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ARTICLE



Comparative study on spatial variability of topsoil moisture content and carbon stocks as influenced by land use and soil and water conservation structures in the semi-arid Ethiopian highlands

Henok Shiferaw ^a, Amdom Gebremedhin^a, Negasi Solomon ^{b,c},
Gebeyehu Taye ^{a,b} and Amanuel Zenebe ^{a,b}

^aInstitute of Climate and Society, Mekelle University, Mekelle, Ethiopia; ^bDepartment of Land Resources Management and Environmental Protection, Mekelle University, Mekelle, Ethiopia; ^cInstitute for Environment and Sanitation Studies, University of Ghana, Accra, Ghana

ABSTRACT

Land uses and soil and water conservation (SWC) structures affect topsoil moisture and carbon stocks, particularly in the water deficit semi-arid environment of the northern Ethiopian highlands. This study was undertaken to assess the effects of land use and SWC structures on topsoil moisture, biomass, and soil carbon. Soil moisture was measured manually using gravimetric methods and theta probes with data loggers. Vegetation was inventoried and soil samples collected to assess carbon stocks of biomass and soils of different land uses. Merebmiti catchment had higher average gravimetric soil moisture content (GSMC; 24%) in wetlands, with the lowest (13%) in exclosures, whereas Mayleba catchment had relatively higher GSMC (14%) in exclosures and the lowest (8%) in rangelands. In both catchments, GSMC was higher at sampling locations closer to SWC structures than farther away. Merebmiti had significantly more biomass carbon (28.9 Mg ha^{-1}) than Mayleba ($6.32 \text{ Mg C ha}^{-1}$). Higher soil organic carbon stocks were found in exclosures ($46.1 \pm 2.20 \text{ Mg ha}^{-1}$) and wetlands ($62.1 \pm 2.9 \text{ Mg ha}^{-1}$) than in frequently cultivated croplands ($24.3 \pm 1.4 \text{ Mg ha}^{-1}$). Effective management of land use and implementation of SWC structures remarkably improves topsoil moisture content and carbon stocks in these catchments.

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KEYWORDS

Carbon stock; Ethiopian highlands; land use; soil moisture; SWC structures

Introduction

In arid and semi-arid areas, biological available water is the most active factor that controls environmental systems and productivity (Zhang et al., 2010). Soil moisture is critically important, controlling various atmospheric, ecological, hydrological, geomorphological, and pedological processes, particularly in water-limited environments (Chen, Zhang, & Wang, 2010; Cook, Bonan, & Levis, 2006; Dyn, Wei, Su, & Liang, 2015; Ersahin & Brohi, 2006; Xiao, Xue, Liu, & Zhang, 2014). Soil moisture flux is critical element of the water cycle to the atmosphere, as it controls the processes of

evapotranspiration from the land surface, namely transpiration and evaporation from bare soil surfaces (Brunswick, Fluid, Brunswick, & Fluid, 2014; Seneviratne et al., 2010). Soil moisture content changes precipitation efficiency and contributes direct surface evapotranspiration (Dyn et al., 2015). Predictions of soil moisture content are necessary for different purposes such as soil survey (McKenzie & Austin, 1992), land evaluation (Fu, Chen, Ma, Zhou, & Wang, 2000), hydrological modeling (Xiao et al., 2014), land-use planning, and management practices (Qiu, Fu, Wang, & Chen, 2010).

Soil moisture content can be affected by various factors. For instance, land uses affect the spatial pattern and vertical distribution of moisture within the soil profile by influencing infiltration rates and surface runoff (Gao, Wu, Zhao, Wang, & Shi, 2014; Niu, Musa, & Liu, 2015; Xiao et al., 2014). Furthermore, soil moisture content depends on topography, spatial variability of soil properties, vegetation cover, land use, variations in precipitation, and other meteorological conditions (Chen et al., 2010). Apart from land use, soil and water conservation (SWC) structures that retain surface runoff also affect soil moisture content by enhancing soil infiltration (Hishe, Lyimo, & Bewket, 2017; Wolka, 2014).

Carbon sequestration is one of the most important ecosystem services in the era of climate change for slowing down the atmospheric accumulation of greenhouse gases, particularly carbon dioxide. In this regard forests and soils play an important role in carbon sequestration processes by storing carbon as carbon in woody biomass and in the soil as soil organic carbon. However, the carbon sequestration potential of terrestrial ecosystems can be affected by different factors (Deng, Zhu, Tang, & Shanguan, 2016; Mekuria et al., 2007; Mesfin, Taye, & Hailemariam, 2018). For example, land-use/land-cover types affect current and potential carbon sequestration (Deng et al., 2016; Mekuria et al., 2007; Solomon, Pabi, Annang, Asante, & Birhane, 2018). Land-use change, such as forest clearance and conversion into other land uses such as cropland, have contributed ~136 (± 55) Gt carbon emissions to the atmosphere over the past 150 years (Watson, Noble, Bolin, Ravindranath, & Verardo, 2000). But, changes in land use from non-forest to forest land through afforestation and reforestation practices are known to improve the carbon sequestration potential of an area (Mekuria, Veldkamp, Haile, Gebrehiwot, & Muys, 2009). In addition, recent studies have also shown that SWC structures play significant roles in soil carbon stocks and sediment storage (Mesfin et al., 2018; Welemariam, Kebede, Bedadi, & Birhane, 2018) by retaining or retarding runoff and enhancing sediment storage.

