0.35	-3.19	-3.19	1.20	-3.29	0.87
CL	Mean	1.21	2.17	1.26	0.18	4.54	0.67	M	1.24	1.86	1.08	0.15	3.96	0.57
	Median	1.22	2.14	1.24	0.19	4.61	0.70		1.23	1.97	1.14	0.15	4.05	0.57
	Variance	0.01	0.06	0.02	0.00	0.17	0.01		0.01	0.22	0.07	0.00	0.72	0.03
	SD	0.11	0.23	0.13	0.02	0.41	0.11		0.08	0.47	0.27	0.04	0.85	0.16
	Minimum	1.05	1.83	1.06	0.15	3.74	0.47		1.12	1.12	0.65	0.09	2.57	0.35
	Maximum	1.38	2.56	1.48	0.21	5.21	0.82		1.42	2.64	1.53	0.21	5.14	0.81
	Skewness	-0.05	0.20	0.17	-0.35	-0.57	-0.83		0.67	-0.37	-0.36	-0.15	-0.43	0.02
	Kurtosis	-0.69	-0.74	-0.73	-1.02	1.34	-0.06		0.61	-0.39	-0.39	-1.32	-0.95	-1.51
GL	Mean	1.14	2.81	1.63	0.17	5.36	0.58	U	1.28	1.72	1.00	0.16	3.79	0.61
	Median	1.20	2.20	1.28	0.19	4.75	0.60		1.26	1.86	1.08	0.18	3.92	0.63
	Variance	0.02	1.17	0.40	0.00	2.00	0.03		0.01	0.3	0.1	0.00	1.23	0.02
	SD	0.13	1.08	0.63	0.06	1.41	0.17		0.10	0.54	0.32	0.04	1.11	0.15
	Minimum	0.96	1.83	1.06	0.09	3.81	0.35		1.14	0.86	0.5	0.08	2.00	0.35
	Maximum	1.30	4.35	2.52	0.27	7.26	0.82		1.45	2.35	1.36	0.22	5.21	0.82
	Skewness	-0.46	0.80	0.80	-0.17	0.65	-0.07		0.38	-0.46	-0.46	-0.74	-0.31	-0.37
	Kurtosis	-1.65	-1.67	-1.68	-1.03	-1.67	-1.25		-0.83	-1.36	-1.37	-0.39	-1.50	-0.62
PF	Mean	1.19	1.95	1.13	0.15	3.98	0.55	OA	1.22	2.10	1.22	0.17	4.28	0.59
	Median	1.20	1.88	1.09	0.15	3.80	0.55		1.22	2.04	1.18	0.17	4.37	0.61
	Variance	0.00	0.23	0.08	0.00	0.74	0.01		0.02	0.76	0.26	0.00	1.76	0.02
	SD	0.05	0.48	0.28	0.02	0.86	0.09		0.13	0.87	0.51	0.04	1.33	0.15
	Minimum	1.12	1.37	0.79	0.12	2.90	0.41		0.96	0.86	0.50	0.08	2.00	0.35
	Maximum	1.24	2.64	1.53	0.18	5.14	0.66		1.45	4.35	2.52	0.27	7.26	0.82
	Skewness	-0.60	0.41	0.41	-0.46	0.34	-0.43		-0.25	1.25	1.26	-0.12	0.62	0.24
	Kurtosis	-1.29	-1.01	-0.96	0.74	-1.34	0.25		-0.21	1.88	1.89	-0.08	0.56	-1.00

(b) Analysis of variance (two-way)

sources	statistics	BD	SOM	SOC	TN	SOC stock	TN stock
LU	F-statistics	18.16	89.55	89.55	23.49	55.91	14.49
	p-value	0.001***	0.001***	0.001***	0.01**	0.001***	0.001***
EC	F-statistics	52.98	137.19	137.19	3.52	46.66	1.42
	p-value	0.001***	0.001***	0.001***	0.05*	0.001***	0.260^{ns}
LU*EC	F-statistics	3.07	22.98	22.98	4.64	9.60	2.15
	p-value	0.05*	0.001***	0.001***	0.001***	0.001***	0.112^{ns}

BD: bulk density, SOM/C: soil organic matter/carbon, TN: total nitrogen, SD: standard deviation, LU: land use type (BL: barren land, Cl; cultivated land, GL: grassland, PF: plantation forest), EC: elevation class (L: lower, M: middle, U: upper), OA: overall descriptive statistics *, **, *** indicates significant at $p < 0.05$, 0.01, and 0.001, respectively, ns: not significant.

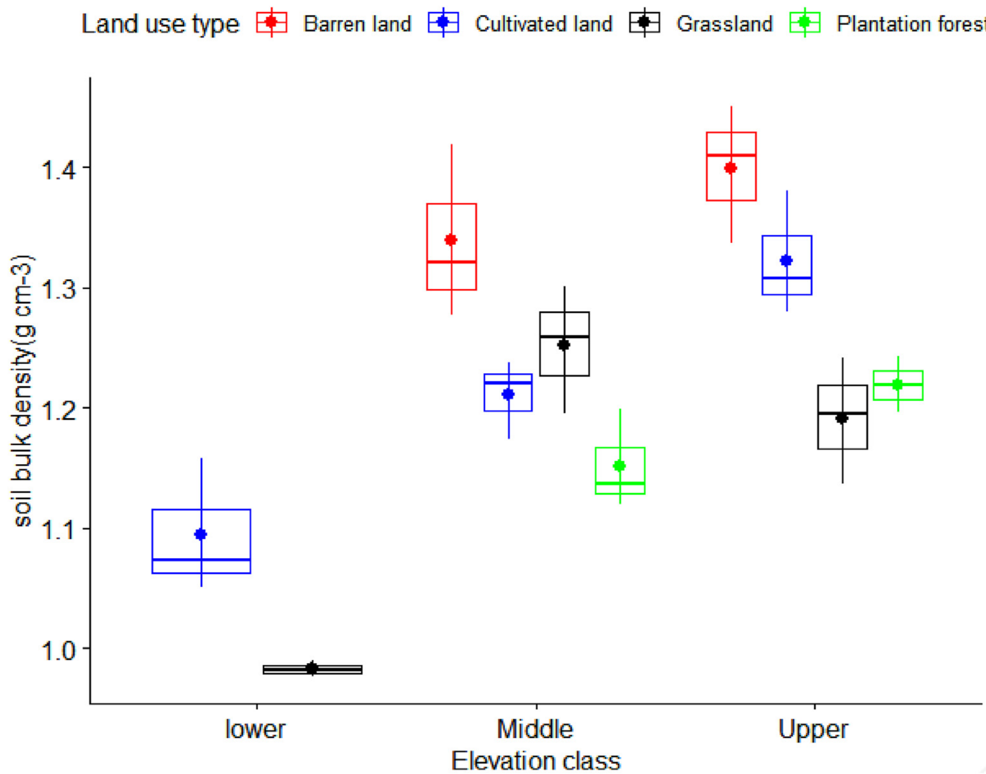


Figure 4. Topsoil (0–30 cm) bulk density of different land-use types across elevation classes at Ayiba watershed.

muffle furnace overnight (Ben-Dor and Banin, 1989). After the combustion period, samples were cooled in a desiccator and weighed. Thus, the SOM (%) was calculated using Eq. (2) and converted into SOC concentration by multiplying with the "van Bemmelen factor" of 0.58 by Eq. (3) as described in the literature (Brady and Weil, 2016; Guo and Gifford, 2002). TN concentration was also analyzed using the Micro-Kjeldahl method, which involves digestion of the sample and a wet-oxidation procedure (Bremner and Mulvaney, 1982).

