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RESEARCH ARTICLE

Land Use Conversion Induced changes in Soil Organic Carbon Stock in Semi-Arid Areas of Africa

[1]Haftay Hailu
[2]Kassa Teka

[1]Department of Land Resources Management and Environmental Protection, College of Dryland Agriculture and Natural Resources, Mekelle University, P.O. Box: 231, Mekelle, Ethiopia

Corresponding author:
Haftay Hailu
Haftay.hailu@mu.edu.et

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ABSTRACT

Change in land use is a common occurrence in the semi-arid climate areas including Ethiopia. This, in turn, is expected to influence the soil environment through its effect on soil organic carbon stock (SOCS). Nevertheless, the status and changes in SOCS as affected by changes in land use type (LUT) were not evaluated. Sixty-four soil samples were collected from three LUTs - rain-fed farmlands (RFL), irrigable farmlands (IFL) and grasslands (GL) in Gergera watershed (900 ha), representing a semi-arid climate in northern Ethiopia, at a depth of 60 cm. The result revealed that there were significant interaction between these LUTs and depths for SOCS and bulk density ($p < 0.0001$) with mean losses of 42% and 65% in SOCS from the surface layer (0–30 cm) of IFL and RFL, respectively, as compared to GL. The results indicated that IFL and RFL in the semi-arid rangelands resulted in significantly decreased SOCS. The highest SOCS in GL reveals that the significance of GL in carbon sequestration. Hence, the present land use trend must be curbed to put back the system on its correct path of resilience and sustainability for its future maintainable benefit and to alleviate the unprecedented increase in CO_2.

Keywords- : Soil organic carbon, soil depth, land use conversion , semi-arid area.

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INTRODUCTION

Soil organic carbon (SOC) is of local importance as it controls ecosystem and agro-ecosystem function and it is of global importance because of its role in the global carbon cycle (1, 2, 3). Several studies revealed that soil is the largest organic carbon pool in the terrestrial biosphere, and minor changes in SOC storage can influence atmospheric carbon dioxide (CO_2) concentrations (4, 5, 6). For instance, climate and land use changes-induced disturbances could result in large losses in soil carbon pools (7, 8). Such carbon dynamics can result in net carbon loss rather than gain from lands being well managed for carbon sequestration (9). Due to conversion of grassland to crop land, grassland area has been decreasing while crop land area has been increasing worldwide (10) particularly in Africa. Such conversion of grassland to croplands could lead to losses up to 60% of SOC stocks (11).

In Ethiopia, where more than 70% of its area is classified as dryland (semi-arid), agriculture is a pillar and policy leading strategy for economic development. Over 85% of the country's population (of greater than 95 million) with an annual growth rate of 2.6% are engaged in agriculture (12). However, the farming practices usually comprise intensive and repeated tillage, with a complete removal of crop residues at harvest, and often intensive free grazing (13). Therewith, the organic matter return to the soil is inadequate (14). For instance, a decline in soil organic carbon (SOC) with increasing agricultural intensity and duration due to changes in soil structure caused by tillage and removal of biomass was observed in Ethiopia (15).

The ever increasing human population has also led to an increased in pasture land area conversion and irrigation area expansion to satisfy the livelihood demand. Some studies such as Gebremedhin et al. (16) and Amanuel et al. (17) in Ethiopia reported the impact of land use conversion particularly pasture conversion to arable on soil properties. But these studies are limited to the highlands (> 2300 meter above sea level) with limited access to information on the mid and low - lands which respectively represent the 1500 – 2300 and less than 1500 m elevation areas as soil properties also vary by agro-ecology. Moreover, studies on the impact of changes in land use type such as conversion to irrigated land on soil properties are very limited. Most of the studies also neglected the land conversion impacts to soil carbon sequestration, which is an important component in the climate changing environment such as the semi-arid areas of Ethiopia where the study took place. Hence, this study aimed at quantifying the SOC stock level on different land use types and along two soil depth, 0 – 30 cm and 30 – 60 cm in Gergera watershed representing the mid-high land agro-ecology.