The Tigray region in the northern Ethiopian highlands has rich experiences with the implementation of SWC measures and exclosures on different land-use types. Various SWC measures and agronomic practices that protect the soil from erosive rainfall and runoff have been carried out in different parts of the region (Haregeweyn et al., 2015). SWC structures such as stone bunds, trenches, stone bunds combined with trenches, deep percolation trenches for recharging ground water, check dams to control gully erosion, and exclosures (natural vegetation restoration) have been widely implemented in the studied catchments to enhance soil moisture availability through reduced runoff speed and increased infiltration rates. The effects of SWC measures in reducing soil erosion, enhancing infiltration, and recharging groundwater and base flow have been documented in other studies (e.g. Nyssen, Clymans, Descheemaeker, Poesen, & Vandecasteele, 2010; Taye et al., 2013; Teka et al., 2013). Despite those efforts,

information on the effects of land use and SWC structures on topsoil moisture content and carbon stocks for the Ethiopian highland remains scarce.

Soil moisture is the most important limiting factor to crop and livestock productivity in the semi-arid Tigray region of northern Ethiopia, where >80% of the total annual rainfall is concentrated during only 2–3 months of the year. In addition, due to centuries-old agricultural practices in the region, soils are often depleted of organic matter content and have poor soil fertility. Since the 1980s, land management has been the top policy priority of the Ethiopian government. Massive SWC measures, exclosures, and various water-harvesting structures have been implemented to reverse rapid soil erosion rates and conserve water to enhance agricultural production. A popular land management approach in Ethiopia is the watershed approach, which demands huge investments of capital and human resources. Although the effects of land management have been extensively studied in the Ethiopian highlands, the effects of land use and SWC structures on topsoil moisture content and above- and below-ground carbon storage are less studied. Hence, the purpose of this study was to assess the effects of land-use types and SWC structures on topsoil moisture content, biomass carbon, and soil carbon stocks. The study addressed three research questions: (1) Does soil moisture content vary with variation in land-use type? (2) Do the implemented soil and water conservation structures affect topsoil moisture content? and (3) Do biomass and soil carbon stock vary across land-use types and SWC structures at catchment scale? Thus, this study has a practical contribution, particularly for semi-arid environments, toward developing and implementing agricultural water management activities that enhance biomass and soil carbon storage as current and future climate-change adaptation and long-term mitigation strategies in the region.

Materials and methods

Study area

This study was conducted in the northern Ethiopian highlands. Two catchments were investigated: the 18-km² Mayleba catchment, located 45 km north of the regional capital, Mekelle, and the 6.3-km² Merebmiti catchment, located 36 km south of Mekelle. Locations and topographic details are provided in [Figure 1](#).

Long-term average annual temperature at Mayleba catchment has been estimated at 19 °C (Taye et al., 2013). Mayleba catchment has a bimodal rainfall distribution pattern. On average, ~ 80% of an estimated 700 mm of long-term mean annual rainfall (Taye et al., 2013) falls in the *Kiremt* season (June to September) and the remaining rainfall occurs in the *Belg* season (March to May). Merebmiti has long-term averages of minimum and maximum temperatures of 10 °C and 28 °C, respectively, and a long-term average annual rainfall of 565 mm. As at Mayleba, a large part of the total annual rainfall for Merebmiti also falls during the *Kiremt* season, with the remaining (8–9) months of the year remain dry.

The lithology of the Mayleba catchment is described as part of the Mekelle outlier, composed of Mesozoic sedimentary rocks comprising Adigrat sandstone, Antalo limestone, and Amba Aradam sandstone, buried under sequences of Tertiary flood basalts (Taye et al., 2013; Van de Wauw et al., 2008). Merebmiti catchment is dominated by