$$SOM_{LOI}(\%) = \frac{(W_{105^{\circ}C} - W_{400^{\circ}C})}{W_{105^{\circ}C}} \times 100 \tag{2}$$

$$SOC(\%) = SOM(\%)*0.58 \tag{3}$$

Where, SOM_{LOI} (%): soil organic matter of loss on ignition, $W_{105^{\circ}C}$: the weight of soil after oven-dried at 105 °C (pre-ignition), and $W_{400^{\circ}C}$: the weight of soil after combustion (post-ignition) at 400°C, and SOC: SOC concentration. Finally, obtained values of SOC, TN, sampling depth (30 cm), and soil BD was used to estimate the SOC and TN stocks (Mg C or N ha^{-1}) by the following models (Ellert and Bettany, 1995; Grüneberg

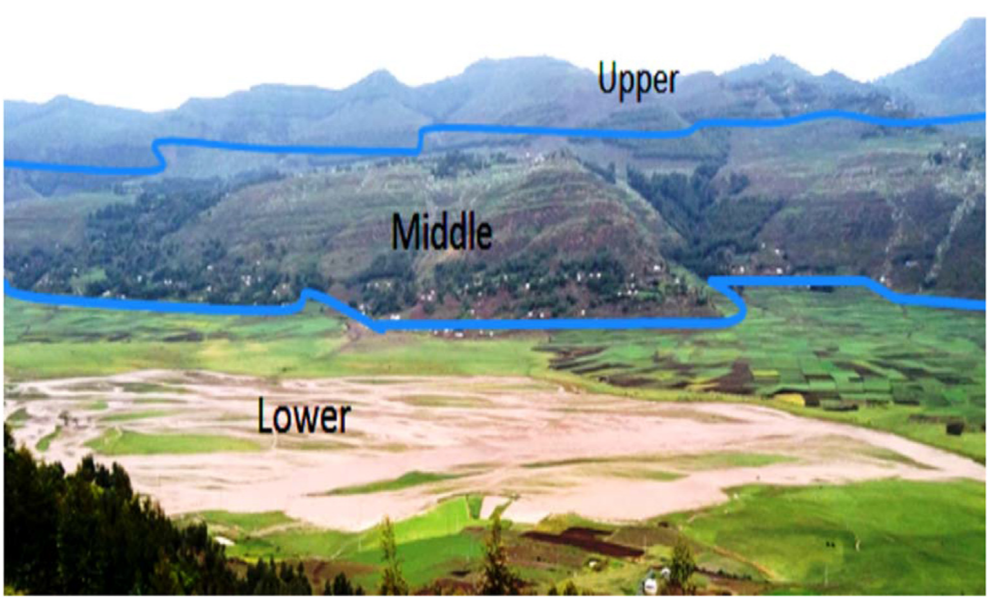


Figure 5. Part of the watershed showing rainwater erosion from upstream causes flooding and sedimentation at a lower elevation (photo credit Seifu et al. (2020)).

Table 4. Soil chemical properties (SOM, SOC, TN) of different land use types per altitudinal belt in Ayiba watershed (Seifu et al., 2020).

variables	Land use types	Altitudinal gradients			Mean ± SE	[1]Rating*
		Low	Middle	Upper		
	Barren land	-	1.18 ± 0.10	0.96 ± 0.10	1.07^{d} ± 0.10	Very low
SOM	Cultivated land	2.40 ± 0.10	1.96 ± 0.10	1.57 ± 0.10	1.98^{c} ± 0.10	Very low
(%)	Grassland	4.24 ± 0.10	1.98 ± 0.10	2.22 ± 1.05	2.81^{a} ± 0.10	Low
	Plantation forest	-	2.32 ± 0.10	2.13 ± 0.10	2.23^{b} ± 0.10	Low
	Mean ± SE	3.32^{a} ± 0.10	1.86^{b} ± 0.10	1.72^{b} ± 0.10	2.02 ± 0.10	Low
	Barren land	-	0.67 ± 0.06	0.56 ± 0.06	0.62^{d} ± 0.06	Low
SOC	Cultivated land	1.39 ± 0.06	1.14 ± 0.06	0.91 ± 0.06	1.15^{c} ± 0.06	Low
(%)	Grassland	2.46 ± 0.06	1.15 ± 0.06	1.29 ± 0.06	1.63^{a} ± 0.06	Low
	Plantation forest	-	1.35 ± 0.06	1.24 ± 0.06	1.30^{b} ± 0.06	Low
	Mean ± SE	1.93^{a} ± 0.06	1.08^{b} ± 0.06	1.00^{b} ± 0.06	1.18 ± 0.06	Low
	Barren land	-	0.10 ± 0.01	0.10 ± 0.01	0.10^{c} ± 0.01	Very low
TN	Cultivated land	0.16 ± 0.01	0.17 ± 0.01	0.17 ± 0.01	0.17^{b} ± 0.01	Optimum
(%)	Grassland	0.23 ± 0.01	0.14 ± 0.01	0.20 ± 0.01	0.19^{ab} ± 0.01	Optimum
	Plantation forest	-	0.20 ± 0.01	0.19 ± 0.01	0.20^{a} ± 0.01	Optimum
	Mean ± SE	0.20^{a} ± 0.01	0.15^{b} ± 0.01	0.17^{b} ± 0.01	0.17 ± 0.01	Optimum

Where Low = 2722–2800 m; Middle = 2800–3100 m; and upper = 3100–3944 m,

[1] Rating* was based on Karltun et al. (2013) and Hazelton and Murphy (2016), Overall means within columns and rows followed by the same superscript letter(s) are not significantly different ($p < 0.05$) as influenced by land use and elevation based on Turkey's HSD test. Values are Mean ± SE (n = 3).

et al., 2014; Poeplau et al., 2017) as stated in Eqs. (4) and (5) below. The fraction of stones and gravel (>2 mm) was considered to avoid the overestimation of SOC stocks (Poeplau et al., 2017); however, excluded due to small to almost negligible concentration (≤3%) in this study.

$$SOC_{stock} = SOC_{conc} * T * BD * 10,000 \ \ m^2 ha^{-1} * 0.001 \ \ Mgkg^{-1} \tag{4}$$

$$TN_{stock} = TN_{conc} * T * BD * 10,000 \ \ m^2 ha^{-1} * 0.001 \ \ Mgkg^{-1} \tag{5}$$

Where: SOC_{stock} or TN_{stock} = SOC stock or TN stock (Mg ha^{-1}; 1 Mg = 10^6 g = 10^3 kg = 1t); SOC_{conc} or TN_{conc} = SOC or TN concentration (kg Mg^{-1}); T = Thickness of soil layer (m), BD = Dry soil bulk density (Mg m^{-3}).

2.4. Statistical data analysis

The normality test was examined by Kolmogorov-Smirnov (KS) test prior to analysis using SPSS software for Windows (version 26, Illinois, USA), and results ($p > 0.05$) suggest that the sample distribution followed a normal distribution in the entire watershed among different land use and elevation class. Statistical variances were then tested using Two-Way ANOVA following the GLM procedure. Mean separation for significant differences was made using Tukey's HSD (honest significance difference) test at $p < 0.05$. Pearson correlation and linear regression were carried out to determine the correlation among measured parameters in different land use and elevation (R Core Team, 2020). Finally, a spatial map (1:10, 000 scale) of SOC and TN concentrations and stocks for the Ayiba watershed was developed by a simple Kriging interpolation technique using the GPS readings and the SOC and TN concentration and stock values in ArcGIS software (version 10.5).

