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# Exclosures backed up with community-based soil and water conservation practices increased soil organic carbon stock and microbial biomass carbon distribution, in the northern highlands of Ethiopia

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## Abstract

**Background:** Land degradation is a treat for natural resources in Tigray high lands of northern Ethiopia, where 30–50 percent of the soil productive capacity has been lost in the past 500 years. Restoration and management of degraded lands improve soil health through enhancing soil organic carbon (SOC) stock and microbial biomass carbon (MBC). The knowledge on SOC and MBC concentration and distribution is essential to refine soil management, thereby restoring the ecosystem. This paper quantified the effect of decades old community-based soil and water conservation (SWC) measures, mainly stone terraces, exclosure with and without stone terraces, and non-conserved communal grazing lands on the distribution of MBC and SOC stock.

**Methods:** Soil sample collection was carried out using systematic sampling design. Transects parallel to each other and to the slope of the landscape were established. In each transect, three landscape positions (i.e., upper, middle, and foot slope) were formed. Composite soil samples were taken from four corners and center of 10 m × 10 m plot of each slope positions under the different SWC measures. Analysis of variance was used to determine the difference in SOC and MBC using SAS 9.2.

**Results:** Total soil organic carbon concentration was significantly higher in exclosures as compared to terraces and non-conserved grazing lands. The highest mean value of SOC stock (29 Mg C $ha^{-1}$) was recorded in exclosures with terraces followed by exclosures without terraces (24 Mg C $ha^{-1}$) and terraces (21 Mg C $ha^{-1}$), while the lowest (16 Mg C $ha^{-1}$) was recorded in non-conserved communal grazing lands. Exclosures with terraces improved SOC stock by 64%, followed by exclosures without terraces by 37%, while terraces improved the SOC stock by 25% compared to non-conserved open communal grazing lands in the last 20 years. The upper (0–15 cm) soil depth had significantly ($P < 0.05$) higher (24 Mg C $ha^{-1}$) SOC stock than the lower (15–30 cm) soil depth (20 Mg C $ha^{-1}$). Microbial biomass carbon was the highest (640 mg $kg^{-1}$ soil) in exclosures without terraces, followed by exclosures with terraces, (570 mg $kg^{-1}$ soil), terraces (440 mg $kg^{-1}$ soil), and non-conserved communal grazing lands (370 mg $kg^{-1}$ soil).

**Conclusion:** Exclosures supported with terraces improved and restored the SOC stock and microbial biomass carbon of degraded free grazing lands in the highlands.

**Keywords:** Conservation, Ethiopia, Land degradation, Microbial biomass carbon, Soil carbon stock

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## Background

Ethiopian highlands have been degraded due to cultivation and deforestation that last for more than 2500 years [1] and around 50 percent of rural highland areas are classified as degraded [2, 3]. The process of land degradation was accelerated due to high human and livestock population pressures; and steep topography [4] in combination with the highly variable (20–40%) and unreliable rainfall, where 70–90% of the rainfall occurs during July and August [1]. The trend is mainly common in Tigray highlands in northern Ethiopia [5]. Overexploitation and mismanagement of these highlands caused serious soil erosion, loss of soil quality, and soil organic carbon [2, 4].

Stone-faced terraces, enforcement of grazing restrictions, and plantation development efforts were implemented as rehabilitation measures since 1970s [3, 6] to tackle land degradation. Majority of the farmers (75%) practice terrace construction on their land [7]. Exclosures have also been important rehabilitation measures to increase biomass production [8].

Area closures (exclosures) were established in the region since 1991 to improve biomass production [9]. They are implemented on biophysically degraded communal grazing lands [8]. Exclosures reduce soil disturbance by decreasing grazing pressure and restricting people's access of uncontrolled cutting of trees and grass for fuel and fodder [10].

Soil management and conservation practices influence soil health through their effect on soil microbiota [11, 12]. Organic carbon and microbial biomass are among the biological indicators describing soil health [13].

Soil organic carbon contains two times as much carbon as the atmosphere and 2.5 times as that of soil biota [14]. It plays a significant role in soil functioning and the global carbon cycle [15] mainly by reducing atmospheric carbon dioxide, and helps to alleviate the problem of global warming and climate change [16]. It also supports biological activity and dictates the physical properties of soil that determine its resistance to erosion [12, 17].