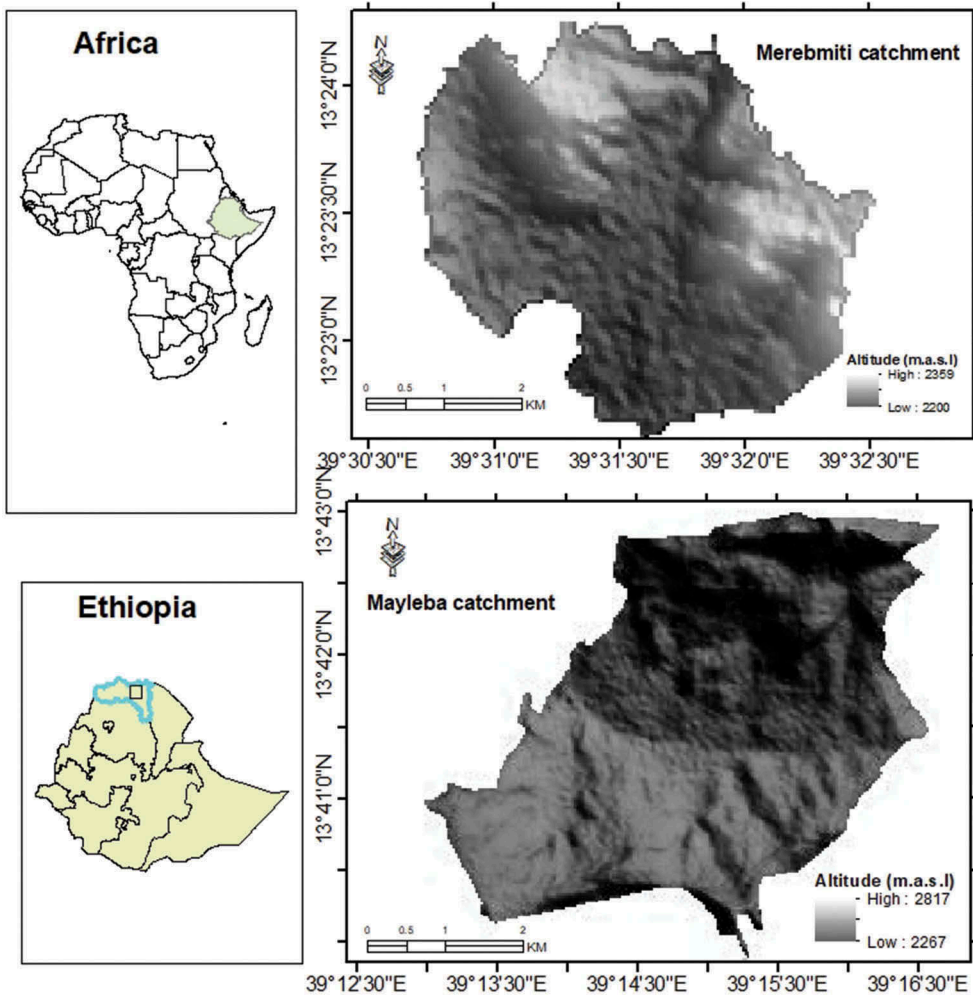


Figure 1. Location and topography of the study area in Ethiopia and the two studied catchments.

deeply weathered limestone and alkaline and transitional basalt flows (Geological map of Ethiopia, 1996). Typical soils of the Mayleba catchment include Calcisol–Regosol–Cambisol–Vertisol along a catena (Van de Wauw et al., 2008). The soils of Merebmiti were characterized as Leptosol and Regosol on sloping and enclosed areas, with Cambisol and Vertisol in croplands and wetland areas of the valley bottom. In both catchments, soil variation is high over short distances due to variations in parent materials, topography, and related soil erosion and sediment deposition processes.

Major land-use types in Mayleba catchment are croplands, grazing lands, enclosures, and homesteads; whereas, in Merebmiti catchment, major land-use types are croplands, wetlands, and enclosures. Croplands in both catchments are owned and managed by private small-holder farmers, whereas grazing lands, enclosures, and wetlands belong to and are managed by the community. Spatial distributions of land-use types in the catchments are shown in Figure 2.

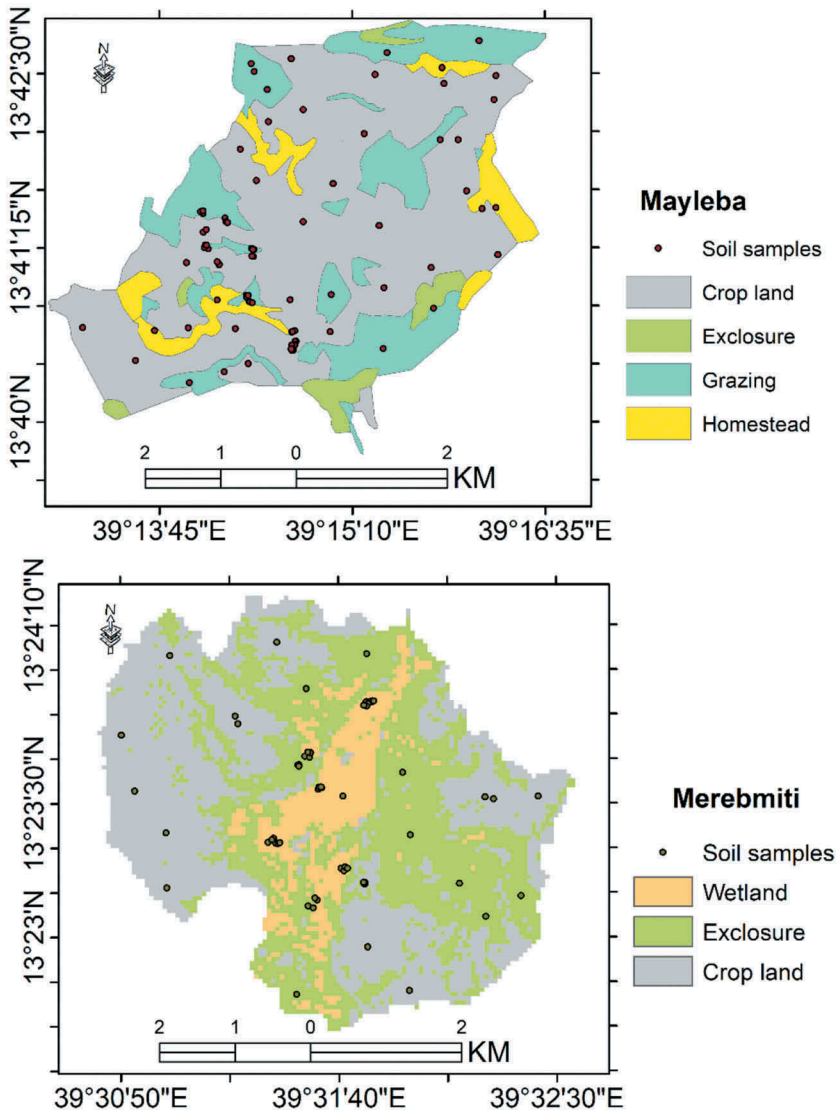


Figure 2. Land-use types and soil sampling locations for each land-use type.

Both catchments are characterized by degraded landscapes due to accelerated water erosion and low vegetation cover. To tackle or manage land degradation in these catchments, different SWC structures were proposed and implemented by the community. Starting from upslope positions in the catchments, hillside terraces, stone bunds, bench terraces, check dams, and deep trenches have been widely implemented. In the lower slopes of the catchments are several percolation ponds, built to increase infiltration and recharge to groundwater. In addition, there are exclosures, i.e. areas protected from human and animal interference for natural recovery of vegetation and soils. The exclosures, together with widely implemented SWC structures, have led to restoration

of natural resources such as soil fertility, vegetation biomass, and water storage by reducing soil erosion rates (Descheemaeker et al., 2006; Mekuria et al., 2007).