3. Results and discussion

3.1. Descriptive and analysis of variance statistics

The descriptive statistics and analysis of variance of the soil properties are presented in Table 3. The mean of soil BD ranged from 1.19-1.37 among land use and 1.04–1.28 along elevation in the topsoil layer. The overall average concentrations of SOM, SOC, and TN at a depth of 0–30 cm were 1.72%, 1.00%, and 0.16% for Ayiba watershed with a stock of 3.79 and 0.61 Mg C or N ha^{-1}, respectively. The descriptive statistics of soil properties imply that the distribution of the soil properties varied from slightly negatively skewed (skewness ≤ −0.1.05, -0.74) to positively skewed (skewness > 0.89, 0.96) among land use and elevation, respectively (Table 3). The median values were almost near the mean values (Table 3a), representing the nonappearance of outliers in calculating the central tendency for the soil characteristics analysis. The variance analysis shows that the soil properties were significantly affected by land use type and elevation variation in the Ayiba watershed (Table 3(b)).

3.2. Soil bulk density and SOM concentration in different land-uses across elevation

Spatial topsoil BD means presented in Figure 4 varied from 0.98 to 1.09 at lower, 1.15 to 1.34 at the middle, and 1.19 to 1.40 at the upper elevations. Significantly, lower BD values were recorded under grassland (GL) and cultivated land (CL) at a lower elevation, followed by plantation forest (PF) at the middle and GL at upper elevations, respectively (Figure 4). In contrast, barren land (BL) soils in the middle and upper elevations recorded higher BD. The BD was also significantly lower in GL and PF than other land-use types that could be ascribed to the continuous addition of organic residues from their root and leave biomass due to sedimentation at the lower elevation (Figure 5). There was a gradual decrease in soil BD down the elevation gradient in all land-use types. The eroded materials (mainly fine particles and organic humus) are transported down the stream with runoff water and deposited in the watershed's downstream parts. Thus, low BD in a lower elevation than middle and upper elevations was recorded due to the sedimentation effect. The influence of runoff and erosion processes from sloped agricultural areas on soil properties was also reported by other studies (Jaleta Negasa, 2020; Tamene et al., 2020; Yuan et al., 2018).

Similarly, the lowest BD in the lower slope position in Yigossa Watershed, Northwestern Ethiopia, is reported by Gebreslassie et al. (2014) due to the higher clay content and organic matter accumulation at the upstream positions. Corresponding to our result, significantly ($p < 0.001$) higher BD in the highland areas compared to the lowland areas have also been reported by Gebresamuel et al. (2020) in northern Ethiopia. Besides, BD was found linearly correlated among land use across elevation except under grassland, which was inconsistent (Figure 4). The overall average bulk densities of the watershed soils were found low as per the rating of Hazelton and Murphy (2016).

Table 5. Spatial SOC and TN stocks of different land use types and altitudinal class in Ayiba watershed.

Soil variables	Land use types	Altitudinal gradients			Total ±SE	Mean ± SE	Summary	
		Lower	Middle	Upper			Area (ha)	Total = total*area
SOC stocks (Mg ha^{-1})	Barren land	-	2.75 ± 0.09	2.34 ± 0.17	5.09 ± 0.26	2.55^{d} ± 0.13	778.23	3,961.19 ± 202.34
	Cultivated land	4.55 ± 0.07	4.14 ± 0.18	3.61 ± 0.25	12.30 ± 0.50	4.10^{c} ± 0.17	1860.93	22,889.44 ± 866.27
	Grassland	7.24 ± 0.09	4.31 ± 0.27	4.61 ± 0.22	16.16 ± 0.58	5.39^{a} ± 0.19	949.23	15,339.56 ± 550.55
	Plantation forest	-	4.65 ± 0.37	4.51 ± 0.18	9.16 ± 0.55	4.58^{b} ± 0.28	510.75	4,678.47 ± 280.91
	Total ±SE	11.79 ± 0.16	15.85 ± 0.91	15.07 ± 0.82	42.71 ± 1.89	16.62 ± 0.77	4099.14	46,868.66 ± 316.64
	Mean ± SE	5.90^{a} ± 0.16	3.96^{b} ± 0.23	3.77^{b} ± 0.21	10.68 ± 0.47	-	-	-
TN stocks (Mg ha^{-1})	Barren land	-	0.21 ± 0.01	0.16 ± 0.02	0.37 ± 0.03	0.19^{d} ± 0.02	778.23	287.95 ± 23.35
	Cultivated land	0.68 ± 0.03	0.58 ± 0.03	0.45 ± 0.03	1.71 ± 0.09	0.57^{c} ± 0.03	1860.93	3,182.19 ± 167.48
	Grassland	1.67 ± 0.10	0.49 ± 0.05	0.76 ± 0.06	2.92 ± 0.21	0.97^{a} ± 0.07	949.23	2,771.75 ± 199.34
	Plantation forest	-	0.81 ± 0.06	0.69 ± 0.04	1.50 ± 0.10	0.75^{b} ± 0.05	510.75	766.13 ± 51.08
	Sum	2.35 ± 0.13	2.09 ± 0.15	2.06 ± 0.15	6.5 ± 0.43	2.48 ± 0.17	4099.14	7,008.02 ± 441.25
	Mean	1.18^{a} ± 0.07	0.52^{b} ± 0.04	0.51^{b} ± 0.04	1.63 ± 0.11	-	-	-

Where Low = 2722–2800 m; Middle = 2800–3100 m; and upper = 3100–3944 m, Mg: megagram, ha: hectare, Overall means within columns and rows followed by the same superscript letter(s) are not significantly different ($p < 0.05$) as influenced by land use and elevation based on Turkey's HSD test. Values are Mean ± SE (n = 3).

Mean values of SOM at upper, middle and lower elevations were 0.96 ± 0.10 to 2.22 ± 0.10%, 1.18 ± 0.10 to 2.32 ± 0.10%, and 2.40 ± 0.10 to 4.24 ± 0.10%, respectively (Table 4). Barren land recorded the least SOM in both upper and middle elevations, 56.76%, and 49.14% less from GL and PF's highest record, respectively. At the lower elevation, SOM was least in cultivated land, and overall SOM decreased as elevation increased in Ayiba watershed. The low SOM is probably due to an unsustainable land-use management system (deforestation, biomass production, crop harvest, intensive tillage) and soil erosion effects. Soil erosion transport downslope organic matter and soil particles from hilltops to deposition areas, thus creating gradients in nutrients (Doetterl et al., 2016). Accordingly, eroded soils may exhibit reduced soil fertility and productivity due to leaching on eroding slopes, and simultaneously, soil fertility may increase in depositional areas due to the additional SOM (Nitzsche et al., 2017). Similar result was reported in Ethiopia and elsewhere (Asmamaw and Mohammed, 2013; Kidanemariam et al., 2012; Panthi, 2010; Shazia et al., 2014). Contrary to our result, decreasing SOM as elevation decrease was also reported by Tsozuéa et al. (2019) in Cameroon, Meliyo et al. (2016) in Tanzania, and Abera and Assen (2019) in north-western Ethiopia, which might be due to the difference in the climatic condition and forest cover of the ecosystem. The availability of all species within ecosystems contributes to regulating carbon cycling because of their functional integration into food webs (Schmitz and Leroux, 2020). Based on the ratings of EthioSIS (Karltun et al., 2013), Ayiba watershed soil was found very low in SOM content at upper and middle elevations and optimum at a lower elevation.