MATERIALS AND RESEARCH METHODS

The Study Area

The study was held at Gergera watershed (900 ha), located in the Eastern Zone of Tigray Regional State in northern Ethiopia. Geographically, the study area is situated between (Fig.1). The climatic of the area is classified under semi-arid (18). Its altitude ranges from 1500 to 2800 meter above sea level.

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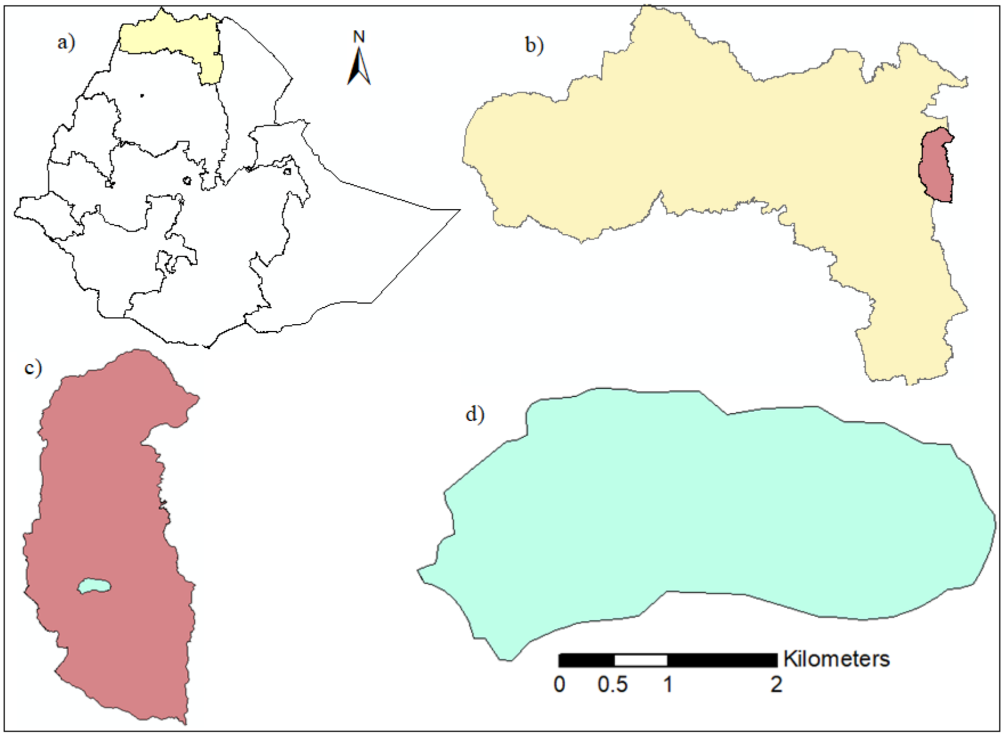

Fig. 1 Location of the study area: a) Ethiopia, b) Tigray indicating Atsbi-Wonberta district, c) Atsbi-Wonberta indicating Gergera watershed and d) Gergera watershed.

The average long-term (1980-2014) rainfall is 585 mm while the mean annual minimum temperature recorded during December is 6.3 °C, while, the mean annual maximum temperature can reach up to 31.5 °C mostly recorded in the month of June. Due to high temperature, the mean annual evapotranspiration is very high which is estimated at 462 mm (ranging from 276 – 1639 mm). Evapotranspiration is greater than the amount of precipitation all-round the year except for the months of rainy season in July and August.

The soil textural classes in the area are categorized as sandy loam (33%), clay loam (32%), sandy clay loam (27.5%) and loam (7.5%). The geology of the area is characterized by Adigrat Sandstone (34.4%), meta-volcanics or basement (30.4%), Enticho Sandstone (2.8%) and alluvial sediments (32.4%).