Soil sampling and experimental design

To investigate the effects of land use and SWC structures on soil moisture content and soil carbon stock, two steps were followed. First, in each catchment, existing land-use types and SWC structures in each land use were identified. Then, for each land use, soil samples were collected at three positions or at distances relative to the locations of SWC structures (Figure 2). Samples were collected at locations 0.5 m upslope and 0.5 m downslope of SWC structures and midway between two successive SWC structures (Figure 3).

From each catchment, 21 topsoil samples were collected at 0–15 cm depth. Undisturbed soil samples were also collected from selected sampling locations using 100-cm³ core samplers for the determination of soil bulk density. Xiao et al. (2014) and Taye et al. (2013) used a similar approach to investigate the spatial variability of soil moisture content in semi-arid areas.

Vegetation sampling

Vegetation was inventoried using a systematic sampling design to determine carbon stock. At each site, three parallel line transects, 200-m apart, were laid throughout exclosures. In

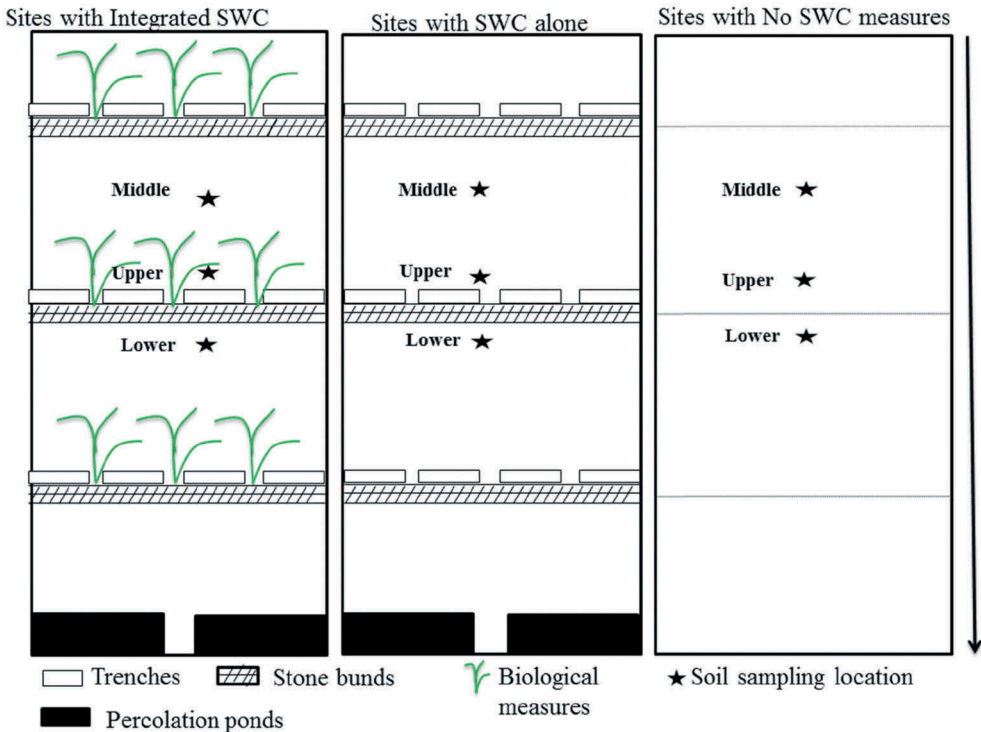


Figure 3. Soil sampling locations with reference to SWC structures. The lower side was immediately 0.5 m downslope, the middle location approximately midway between two successive SWC structures, and the upper location immediately 0.5 m upslope of SWC structures.

each enclosure, six plots (20 m x 20 m) were demarcated using 100-m long tape to determine the biomass of trees and shrubs. A total of 24 (2x3x4) sample plots were set for biomass and carbon stock estimation in each catchment. Likewise, at each plot, tree diameter at breast height (DBH) and height (H) of all trees and shrubs with DBH \geq 2 cm were measured using calipers and a 5-m pole graduated with 10-cm markings, respectively, as by Giday, Eshete, Barklund, Aertsen, and Muys (2013). However, trees $>$ 5 m in height were measured using clinometers positioned at 10 m from the base of the tree and focused on the highest point of the tree (Ubuy, Gebrehiwot, & Raj, 2014).

Spatial data set of remote sensing

The Operational Land Imager (OLI) for the year of 2015 was downloaded from USGS (<http://glovis.usgs.gov/>) for land-use/land-cover analysis of the two catchments. The catchments are located in paths 168 and 169 and rows 51, 52. All images were downloaded for the dry season, mainly the month of January, to minimize errors due to haze and cloud. In total, 120 Geographical Positioning System (GPS) points were collected from both catchments. Half of the collected ground control points (60) were used for supervised classification of the land-use/land-cover and the remaining half used for accuracy assessment to validate the classification. Google Earth was used to verify the overall classification of the training samples.

Data analysis

Land-use/land-cover analysis and accuracy assessment

ERDAS Imagine 2014 and ArcGIS 10.4 Geo-spatial software were used to produce the land-use units and land-use maps of the catchments. Image pre-processing, image processing, and post-processing activities were carried out. The Universal Transverse Mercator (UTM) Adindan Zone 37 local projection type was used to eliminate geometric distortions. All of these corrections were done in the Environment for Visualizing Images (ENVI) v 5.3 and ERDAS v. 2014 remote sensing and GIS software packages. Land-use classification was conducted with the commonly used supervised image classification of Maximum Likelihood Classifier techniques. Hence, to interpret the image created, false color composites of band combinations 4, 3, 2 for Landsat TM and 5, 3, 2 for ETM+ & OLI were used. Accuracy of image classification was assessed. Total accuracy and Kappa statistics were computed as:

$$K = \frac{N \sum_{i=1}^k x_{ii} - \sum_{i=1}^k (x_{i+} * x_{+i})}{N^2 - \sum_{i=1}^k (x_{i+} * x_{+i})} \quad (1)$$

where K is Kappa coefficient, x_{i+} is the marginal totals of row i , x_{+i} is the marginal totals column i , C_i are the total number of classified pixels belonging to class, G_i is the total number of ground truth pixels belonging to class i , and N is the total number of observations.