3.3. SOC and TN concentrations in different land-uses across elevation

The analysis of variance test results revealed a statistically significant interaction effect of land-use type and elevation on SOC ($p < 0.001$) and TN ($p < 0.01$) (Table 3). SOC concentration values varied in the ranges of 1.39–2.46%, 0.67–1.35%, and 0.56–1.29% in land-use types of the lower, middle, and upper elevations, respectively. The TN concentration values in different land-use also varied in the range of 0.16–0.23% at the lower elevation and 0.10–0.20% at both middle and upper elevations. The overall SOC and TN concentrations mean differences among land use types at the watershed scale were statistically different (Table 4). The spatial overall mean SOC concentrations in topsoil under different land-use decreased with increase in altitude but varied with TN concentration. The SOC and TN concentrations in GL at lower (2.46 ± 0.06%, 0.23 ± 0.01%, respectively) and upper (1.29 ± 0.06%, 0.20 ± 0.01%, respectively) elevations and in PF at the middle (1.35 ± 0.06%, 0.20 ± 0.01%, respectively) elevation were significantly higher than other respective land-uses (Table 4). The lowest SOC and TN concentrations were measured in BL of the upper (0.56 ± 0.06%, 0.10 ± 0.01%, respectively) and middle (0.69 ± 0.06%, 0.10 ± 0.01%, respectively) elevations (Table 4). The SOC concentration in GL at upper and in PF at middle elevations was 56.59% and 50.37% higher than BL in both elevations. The discrepancy is attributable to the inputs of organic matter residues. However, their conversion into BL and CL reverses the situation due to reduced organic matter inputs and frequent tillage, stimulating organic matter oxidation. Corresponding to our result, high SOC in GL and PF than other land-uses in Ethiopia was reported by previous studies (Abera and Belachew, 2011; Delelegn et al., 2017; Girmay and Singh, 2012; Yimer et al., 2007). The SOC concentration of different land-use types followed the order of GL > PF > CL > BL at the upper, PF > GL > CL > BL at the middle, and GL > CL at the lower elevations, respectively. Total nitrogen concentration followed the same trend except at the middle elevation, where CL was slightly higher than GL (Table 4). Likewise, Gol (2009) and Xue et al. (2013) enlightened that the soil carbon and nitrogen cycle are positively strongly linked; hence a change in one directly influences the other.

The overall mean SOC concentration values in upper and middle elevations were low by 48.19% and 44.04% than the lower elevation, respectively (Table 4). It is probably due to the continuous biomass removal/harvest/deforestation and unsustainable land management practices. For example, vegetation clearing and steep slope cultivation (as high as 30%) accelerates the humus and fine particles transportation downslope from the upper streams with runoff water and accumulated at the lower stream (Figure 5). The process removes the soil nutrients (mainly organic matter) of the upper landscape positions and is deposited in the lower landscape position through water erosion (see field photograph below). In harmony with the current result, McClain et al. (2003) reported high rates of carbon dioxide (CO_2) and nitrous oxide (N_2O) production at low-lying topographic positions due to the convergence of hydrological flow transporting solutes and particulates that serve as substrates for the biogeochemical processes producing these greenhouse gases. Likewise, Bhunia et al. (2018) reported a decrease in OC concentration as elevation increases. Xue et al. (2013) also described the highest soil nitrogen value in valleys compared to other different landscape positions in a small watershed on China's loess plateau. Qiu et al. (2021) also highlighted a significant reduction of OC and N mineralization at eroding sites. Other studies also show that land is becoming vulnerable to soil erosion, soil fertility depletion, crop yield reduction, and associated changes in physical and chemical properties (Guadie et al., 2020; Mekonnen and Getahun, 2020).

Similarly, Cerdà and Rodrigo-Comino (2020) elucidated the erosion-deposition process as "at the hillslope scale, the upper slope position yields material, transport is dominant at the backslope section,

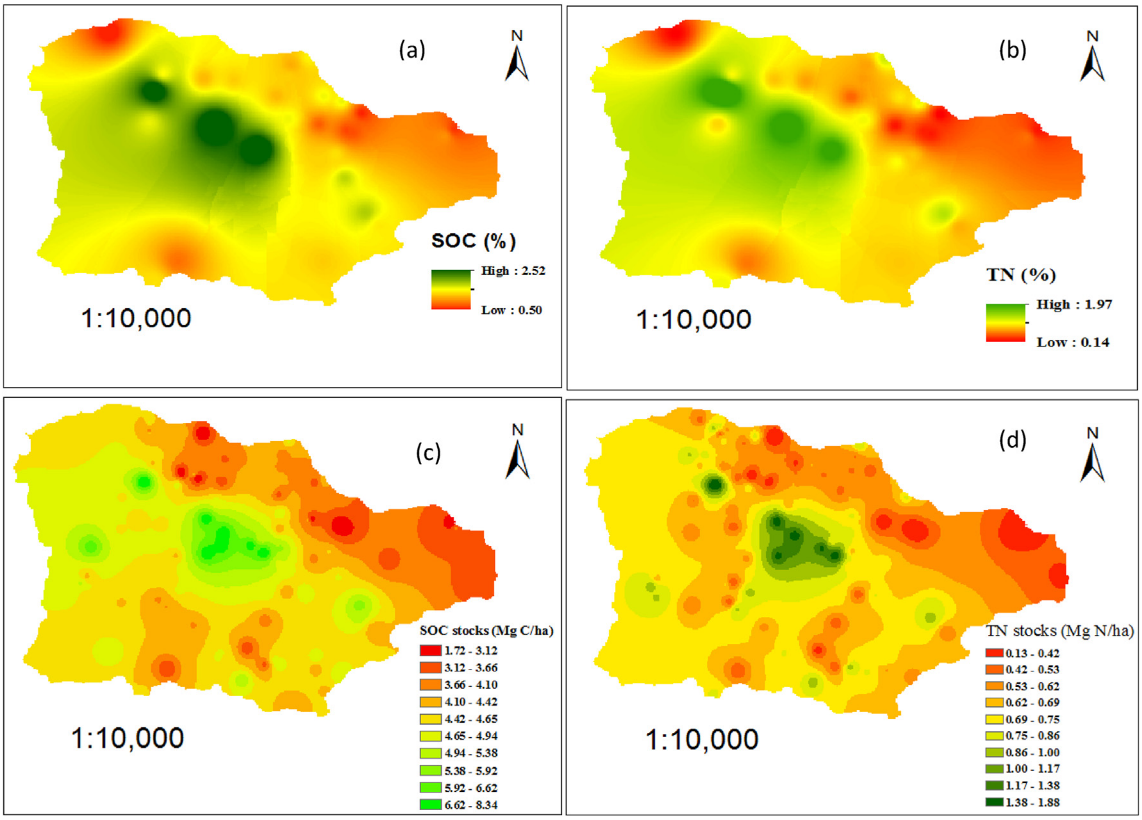


Figure 6. Interpolated (by kriging) distribution of topsoil (a) SOC and (b) TN concentrations (%) and (c) SOC and (d) TN stocks (Mg ha^{-1}) in Ayiba watershed, northern Ethiopia.