Irrigable farmlands, rain-fed farmlands, grasslands, bare land (e.g. rock out crop and areas denuded of vegetation) and built-up areas were identified as major land use types in the study area (Fig. 1). Of these, bare land constitutes 37.8%, which is the largest portion of the watershed. The irrigable farmlands, rain-fed farmlands and grasslands constitute 33.3%, 22.2% and 6.7% area of the watershed respectively.

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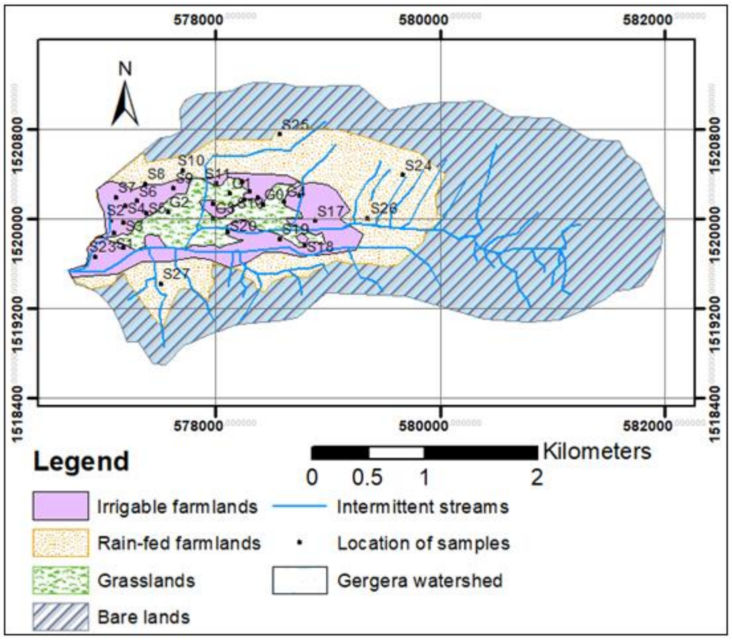

Fig. 2 Illustrating the land use types, intermittent streams and position of samples (S = soil sample from farmland and G = soil sample from grassland).

Agriculture (both irrigated and rain-fed) is principal occupation of the people and is backbone of Ethiopia's economy, which accounts to an average of 46.25% GDP (19). Majority of the rain-fed farm land is situated at the foot slope next to grass land as well as at the sloppy areas. whereas, the irrigated farmlands are located just near the grassland where there is shallow groundwater accessible for irrigation. The major crops cultivated in both rain-fed and irrigated farm lands, during rainy season, are wheat (*Triticum aestivum*), barley (*Hordeum vulgare*), maize (*Zea mays*), beans (*Phaseolus vulgaris*) and peas (*Pisum sativum*). However, the major crops grown during the irrigation season are vegetables such as potatoes (*Solanum tuberosum*), tomato (*Solanum lycopersicum*), onion (*Allium cepa*), lettuce (*Lactuca sativa*), hot pepper (*Capsicum frutescens*) and cabbage (*Brassica oleracea*). The other land use types are located at the side slope.

The grass land is situated at the foot slope, alluvial deposit, of the watershed. This land use type is currently facing a challenge of conversion to both irrigated and rain-fed farm/arable land to satisfy the farm land demand of youngsters and land less people.

Sampling Design and Soil Sampling Techniques

The watershed boundary was delineated from a 30-m ASTER digital elevation model (DEM) using the Spatial Analyst extension of ArcGIS. A reconnaissance survey was conducted to obtain a general overview of the watershed and identify the existing land use types. Hence, the major land use types were irrigable farmlands, rain-fed farmlands, grasslands, and bare land (Fig.2) in somewhat similar to the FAO (10) description approach. Among these, three land use types (rain-fed farm land, irrigated farm land and grass land), which are the main basis for the socio-economy of the local people were selected for the study. ArcGIS software v10.5 was used to map the

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sample locations and land use types. A total of 32 soil profiles pits having a size of each of 1 m x 1 m with 60 cm depth, (i.e. 6 for rain-fed farmlands, 5 for grasslands and 21 for irrigable farmlands), were opened depending on the size of the land use types. A total of sixty four composite soil samples, both undisturbed (for bulk density) and disturbed (for SOC), were collected from 0–30 and 30–60 cm soil depths following the USDA-SCS (20) soil sampling standard procedure. This was done following the principle that the soil organic carbon content (SOC) distribution could be found mainly above the 60 cm soil depth in the soil profile and considering the small land unit bases for sampling (21).