Determination of soil moisture content and soil carbon stock

Collected soil samples were analyzed at Mekelle University soil laboratories using standard soil analysis procedures. Soil moisture content was determined gravimetrically on the same date that the samples were collected from the field. Field weight was measured for each sample using a digital balance, and samples were oven-dried at 105 ° C for 24 hours. The dry weight was measured and gravimetric soil moisture content (GSMC) calculated as:

$$GSMC = \frac{Wetweight - Dryweight}{Dryweight} * 100 \quad (2)$$

Soil organic carbon (SOC) stock was determined from the obtained soil organic carbon concentration determined using the Walkely-Black method (Walkley, 1934). Bulk soil organic carbon stock (SOC) was determined using soil bulk density (BD), soil sampling depth, and percentage soil organic carbon concentration (% carbon):

$$SOC = BD * depth * \%carbon \quad (3)$$

where soil bulk density (BD) was calculated as:

$$BD(gcm^3) = \frac{Ovendrymass(g)}{Volume(cm^3)} \quad (4)$$

and %carbon is soil organic carbon concentration (%) determined in the laboratory following the Walkley-Black (1934) method.

Biomass carbon stock estimation

An allometric equation was used to calculate aboveground biomass (Kuyah, Sileshi, & Rosenstock, 2016):

$$AGB = 0.1428 * DBH^{2.2471} \quad (5)$$

where AGB is aboveground biomass (kg/tree) and DBH is diameter at breast height (cm). Similarly, belowground biomass (BGB) was estimated using the regression model given by Cairns et al. (1997):

$$BGB(kg) = \exp(-1.0580.8836 \ln AGB) \quad (6)$$

where AGB = aboveground biomass density.

To convert tree biomass to carbon stock, we considered a common proxy based on the assumption that 50% of the biomass is carbon (Andalo, Cairns, Cairns, & Chambers, 2005). Carbon stock was calculated by summing carbon stocks of the individual carbon pools of the exclosures:

$$C (Mgha^{-1}) = AGC + BGC \quad (7)$$

where C is carbon stock density [Mg C ha⁻¹], AGC is aboveground carbon [Mg C ha⁻¹], and BGC is belowground carbon [Mg C ha⁻¹].

Statistical analysis

Analysis of Variance (ANOVA) was conducted to test soil organic carbon means across land-use types and the different sample positions relative to SWC structures in each catchment. Before conducting ANOVA, the collected data were tested for normality and equality of variance. Tukey HSD post-hoc tests were performed to separate soil organic carbon means across land-uses. Statistical mean differences were considered significant at $p < 0.05$.

Results

Land-use and land-cover types

Land-use maps of the two catchments are shown in [Figure 2](#). Detailed descriptions of the land uses are provided in [Table 1](#). Overall accuracies of land-use/land-cover classifications for Merebmiti and Mayleba were found to be 88% and 87%, respectively, with kappa coefficients of 0.88 for Merebmiti and 0.87 for Mayleba. In Mayleba catchment, the four major land-use types were cropland, exclosures, grazing land, and homesteads. In Merebmiti, cropland and exclosures were the dominant land-use types. Merebmiti catchment also contains considerable area of wetlands. In Mayleba, cropland covers 13.4 km² (72%), rangeland 2.6 km² (13.9%), homestead 1.8 km² (9.6%), and exclosures 0.82 km² (4.4%). In Merebmiti catchment, croplands are still the most dominant land-use type. They cover 2.9 km² (45.3%), followed by exclosures with 2.8 km² (43.8%), and wetlands with 0.7 km² (10.9%) ([Table 1](#)).

Effects of land-use types and SWC structures on topsoil moisture contents

The results presented in [Figure 4](#) show the effect of land-use type on topsoil moisture content in the two catchments. In the Merebmiti catchment, the highest GSMC was recorded in wetlands, while the lowest was recorded in exclosures. In Mayleba, the highest GSMC was found in exclosures ([Figure 4](#)) and the lowest in rangelands.

In Merebmiti catchment, the highest average soil moisture content, 24%, was found in wetlands just below SWC structures, and the lowest soil moisture content, 13%, was recorded in exclosures midway between successive SWC structures. Similarly, in Mayleba, the highest average soil moisture content, 14%, was recorded in exclosures upslope (0.5 m) of SWC structures while the lowest soil moisture content, ~ 8%, was recorded in rangelands just above the SWC structures.

Table 1. Land-use/land-cover types and areas covered in the studied catchments.

Land-use type	Merebmiti		Mayleba	
	km ²	%	km ²	%
Cropland	2.9	45.3	13.44	72.0
Exclosures	2.8	43.8	0.82	4.4
Rangeland	-	-	2.6	13.9
Homestead	-	-	1.8	9.6
Wetlands	0.7	10.9	-	-
Total	6.4	100.0	18.66	100.0