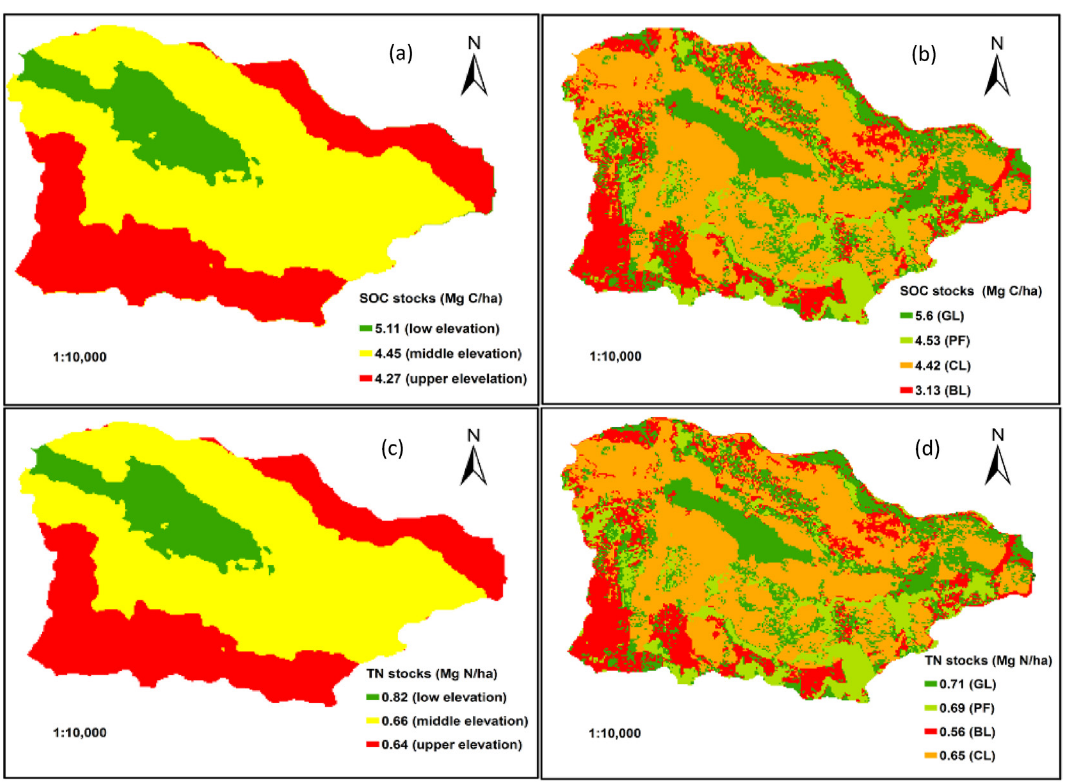


Figure 7. Interpolated (by kriging) distribution of topsoil SOC (a-b) and TN (c-d) stocks (Mg ha^{-1}) based on elevation and land use classes, respectively, in Ayiba watershed northern Ethiopia.

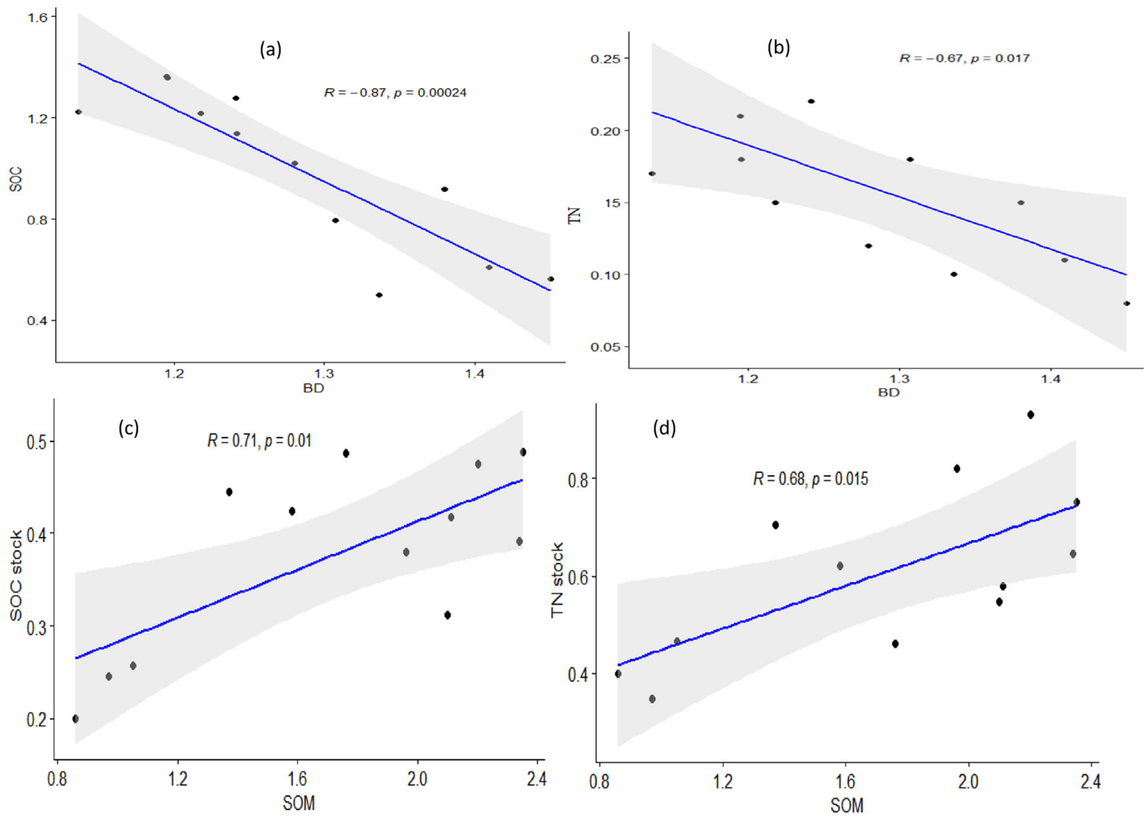


Figure 8. Relationship of (a) SOC concentration and (b) TN concentration (%) with soil BD (g cm^{-3}) and (c) SOC and (d) TN stocks (Mg ha^{-1}) with SOM (%) at upper elevation in Ayiba watershed.

and at the foot slope part the sedimentation is prevalent." Our result is also in line with the finding of some other previous studies in Ethiopia (Asmamaw and Mohammed, 2013; Elias, 2017; Gebreselassie et al., 2015). Nsalambi (2018) and Jendoubi et al. (2019) also reported a marked decline in SOC concentration with increased slopes under different land-uses and topography at Busby forest central Missouri and Mediterranean landscape, respectively. Moreover, current knowledge shows that plants, microbes, and invertebrate decomposer species are relevant to the carbon cycle, and all species within ecosystems contribute to regulating carbon cycling because of their functional integration into food webs (Schmitz and Leroux, 2020). Based on the ratings of EthioSIS (Karltun et al., 2013), the SOC concentration of the study watershed soils was found very low to a low level, and TN concentration was also found in the range of low to optimum level spatially (Table 4).

3.4. SOC and TN stocks in different land-uses across elevation

Estimating the content and spatial variability of SOC and soil TN and assessing the influence of topography and land-use type on SOC and TN after years of soil erosion control is essential for vegetation restoration and ecological reconstruction (Zhang et al., 2020). In this study, SOC ($p < 0.001$) and TN ($p < 0.01$) stocks among land-use and elevation gradients revealed significant variability (Table 3(b)). Table 5 shows the SOC and TN stocks' mean values under different land uses and altitudes, demonstrating noticeable variations in land use and altitude changes. The highest SOC stock was recorded at lower elevation in grassland (7.24 Mg C ha^{-1}), followed by PF (4.65 Mg C ha^{-1}) in the middle and GL (4.61 Mg C ha^{-1}) in the upper elevations. The lowest SOC stock was obtained in BL of upper (2.34 Mg C ha^{-1}) and middle (2.75 Mg C ha^{-1}) elevations. Spatially, the mean SOC stocks of the different land-uses were in the following order: GL˃PF > CL > BL in the upper elevation, PF > GL > CL > BL in the middle elevation, and GL˃CL in the lower elevation (Table 5). TN stock also followed the same trend in both upper and lower elevations, but the order was inconsistent in the middle elevation. The SOC stock stored in GL of the upper elevation was about 2.17%, 21.69%, and 49.24% higher than PF, CL, and BL, respectively. In agreement with our result, GL soils showed significantly ($p < 0.01$) higher SOC stocks compared with forest and cropland soils in Bavarian, southeast Germany (Wiesmeier et al., 2012). Gelaw et al. (2014) also reported that open communal grazing/pasture land accumulated the highest SOC stock (36.5 Mg ha^{-1}) than other land uses in Tigray, northern Ethiopia. Simultaneously, the SOC stock stored in the middle elevation in PF was about 7.31%, 10.97%, and 40.86% higher than GL, CL, and BL, respectively. Amanuel et al. (2018) also reported higher SOC stocks under natural and mixed forest and *Eucalyptus* plantation than other land use types in Birr watershed, upper Blue Nile River Basin, Ethiopia. The significant influence of land-use types (grassland > forestland > cropland > construction land) and altitude on the spatial pattern of SOC stock was also reported by Yuan et al. (2018) in Changhe watershed, Shanxi Province.