Prior to laboratory analysis, the soil samples were air-dried at room temperature, milled, and sieved using 2 mm diameter sieve. The gravel content (> 2 mm) and the soil (< 2 mm) were carefully weighted after milling in order to determine the proportion of gravel content in the soil. Soil texture was determined following the hydrometer method (20). Soil bulk density (BD) was determined after the soil sample was oven dried at 105 °C for 24 hours (22). Soil organic carbon (SOC %) was determined using Walkely and Black methods (23). The SOC stock (SOCS) in the studied land uses was estimated following equation 1 proposed by Poeplau et al. (24).

$$\text{SOC stock} = OCi*BDi*Di*(1-f) \quad \text{(eq. 1)}$$

Where SOC stock is the total amount of soil organic carbon (SOC, C kg m^{-2}) sequestered above depth Di, BDi (g cm^{-3}) is the bulk density of layer i, OCi is the concentration of organic carbon (%) in layer i, Di is the thickness of this layer (cm), and f is corresponding to the mass fraction of rock fragments (coarse fragment weight (g) divided by the total weight of the sample (g)). After the computation of the SOC stock of soils to the depth of 0–30 cm and 30–60 cm respectively, the estimates were grouped by land use type to give estimates of representative values. The representative values of SOC stock in each soil depth were averaged and converted to SOC stock in tonne (t) for each land use type.

Laboratory results were analysed using the PAST (Palaeontological Statistical) v.2.16 software. Analysis of variance (ANOVA) for comparison of means, and Shapiro-Wilk test for normality distribution of samples were employed. In addition to this, boxplot was used to compare the vertical variability of SOC concentration across the land use types at the corresponding depths of soils.

RESULTS

Table 1 summarizes the measured soil organic carbon (SOC) concentration on different land use types for both top (0–30 cm) and bottom (30–60 cm) soil layers. A statistically significant variation ($p < 0.0001$) was obtained among all land use types (IFL, RFL and GL) for SOC concentration in both soil layers. The highest SOC concentration was recorded in the GL (2.3%) followed by IFL (1.84%) and RFL (0.78%).

Table 1 Range and mean of soil organic carbon content by land use types for two soil layers of the watershed

	SOC (%), 0–30 cm		SOC (%), 30–60 cm		Mean SOC (%) 0–60 cm
LUT	Range	Mean	Range	Mean	
IFL	0.43–1.84	1.03(0.09)	0.31–1.41	0.86 (0.08)	0.95 (0.09)
RFL	0.37–0.78	0.61 (0.06)	0.36–0.65	0.50 (0.05)	0.56 (0.06)
GL	1.82–2.3	2.95 (0.09)	1–2	2.65 (0.09)	2.8 (0.09)

DOI: https://doi.org./10.24163/ijart/2017/5(3):72-82

LUT: land use type, IFL: irrigable farmlands, RFL: rain-fed farmlands, GL: grasslands, BD: bulk density (g cm-3) and the values in parentheses are standard errors (SE)

A decreasing trend in SOC was also observed along depth in all studied land use types. A higher SOC content (a mean increase by 10.2% in GL, 18% in RFL and 16.5% in IFL) was observed on the top layer (0–30 cm) (Fig. 3).