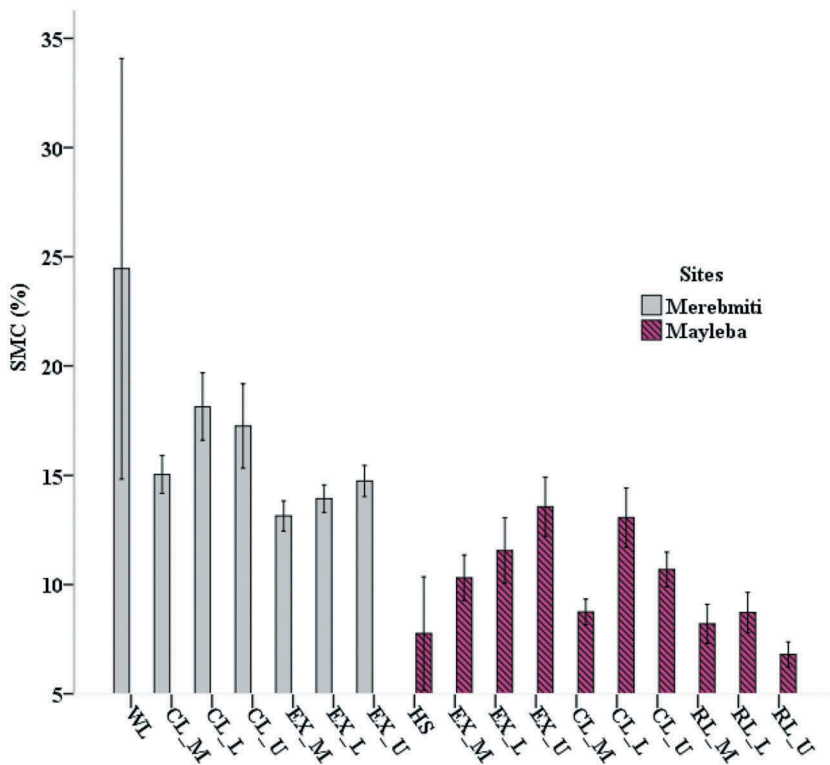


Figure 4. Percentage gravimetric soil moisture content relative to SWC structures and land-use types (Error bars: ± 1 SE); RL is rangeland, CL is cropland, EX is enclosure, HS is homestead, and WL is wetla

The results presented in [Figure 5](#) show GSMC at different sampling locations relative to SWC structures. In both catchments, GSMC was higher at sampling locations closer to SWC structures than far distance from SWC

Carbon stock as influenced by land-use types and SWC structures

Vegetation properties in enclosures of the two catchments

Average values of diameter at breast height (DBH), tree height, and density of woody species collected from enclosures in the two catchments are presented in [Table 2](#). Average tree densities for Mayleba and Merebmiti were 702 and 696 individual trees per ha, respectively. A total of 475 individual trees and shrubs were measured in both catchments. Seven dominant species contributed 94.3% of the total species abundance ([Table 2](#)): *Acacia etbica* (41.6%), *Eucalyptus camaldulnesis* (28%), *Carissa spinarum* (10%), *Dodonaea angustifolia* (4%), *Euclea schimperi* (3.5%), *Rhus natalensis* (2.9%), and *Acacia saligna* (2.9%). Seven other species – *Clerodendron myricoides* (1.7%), *Osyris quadripartite* (1.3%), *Maytenus arbutifolia* (1.2%), *Meriandra bengalensis* (1.3%), *Cupressus lusitanica* (0.8%), and *Acacia abyssinica* (0.6%) – make up the remaining 6.3%. Average DBH of all tree species was 7.35 cm (Merebmiti) and 4.12 cm (Mayleba) ([Table 2](#)). Similarly, the average height of all species was 7.14 and 2.09 m for Merebmiti and Mayleba catchments, respectively.

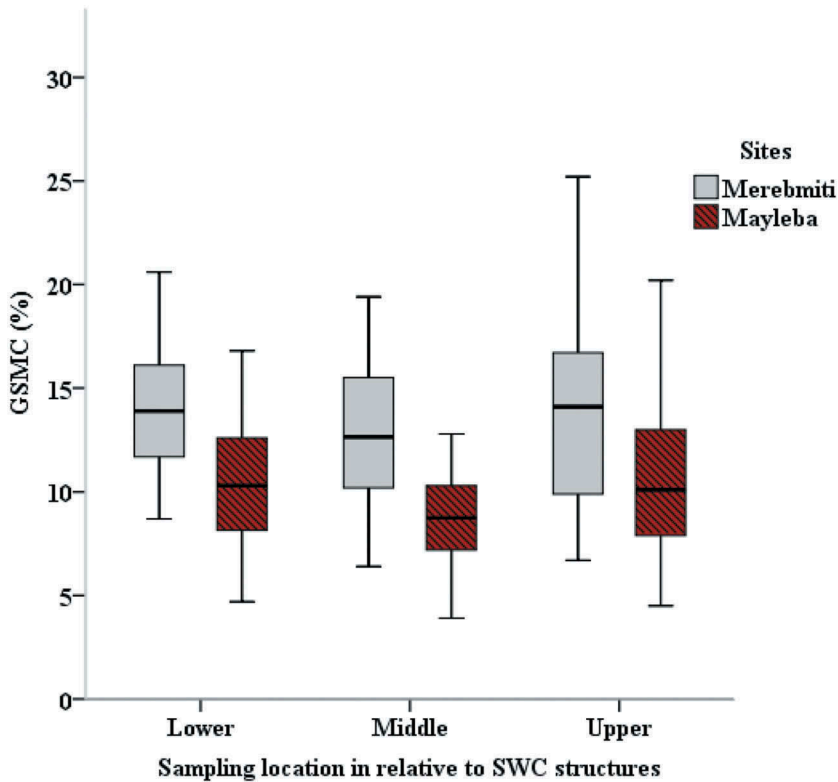


Figure 5. Percentage gravimetric soil moisture content (GSMC %) at different sampling locations from the SWC structures: lower (0.5 m downslope of the SWC structure), middle (approximately midway between two successive SWC measures), and upper (0.5 m upslope from SWC structures).

Table 2. Average woody plant dendrometric variables used for biomass and carbon estimation.