The decline of SOC pool leads to soil quality degradation and reduces biomass production. The loss is enhanced by erosion and other degradation processes [18]. A practical option to increase SOC stock is through SOC sequestration and decrease soil degradation [2] by implementing hillside terraces combined with enrichment plantation in exclosures [9].

Soils and the microbes that live in them regulate the carbon storage, nutrient cycling, and climate change mitigation [19]. Soil microbial biomass (SMB) is responsive to environmental changes [20]. It indicates the soil's capacity to perform ecosystem processes [21]. It also acts as biological early indicator of changes [22, 23]. It makes up 1–5% of total SOC [24] and acts as the most active component in the biochemical process of SOC turnover [25]. A little change in SMB affects directly ecosystem stability [26].

Soil microbial biomass is more sensitive to changes in soil management compared to soil organic matter [27]. Determination of SMB can help to quantify the extent of land degradation and can provide methods for the restoration of degraded ecosystems [28]. The MBC to SOC ratios are also useful measures to manage soil organic carbon content [29].

Restoration and management of degraded lands significantly contribute to enhanced SOC [30] and MBC [31] which are considered as soil health indicators during restoration process [32]. They vary spatially under different management and plant cover [21], though studies that examine the distribution of these soil properties are limited in the area [33].

Quantifying and determining the distribution of SOC stock and MBC are important for site-specific sustainable soil management and to provide a valuable basis for subsequent measurements [15, 34]. Effective carbon sequestration methods can also be implemented [35]. Thus, the objective of this study was to determine the effect of community-based SWC measures mainly terraces and exclosures on distribution of SOC stock and microbial biomass carbon.

The research questions considered include (1) Did the development of terraces on free grazing lands increase concentration of SOC, SOC stock, and microbial biomass carbon? (2) Did the protection of free grazing lands through exclosures significantly increase concentration of SOC, SOC stock, and microbial biomass carbon? (3) Could the support of exclosures with physical SWC measures bring a significant increase in concentration of SOC, MBC, and SOC stock?

## Methods

### Description of the study area

The study was conducted in Degua Temben district, which is located 50 km west of Mekelle, regional capital of Tigray region, northern Ethiopia. Geographically, it is located at 13°16′23″ to 13°47′44″ Latitude and 39°3′17″ to 39°24′48″ Longitude (see Fig. 1).

The lithology of the study area comprises Mesozoic sedimentary rocks and Tertiary basalt [36]. Soils of the study sites are developed from calcium carbonate-rich parent material of the Agula shale formation, which consists mainly of marble and limestone [37]. According to world reference base [38] soil classification system, *Calcaric Cambisols*, *Vertic Leptosols*, *Vertic Cambisols*, and *Lithic Leptosols* are the dominant soil types.