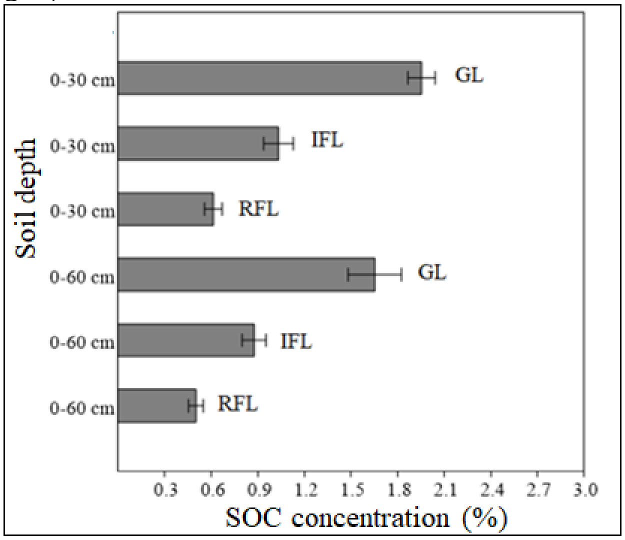

Fig. 3 Vertical variability of SOC concentration across land use types of grasslands (GL), irrigable farmlands (IFL) and rain-fed farmlands (RFL) at the corresponding depths with their standard errors.

The statistical summary of the soil bulk density of the study area is presented in Table 2. The studied land use types significantly ($p = 0.004$) affected soil bulk density (BD).

Table 2 Range and mean of soil BD (g/cm³) by land use types for two soil layers

	BD (0–30 cm)		BD (30–60 cm)		Mean BD
LUT	Range	Mean	Range	Mean	(0–60 cm)
IFL	1.14–1.65	1.41 (0.26)	1.13–1.77	1.48 (0.04)	1.45 (0.15)
RFL	1.41–1.72	1.50 (0.05)	1.41–1.55	1.50 (0.02)	1.50 (0.04)
GL	1.06–1.52	1.29 (0.07)	1.28–1.47	1.33 (0.03)	1.31 (0.05)

LUT: land use type, IFL: irrigable farmlands, RFL: rain-fed farmlands, GL: grasslands, BD: bulk density (g cm-3) and the values in parentheses are standard errors (SE).

The soil organic carbon stock (SOCS) values for each land use type are summarized in Table 3. Both land use types ($p < 0.0001$) and soil depths ($p < 0.0001$) had significant impact on the SOCS. It decreased with soil depth for all the considered land use types; and generally differed with land use type for every depth (Table 3).

DOI: https://doi.org./10.24163/ijart/2017/5(3):72-82

Table 3 SOC stock by land use types for two soil layers

	Mean SOC stock (kg m^{-2})			SOCS (t ha^{-1})		
LUT	0–30 cm	30–60 cm	0–60 cm	0–30 cm	30–60 cm	0–60 cm
IFL	4.30 (0.40)	3.82 (0.34)	8.12	43	38.2	81.2
RFL	2.61 (0.28)	2.20 (0.27)	4.81	26.1	22	48.1
GL	7.44 (0.25)	6.64 (0.81)	14.08	74.4	66.4	140.8

Values in parenthesis are SE. SOCS: soil organic carbon stock & for other abbreviations see Table 1 & 2.

DISCUSSION

GL conversion to IFL and RFL reduces soil organic carbon by 42% and 65% in the surface layer (0–30 cm) respectively. The current results are in line with studies conducted in parts of the tropics and sub-tropics that found a 20–65% loss of SOC in the top soil when GL converted into cultivated lands (25, 26, 27). The removal of crop residues from both RFL and IFL during crop harvesting and continuous tilling could be the main reason for the low SOC contents compared to GL soils (28, 29). These authors reported a decrease in SOC due to lengthy and continuous cultivation with the absence of organic substrate inputs in soils. Cultivation / tillage reduce soil carbon by 25–35% due to nutrient pumping by crops (17, 30, 31, 32). Moreover, the removal of crop residues for cooking and animal feed, which are common practices in the study area, leaves no biomass to be returned to the soil (33). The frequent cultivation which exposes the available SOC to moisture (particularly during irrigation period), and aeration, and other decomposing agents, enabling the fast decomposition of the available organic sources (17, 34) thereby decreasing SOC.