Vegetation parameters	Mayleba	Merebmiti	Total average
Average DBH (cm)	4.12	7.35	5.67
Average Height (m)	2.09	7.14	4.51
Number of trees/ha	702	696	699

Table 3. Above and belowground biomass carbon stock (Mean \pm standard error of the mean) for exclosures of the two catchments.

Carbon pools	Mayleba exclosures	Merebmiti exclosures
Aboveground carbon (Mg C ha ⁻¹)	5.05 \pm 0.93	23.13 \pm 6.8
Belowground carbon (Mg C ha ⁻¹)	1.26 \pm 0.23	5.78 \pm 1.7
Total carbon (Mg C ha ⁻¹)	6.32 \pm 1.2	28.9 \pm 8.5

Above and belowground biomass carbon stock

Results (Table 3) show biomass carbon stocks in the two catchments. In Mayleba catchment, biomass carbon was 6.32 Mg ha⁻¹, whereas, in Merebmiti, biomass carbon was 28.9 Mg ha⁻¹. Thus, Merebmiti catchment had more carbon stored in biomass.

Table 4. Soil organic carbon stocks (Mg ha^{-1}) of different land-use types for each catchment.

Catchment	Land uses					P- value
	Exclosure	Cropland	Rangeland	Homestead	Wetland	
Mayleba	25.82 ± 1.83^b	24.11 ± 2.43^b	42.4 ± 2.6^a	42.53 ± 2.02^a	-	<0.0001
Merbmiti	49.95 ± 4.32^b	47.85 ± 2.32^b	-	-	62.2 ± 4.3^a	0.0091

Values within a row with same letters are not significantly different.

Soil organic carbon stock

The study also compared soil organic carbon stocks of different land-use types. Both catchments showed significant differences in soil organic carbon among the different land-use types, with P values of <0.0001 and $P = 0.0091$ (Table 4).

The results presented in Figure 6 show soil organic carbon stocks at different sampling locations relative to SWC structures for the land-use types of the two catchments. Soil organic carbon stocks at the three sampling positions relative to SWC structures (upslope and downslope of the SWC structures and midway between two successive SWC structures) showed remarkable variability (Figure 6). In Merbmiti catchment, the highest (54.2 Mg ha^{-1}) carbon stock was recorded at a sampling location upslope of a SWC structure in an exclosure. In Mayleba catchment, the highest soil

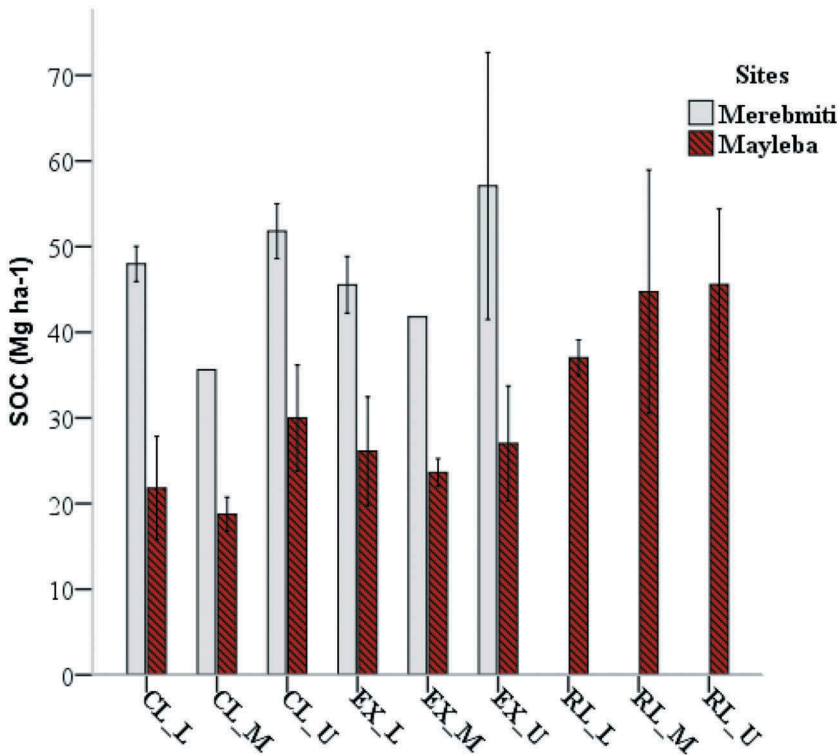


Figure 6. Average values of soil organic carbon stock in Mg ha^{-1} for both catchments, taking into account sampling distance relative to the location of the SWC structures (U = 0.5 m upslope of the structure, L = 0.5 m below the structure, M = Midway between structures; CL = cropland, EX = exclosure, RL = rangeland).

organic carbon stock (46.5 Mg ha^{-1}) was also recorded upslope of a SWC structure. In both catchments, the lowest soil organic carbon stock was obtained in cropland at a sampling location midway between two successive SWC structures.

Discussion

Effects of land-use types and SWC structures on soil moisture content

The present study revealed considerable variability of topsoil moisture content across the different land-use types in both studied catchments, as has been shown in other studies (e.g. Nyssen et al., 2007; Taye et al., 2013). In this study, in Merebmiti catchment, the highest soil moisture content was observed in wetlands, while, in Mayleba catchment, the highest average soil moisture content, recorded in exclosures, was somewhat lower. The wetland area, waterlogged and covered by grasses for at least part of the year, stores a large volume of water in topsoil compared to land-use types that drain rapidly. In contrary, exclosures, situated on degraded steep slopes with rapid internal and external drainage, have shallow soil systems with limited water storage and water-holding capacity; hence, the soil moisture content in exclosures is significantly lower.