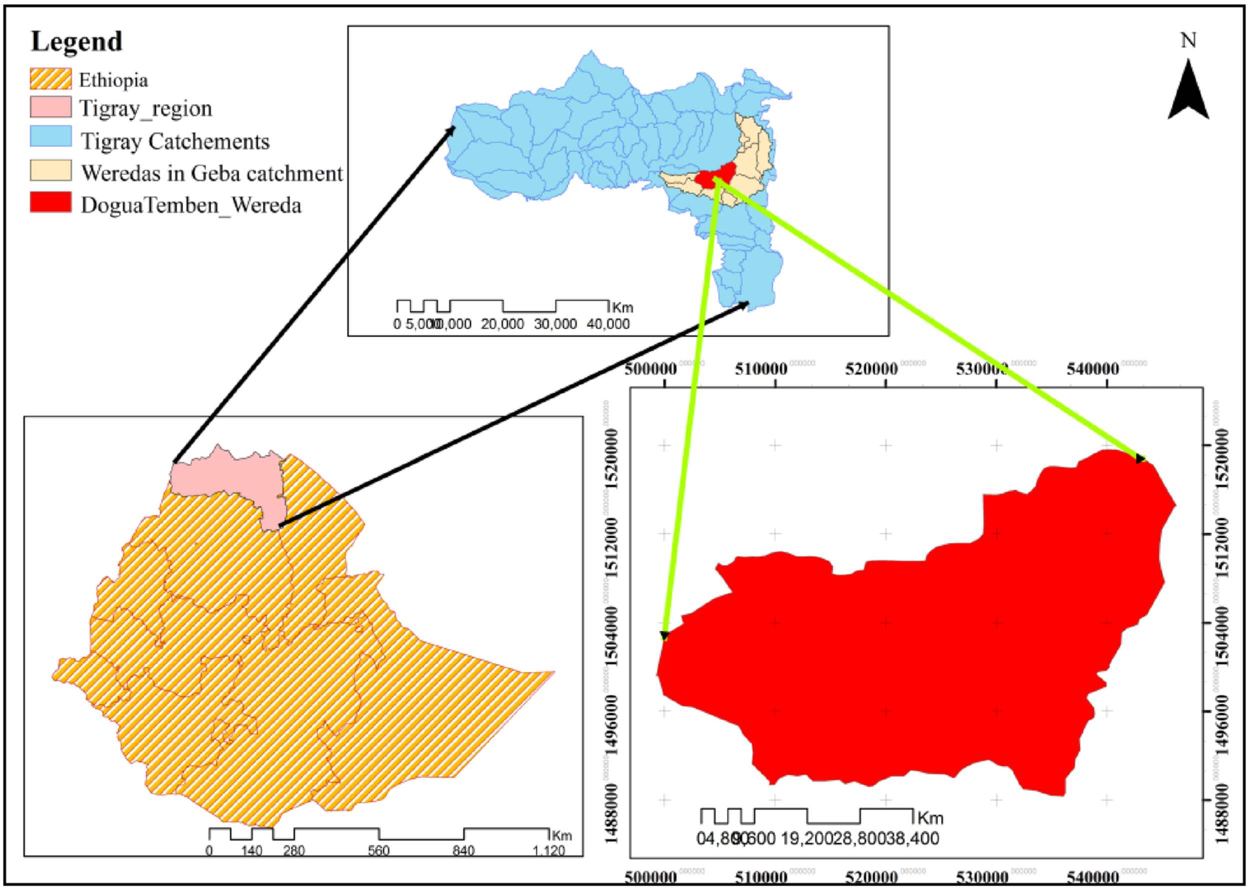

**Fig. 1** Location map of the study area

The area receives annual rainfall of 290–900 mm year$^{-1}$ with an average value of 615 mm year$^{-1}$. The main rainy season is June–August and stops in September. All the study sites are classified as mid-altitude (1800–2200 m above sea level) according to the traditional agro-climate classification system of the country.

*Acacia etbaica*, *Carissa edulis*, *Dodonaea angustifolia*, *Stereospermum kunthianum*, *Rhus Vulgaris,* and *Euclea racemosa* are commonly found woody vegetation species in exclosures and in communal grazing lands. The understory vegetation is also dominated by a diverse assemblage of grass and herbs which are palatable to livestock.

Mixed farming system (crop and livestock) is the main of livelihood in the study area. Cultivated lands, forest land, exclosure, and communal grazing lands are the major land uses. Barley (*Hordeum vulgare*), tef (*Eragrostis tef*), wheat (*Triticum aestivum*), and Maize (*Zea mays*) were the major crops in the area.

The site was selected, because it has an extensive exclosures system and terraces [9] with comparable edaphic and topographic features. The common community-based soil and water conservation measures (CBSWC) were terraces and exclosures. These soil and water conservation measures were accepted and practiced by the community for more than two decades.

## Characteristics of the main community-based SWC measures

The most commonly accepted and practiced SWC measures (i.e., terraces and exclosures with and without terraces) were established since 1997 by the community. Many of the SWC structures constructed are fully owned by the communities. This has contributed towards ensuring their sustainability [39]. Before their establishment, the selected conserved with CBSWC grazing lands had similar history in terms of grazing with the non-conserved communal grazing lands.

Each of the three selected sites (Kerano, Tesemat, and Alasa) was categorized into four management units described as terraced grazing land, exclosure with terrace, exclosure alone, and non-conserved open communal grazing land. Exclosure with terrace is restricted from the interference of animals, biological and physical SWC measures, mainly stone terraces were commonly implemented in exclosures. Accumulation of sediment, grasses, and litter fall was common on terraces. More woody species are observed compared to the other SWC measures.