The overall SOC and TN stock mean comparison among elevation showed the trend of lower ˃middle > upper, respectively (Table 5), which relates to the fact that the middle and upper landscape position of the watershed is the area where erosion occurs (organic humus and fine soil particles severely eroded) while the lower landscape position of the watershed is the area where deposition occurs. This result agreed with Belay and Eyasu (2019) finding, who reported lower SOC stock in the upper sub-catchments than the lower foot slope positions in northeast Ethiopia. Similarly, Nitzsche et al. (2017) said that the accumulation of particulate or soluble carbon transported downslope via erosion or hydrological flow could increase SOC in depositional areas. Current research findings by Moges et al. (2020) also confirmed that soil erosion caused by land-use change is one of the biggest environmental challenges in Ethiopian highland soils. Contrary to this result, de la Cruz-Amo et al. (2020) reported that total carbon stock did not change with altitude in Andean Tropical Montane Forests.

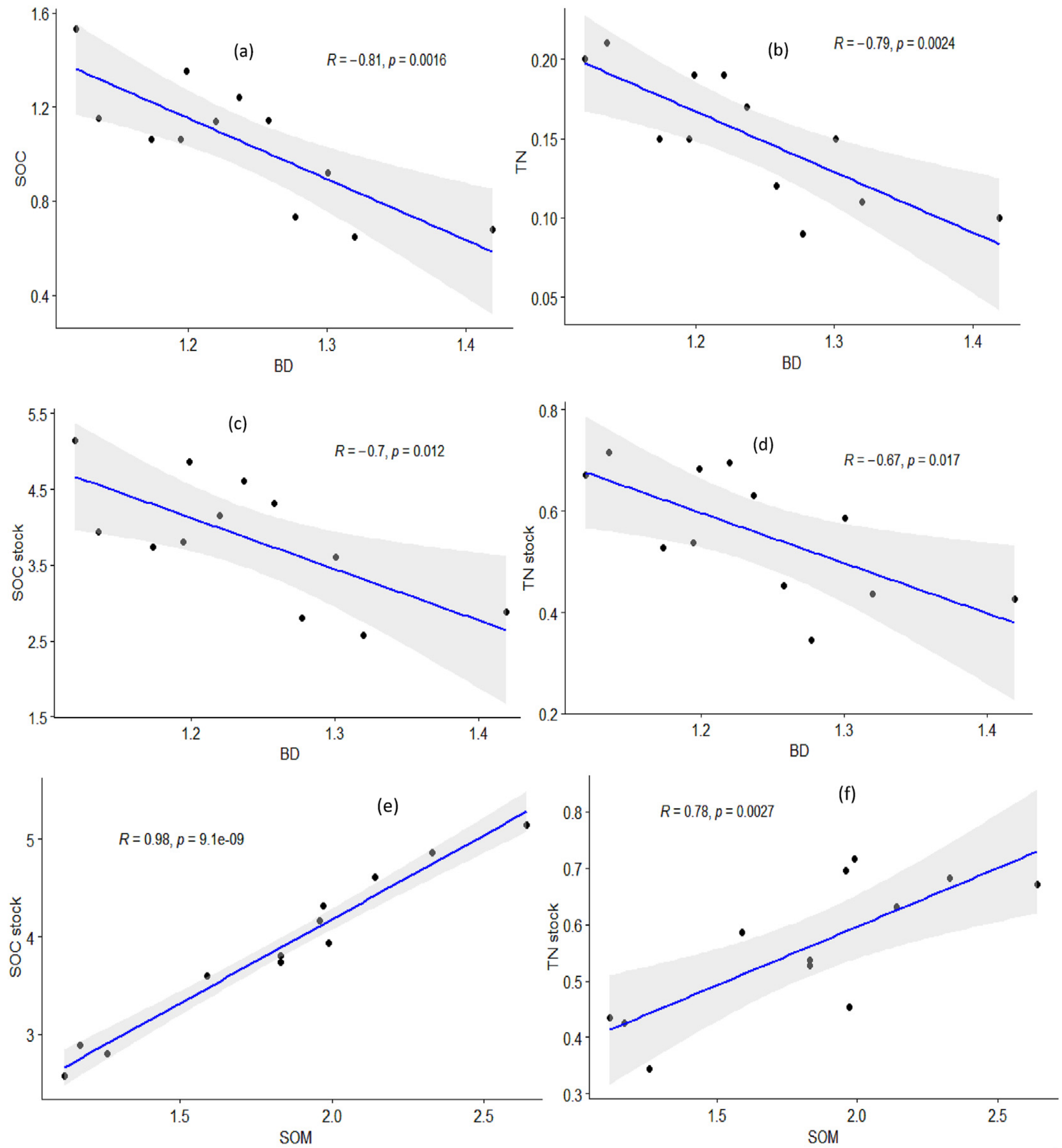


Figure 9. Relationship of (a) SOC concentration (%), (b) TN concentration (%), (c) SOC stock (Mg ha^{-1}), and (d) TN stock (Mg ha^{-1}) with soil BD (g cm^{-3}) and (e) SOC and (f) TN stocks (Mg ha^{-1}) with SOM (%) at middle elevation in Ayiba watershed.

The watershed's total SOC and TN stocks were about 42.71 ± 1.89 Mg C $ha^{-1}$and 6.50 ± 0.43 Mg N ha^{-1}, respectively. The estimated whole SOC and TN stocks of the entire study watershed were also about 46,868.66 ± 316.64 Mg C and 7,008.02 ± 441.25 Mg N (Table 5). In this study, deforestation and the cultivation of marginal and steep slopes were considered as significant factors causing SOC and TN losses. Although the impact of land-use on soil properties varied among soils and ecoregions, its change in this study area is visible as a result of intensified soil degradation and the rugged nature of the landscape. Hence, soil erosion management has significant potential as a mitigation strategy focusing on improving the herbaceous and woody covers and implementing enhanced grazing and better livestock management (especially at the middle elevation) in the study watershed.

A spatial distribution map of SOC and TN concentrations and stocks were created based on the Kriging interpolation for the study watershed from Eqs. (4) and (5) and revealed in the range of 0.5–2.52% and 1.72–8.34 Mg C ha^{-1}, and 0.14–1.97% and 0.13–1.88 Mg N ha^{-1}, respectively (Figure 6). Based on the rating of EthiSIS (Karltun et al., 2013), the level of SOC and TN were found low to very low and low to optimum, respectively. But in the interpolated map, the level is different from place to place in the study area (Figure 6). Highest SOC and TN concentrations and stocks were observed at the central part, westward, and in most southward directions. Whereas the lowest SOC and TN concentrations and stocks are displayed at northward, eastward, and some landscape features of southward directions.