Implemented SWC measures increase the availability and amount of soil moisture, as observed in other studies (Fua, Wangb, Liding, & Qiu, 2003; Nyssen et al., 2007; Taye et al., 2013). Similarly, in this study, areas close to SWCs retained more surface runoff, hence had higher soil moisture contents than areas far from SWC structures. In both catchments, the highest soil moisture content was found at locations upslope and downslope of SWC structures, compared to locations far from the structures (midway between the two successive SWC structures). This is mainly due to runoff and sediment retention effects of the SWC structures (Nyssen et al., 2007; Rashid, Rehman, Alvi, Kausar, & Akram, 2016). The retained runoff has a longer time to infiltrate into the soil, particularly around SWC structures, and thus increases soil moisture around these structures. This has significant implications for increasing topsoil moisture and groundwater recharge or for use by crops planted close to the structures. As observed in the field, the upper side of SWC structures stored a considerable amount of water from intercepted surface runoff. Nyssen et al. (2007) indicated that the effect of SWC structures on soil moisture is more important at greater depth, i.e. below the root zone compared to topsoil, due to rapid evapotranspiration of soil water from the topsoil layer.

Carbon stock as influenced by land-use types and SWC structures

Our results showed how carbon stocks in vegetation and soils varied across the different land-use/land-cover types in the two catchments. Carbon stocks estimated for the two catchments have similarities with results reported by other studies conducted in semi-arid areas (Giday et al., 2013; Hishe et al., 2017; Mekuria et al., 2015). For example, Giday et al. (2013), in their study of wood biomass functions in a community-managed exclosure in Tigray, Ethiopia, found 12.7 Mg ha^{-1} of carbon. Similarly, Mekuria et al. (2015) found 7 Mg C ha^{-1} in a 7-yr old exclosure in the Nile basin, Ethiopia. However, biomass carbon stocks found in this study were four times lower than woody biomass

carbon stocks reported from exclosures that had been closed for about 20 years in southern Ethiopia (Gilo, Kelkay, & Gedda, 2016). As suggested by various authors, grazing exclusion is a positive way to restore degraded areas and has a high potential for sequestering carbon in semi-arid areas (Gebregergs, Tessema, & Solomon, 2019; Li, Zhao, Chen, Luo, & Wang, 2012).

In both catchments, wetlands and exclosures had the highest soil organic carbon stocks, whereas croplands had the lowest. Differences in SOC stocks between land uses could be attributed to the differences in annual turnover of organic matter from dying grass roots, vegetation biomass, and rates of production and decomposition of litter from vegetation that adds organic matter into the soil systems (Gebregergs et al., 2019; Solomon et al., 2018). Our results have similarities with those of other studies carried out in semi-arid environments (Corral-Nuñez et al., 2014; Girmay, Singh, Nyssen, & Borrosen, 2009). Thus, land uses with more aboveground vegetation biomass contribute more to the soil carbon sequestration potential compared to land uses having less aboveground vegetation biomass. The lower soil organic carbon stock recorded in cropland is due to the low input of organic matter returned to the soil, high rates of oxidation of soil organic matter by tillage, poor land management, and frequent destabilization of the soil (Dalal & Chan, 2001). In the farming system of Ethiopian highlands, complete removal of crop residue during harvesting is a common practice. Moreover, free stubble grazing after harvest ultimately removes all organic materials from the soil surface, leading to low organic matter input to cropland.

Soil organic carbon upslope of SWC structures in the studied catchments is higher than that on the lower sides of SWCs or midway between structures. In the study area, different SWC structures have been implemented, aiming to improve soil physicochemical properties by reducing soil erosion rates and accumulating organic matter. SWC structures improve soil organic carbon content as observed and reported by various researchers (Hishe et al., 2017; Welemariam et al., 2018). Hishe et al. (2017) reported a higher mean soil organic carbon content for a conserved landscape compared to a corresponding non-conserved landscape in the Middle Silluh Valley, northern Ethiopia. They attributed these variations to SWC structures and rehabilitation measures applied in the area. Mesfin et al. (2018) also reported higher soil organic carbon in areas with SWC structures in the farmlands compared to farmlands without SWC structures in semi-arid areas of Northern Ethiopia. Other scholars (e.g. Husen, Esimo, & Getechew, 2017; Tiki, Yimer, & Resources, 2015) have shown higher values of soil organic carbon on farmlands treated with SWC than on non-conserved land.

Conclusions

The spatial variabilities of soil moisture and carbon stocks observed in the study catchments were attributed to differences in land use and to SWC structures. In Merebmiti catchment, the highest soil moisture content was recorded in wetlands and the lowest in exclosures, whereas, in Mayleba catchment, the highest GSMC was recorded in exclosures and the lowest in rangelands. In general, average topsoil moisture content was higher in the Merebmiti than in the Mayleba catchment. SWC structures strongly influence surface runoff and infiltration rates. For both catchments, the highest soil moisture content was recorded at a sampling location close to a SWC

structure, compared to locations farther from the structures. The results of the study verify that land uses and SWC structures have influenced soil organic carbon stocks. Higher biomass carbon stock was recorded in Merebmiti as compared to Mayleba. In Merebmiti, significantly higher soil organic carbon was found in exclosures and wetland as compared to cropland. Thus, the study concludes that effective management of land use and installation of SWC structures enhances topsoil moisture content and soil organic carbon stock in the study catchments and also in similar environments. The study provides empirical evidence, with respect to the effects of land use and SWC structures, of a how land management system influences soil moisture and carbon stocks in the soil.

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ORCID

Henok Shiferaw  <http://orcid.org/0000-0002-3889-4965>
Negasi Solomon  <http://orcid.org/0000-0003-0767-158X>
Gebeyehu Taye  <http://orcid.org/0000-0003-3078-5016>
Amanuel Zenebe  <http://orcid.org/0000-0001-6571-9065>

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