The lower SOC content (Fig. 3) at the bottom layer (30–60 cm) could be associated with the reduced quantity of external inputs addition compared to the top layer (0–30 cm). Moreover, surface layer is dominated by young fast-cycling carbon compared to subsoil dominated by ancient slow-cycling carbon indicating decomposition is strongly reduced at depth (17, 30, 35, 36).

The lowest BD was estimated from Grass land – GL, which is lower by 14.5% and 10.7% as compared to the rain-fed farm land – RFL and irrigated farm land – IFL respectively. Similar findings were reported in Negasa et al. (37) for southern part of Ethiopia; Abbasi and Rasool (28) for Rawalakot Azad Jammu and Kashmir; Chen et al. (29) for montane area of central Taiwan. According to these authors, BD is directly affected by SOC content and Tillage. The lowest BD on GL compared to RFL and IFL could be related to higher SOC content on GL which increases the soil volume with no effect on its weight (38). It can also be related to increased decompositions rate of soil organic matter in cultivated land due to tillage (34). The repeated tillage without leaving crop residue also interrupts the soil structure, resulting in a loss of soil organic matter and a compacted surface soil stratum. The rain-fed farm land (RFL) has been cultivated for prolonged period (> 50 years) and receives rainfall for about 3 months per year; while irrigated farmland (IFL) has been cultivated for not more than 20 years and receives irrigation for at least 6 months per year. Thus, the cultivation of soil for long period

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with limited moisture content under RFL compared to IFL could be attributed to soil degradation thereby higher BD (37).

With respect to depth, BD showed significant variation ($p = 0.013$). It followed an increasing trend with increasing depth in all land use types. With regard the RFL and IFL, the BD on the surface soil (0-30 cm) was slightly higher as compared to the GL. This can be attributed to soil disturbance causing from tillage practice which has caused in the relatively higher BD due to loss of SOC in surface soil. In addition to this, mechanical disintegration of soil aggregates and loss of aggregate-protected SOC exposed to lose due to microbial activities as reported by FAO (34). Moreover, practicing this soil disturbance for prolonged period in RFL makes higher BD as compared to IFL on the surface soil.

Grass land (GL) has the highest SOCS (140.8 t ha^{-1}), which is by more than three folds higher than that of rain-fed farm land (RFL). This could be attributed to high return rate of grass or may be slower microbial activity in the grasslands, with the opportunity to sequester more C than the other land uses (39, 40). Hence, GL cultivation resulted in a decline of SOC concentration and the net release of CO_2 to the atmosphere as also described in Guo (3, 6, 11), Yang et al. (3), Zhi et al. (6) and Guo (11).

CONCLUSIONS

This study analysed differences of SOC stock distributions with depth and land use type in soils of semi-arid areas of northern Ethiopia with the following findings:

1. The mean wise vertical and horizontal variation of SOC stock has shown a trend of RFL < IFL < GL and along depth. This result indicates that the largest soil carbon storage is in GL which is a vital ecosystem service. However, the conversion of grasslands to cultivated lands due to human activities can lead to loss of carbon.
2. Data in this study indicate that intensive cultivation with limited C inputs results in lower SOC stocks compared to grasslands. However, most of the SOC stocks (53%) in grasslands were located in the top 0–30 cm soil depth, showing the risks of huge quantity of CO_2 to be released from this top soil if these grasslands are transformed into farmlands.
3. Thus, the present land use trend must be restricted to put back the system on the correct path to the resilience environment for sustainable land use ecosystem service.
4. Grasslands have vital practical potential for SOC storage in the region. Sequestering C in SOC is understood as one way to mitigate climate change and stabilize environment in the country by decreasing atmospheric CO_2. Therefore, a small increase of SOC over large areas of grasslands will significantly decrease net CO_2 emissions to the ecosystems.

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