Besides, zonal statistics with mean values that calculate the average of all cells in the value raster that belong to the same zone as the output cell were also used to map the SOC and TN stocks for the different land use types and altitudinal gradients of the study watershed. The result showed that SOC and TN stocks ranged from 3.13-5.6 Mg C ha^{-1} and 0.56–0.71 Mg N ha^{-1} among land-use types and from 4.27-5.11 Mg C ha^{-1} and 0.64–0.82 Mg N ha^{-1} among altitudinal gradients, respectively (Figure 7). Highest SOC and TN stocks were recorded at GL than others in terms of land use type and lower elevation than the others in terms of altitude (Figure 5). SOC and TN stocks in BL recorded were less by about 44.12% and 21.13% than GL, respectively, and SOC and TN stocks recorded in the upper altitudinal class were also less by approximately 16.44% 21.95% than the low altitudinal class, respectively. Based on FAO guidelines for soil description, the landform of the area with low SOC and TN is dominated by sloping land to steep land (includes

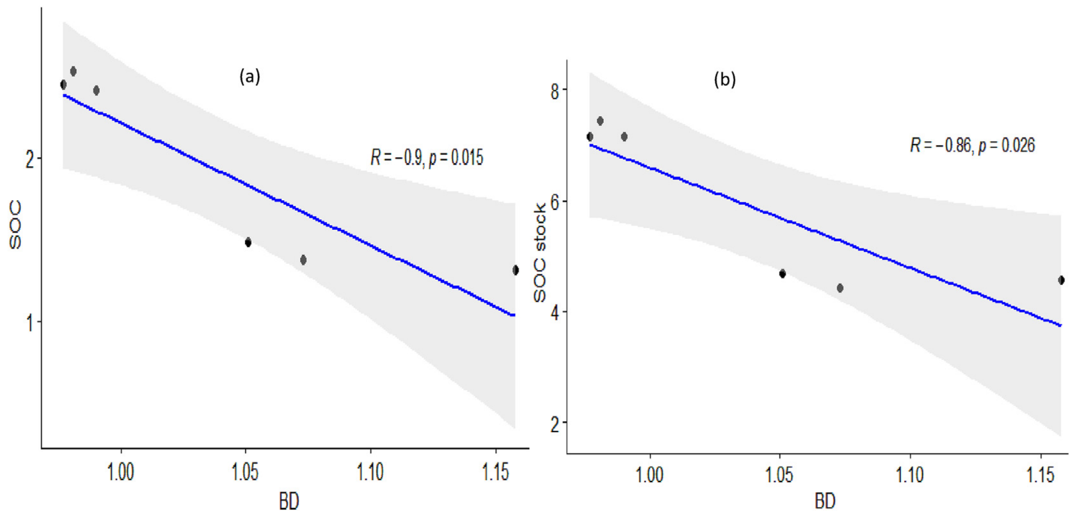


Figure 10. Relationship of (a) SOC concentration (%) and (b) SOC stock (Mg ha^{-1}) with soil BD (g cm^{-3}) at lower elevation in Ayiba watershed.

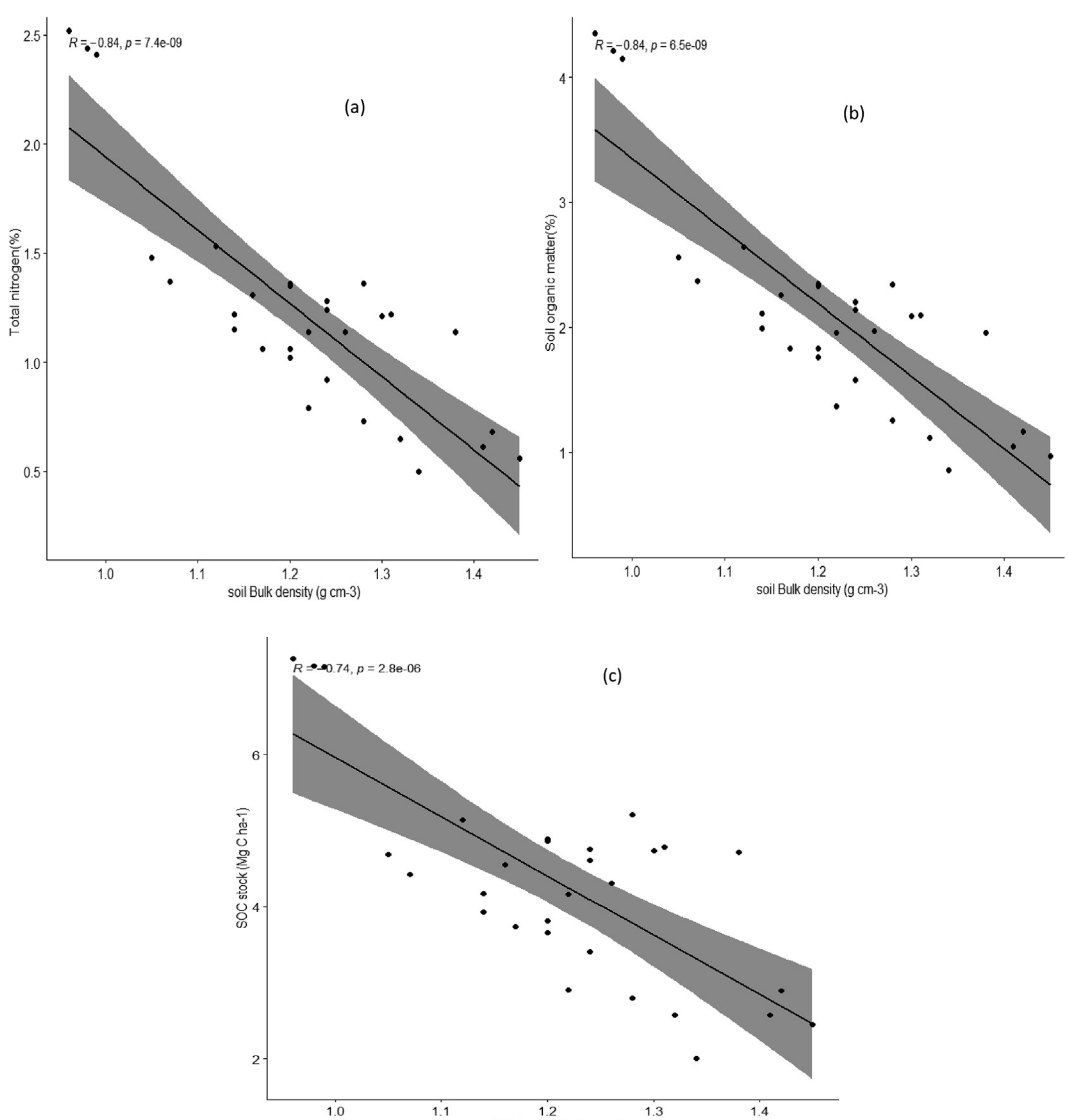


Figure 11. Relationship of (a) TN concentration (%), (b) SOM concentration (%), and (c) SOC stock (Mg ha^{-1}) with soil BD (g cm^{-3}) in Ayiba watershed, northern Ethiopia.

Table 6. Linear regression relating physico-chemical properties in different land-use types and elevation at Ayiba watershed.

	BD (g cm^{-3})	SOM (%)	SOC (%)	TN (%)	SOC stock	TN stock
Intercept	1.163***	2.497***	1.448***	0.127***	5.145***	0.388***
Cultivated land	-0.091**	0.434^{ns}	0.251^{ns}	0.054**	0.346^{ns}	0.189**
Grassland	-0.158***	1.204***	0.698***	0.084***	1.158**	0.251***
Plantation forest	-0.183***	1.155***	0.669***	0.093***	1.009*	0.277***
Middle elevation	0.183***	-1.376***	-0.798***	-0.032^{ns}	-1.906***	-0.009^{ns}
Upper elevation	0.227***	-1.475***	-0.855***	-0.025^{ns}	-5.397***	0.038^{ns}
Residual SE	0.056	0.396	0.229	0.031	0.706	0.109
Multiple R square	0.797	0.831	0.831	0.637	0.925	0.515
F-statistic	23.85***	22.63***	23.63***	8.443***	59.32***	5.101**
Error (%)	4.6	19.06	19.06	19.05	0.245	0.185

Note: Low elevation = 2722–2800 m; Middle elevation = 2800–3100 m; and upper elevation = 3100–3944 m, *, **, and *** indicates $p < 0.05.0.01$, and 0.001, respectively, ns = non-significant.

medium-gradient escarpment zone, medium-gradient hill and mountain, high-gradient hill, and mountain landscapes). The high SOC and TN area are also featured with landforms of sloping land to level land (includes medium-gradient valley, dissected plain, valley floor, depression, plateau, and plain landforms) (FAO, 2006).

Areas with low SOC and TN concentrations and stocks are covered by degraded barren land, grazing land, and cultivated marginal and steep slope areas. The spatial distribution of mean SOC and TN storage decreased with an increase in altitude in Ayiba watershed (Figure 7). It implies that both land-use and altitude significantly influence SOC and TN concentrations and stocks in the mountainous watershed, indicating anthropogenic pressure coupled with rugged and mountainous landscape structures causing large impacts on SOC and TN concentrations stocks the study watershed.

3.5. Correlation and linear regression analysis

A correlation matrix was calculated to understand the association between measured soil nutrients. The SOC and TN concentrations and stocks were significantly and positively correlated with SOM in all elevation classes (Figures 8, 9, and 10), except TN concentration and stock at a lower elevation, which revealed a positive but not significant relationship (p-value > 0.05 in all cases).

On the other side, the spatial relationship between SOC and TN concentrations and stocks with BD showed a significant negative correlation, except SOC and TN stocks at upper elevation and TN concentration and stock at lower elevation, which showed a weak and non-significant negative correlation with BD (Figures 8, 9, and 10).

Soil bulk density shows a negative correlation with SOC and TN concentrations and stocks in the Ayiba watershed (Figure 11). This paper agrees with other previous and recent studies (Liu et al., 2012; Wang et al., 2020; Xue et al., 2013), but, Céspedes-Payret et al. (2017) reported it contrary. The negative association of SOC with BD suggests that the more the BD of a soil increase, the more the soil becomes compacted. Finally, this physical soil disturbance will reduce many SOM and SOC's services, slow down the gas exchange, cause aeration-related problems, and reduce soil water infiltration and drainage capacity. Therefore, BD indirectly affects SOC spatial distribution. Bulk density is also closely associated with several key soil physical properties and processes, such as soil aeration, water dynamic, and mechanical resistance to root growth (Cherubin et al., 2017).

The bulk density of barren land was significantly higher than cultivated land, grassland, and plantation forest by 0.091, 0.158, and 0.183 units, respectively (Table 6). The predictors explained 79.7% variation in the dependent variable with the residual standard error was 0.056. The overall model was significant (F = 23.85, $p < 0.001$), with a 4.6% error (Table 6). Moreover, upon analysis, it can be revealed that the bulk density at middle elevation and upper elevation was significantly higher than that of lower elevation by 0.183 and 0.227 units, respectively.

4. Conclusion and remarks

Sustainable soil carbon and nitrogen sequestration practices need to be scaled up rapidly and implemented to contribute to climate change mitigation. Thus, SOC and TN stocks' spatial variability is necessary for cost-effective monitoring and managing their sequestration in the ecosystems at different spatial scales for sustainable soil resource management. In this study, evaluation of SOC and TN concentrations and stocks based on land-use types (BL, CL, GL, and PF) and landscape positions (upper, middle, and lower) factors were studied in the surface soil layer (30 cm) of Ayiba watershed, northern Ethiopia. The present study revealed that the overall mean SOC concentrations and stocks of the major sampled land-use type across elevational class were found in the following order: GL > PF > CL > BL at upper, PF > GL > CL > BL at the middle, and GL > CL at lower elevations, respectively (Tables 4 and 5). Total nitrogen concentration and stocks also followed the same trend, except at the middle elevation, where CL was slightly higher than GL. In lower and upper elevations, SOC and TN stock values were significantly greater under GL, while in the middle elevation, SOC and TN stocks were more significant under PF than other land-use types. The overall SOC and TN stock values were found about 42.71 ± 1.89 Mg C ha^{-1} and 6.5 ± 0.43 Mg N ha^{-1}, respectively, with 46, 868.66 Mg total SOC stock and 7,008.02 Mg soil TN stock at watershed level (Table 5).

Spatially, across the entire studied watershed, the result of the simple Kriging interpolation (Figure 6) revealed that the SOC and TN concentrations ranged from 0.50 to 2.52 (%) and 0.14 to 1.97 (%), and their stocks ranged from 1.72 to 8.34 (Mg C ha^{-1}) and 0.13 to 1.88 (Mg N ha^{-1}), respectively. The Zonal statistics result showed that SOC and TN stocks ranged from 3.13-5.6 Mg C ha^{-1} and 0.56–0.71 Mg N ha^{-1} among land-use types and from 4.27-5.11 Mg C ha^{-1} and 0.64–0.82 Mg N ha^{-1} among altitudinal gradients, respectively (Figure 7). The results supported the hypothesis that natural ecosystems' transformation to other land-uses causes a massive loss of SOC and TN. This phenomenon reduces soil carbon and nitrogen storage and stability and is subjected to soil degradation, consequently ruining the soil quality. Therefore, soil erosion and degradation are a major threat to the continued provision of ecosystem services. As a result, a decline in soil quality becomes a problematic concern local to a global scale, especially in mountainous landscapes [like the Ayiba watershed]. Steep mountain ecosystems are influenced by gravity and high kinetic potential, manifesting in high-energy mass movement and erosion events developing over long periods. Soils on steep slopes are highly susceptible to erosion in the absence of stabilized vegetation cover. Therefore, suitable soil erosion control measures and suitability analysis should be adopted according to the different terrain characteristics in the hilly Ayiba watershed for soil fertility recovery.

Evidence shows that land-use changes caused by returning cultivated land to forestland stimulated SOC and TN accumulation. Therefore, identifying site-specific suitable land-use and management practices is of utmost importance to keep soil health sustainable. Specifically, maintaining soil carbon and nitrogen balance mitigates climate change through increased sequestration in soils. To determine the spatial distribution of SOC and TN reservoirs, the relationships between soil, vegetation species, and other diverse environmental factors are essential to developing an explicit picture of the soil carbon and nitrogen sink potential for better management policy options in Ayiba massif. Also, to improve our understanding of the local-scale spatial variability of SOC and TN in response to various environmental covariates, future studies on the long-term spatiotemporal dynamics of SOC and TN are compulsory.

Declarations

Author contribution statement

Weldemariam Seifu: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Eyasu Elias, Girmay Gebresamuel: Conceived and designed the experiments; Performed the experiments; Wrote the paper.

Subodh Khanal: Analyzed and interpreted the data.

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Data availability statement

Data will be made available on request.

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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