In the case of exclosures without SWC, there was no interference of human and livestock. Besides, no other management practices such as physical structures were observed. Trees regenerate naturally and hence have a better vegetation cover than terraced open grazing lands. Erosion types such as sheet, rill, and gully formation are relatively less common compared to terraces and non-conserved communal grazing lands.

The stone terraces in grazing lands were selected as the third management unit, because they are relatively more stable and durable measures than other physical SWC measures. Terraced grazing lands had more accumulated sediments, organic matter, and vegetation cover. Sheet, rill, and gully erosion are less common compared to the open communal grazing lands.

The open, non-conserved communal grazing land was characterized by the low vegetation cover and higher proportions of bare soil with high stone cover. Sheet, rill, and gully erosion were common. It is assumed that the terraces, exclosures, and non-conserved grazing lands had comparable initial conditions at the time of terrace construction and exclosure establishment. Changes in soil SOC and MBC are assumed to be as a consequence of terraces and exclosures establishment.

### Sampling technique and sample size

The study was conducted in three nearby sites (Kerano, Tesemat, and Alasa with in the district) and having all the SWC measures. In each SWC measures, three transects separated at a minimum distance of 75 m were established. Transects were parallel to each other and to the topography of the landscape. In each transect, three landscape positions (i.e., upper, middle, and foot slope) were established. The upper slope (US) position is the uppermost portion of each study site, and it can receive little or no overland flow but may contribute runoff to down slope areas. The middle slope (MS) position receives overland flow from the upper slope and contributes runoff to the foot slope (FS). The FS represents the lowest part of each study site, and receives overland flow from both mid and upper slopes [40].

Soil samples were collected from the top 0–15 and 15–30 cm at four corners and center of a 10 m × 10 m size plot using "*X*" sampling design from terraces, exclosure with terrace, exclosure without terraces, and from non-conserved communal grazing lands from three transects spaced at a minimum distance of 75 m [41].

A total of 108 soil samples (i.e., four conservation measures*three slope positions * three samples * three replications) from surface (0–15 cm) for microbial biomass and 216 soil samples (i.e., four conservation measures * three slope positions*three samples * two depths*three replications/sites) from surface (0–15 cm) and subsurface (15–30 cm) were collected for soil organic carbon stock determination.

### Determination of soil microbial biomass carbon

The soil samples were sieved through a 2 mm mesh to remove stones, roots, and large organic residues, and then sealed in plastic bags and stored at 4 °C. Soil microbial biomass-C (Cmic) was determined using the substrate-induced respiration (SIR) method [42]. The samples were immediately taken to the laboratory for MBC determination. In the laboratory, 100 g of the field moist soil was thoroughly mixed with 400 mg glucose, and 20 g of the mixture was weighed to four nylon bags. Each bag was mounted into a 500 ml laboratory bottle filled with 20 ml 0.1 M NaOH solution. The bottles were immediately closed with gas-tight caps, and incubated 4 h at 22 °C together with two blanks (without soil samples) for each sample group.

After incubation, the soil samples were immediately removed from the bottles and the absorbed $CO_2$ was precipitated as barium carbonate by adding 2 ml of 0.5 M barium chloride solution. The remaining sodium hydroxide was titrated against 0.1 M HCl using 3–4 drops of phenolphthalein solution as indicator. The result was calculated according to Schuman et al. [43] (Eq. 1):

$$\mathrm{mg\,CO_2\;100\;g^{-1}h^{-1}} = \frac{(B-S)*2.2*100}{4*\mathrm{SW}*\mathrm{dm}}, \tag{1}$$

where $B$ = mean volume of HCl consumed by blanks (ml), $S$ = mean volume of HCl consumed by samples (ml), 4 = Incubation time (h), 100 = conversion factor (100 g dm), 2.2 = conversion factor (1 ml 0.1 M HCl corresponds to 2.2 tolerant mg $CO_2$), SW = initial soil weight (g), dm = soil dry matter (%). Assuming a respiratory quotient of 1.1 mg $CO_2$, 0.100 $g^{-1}$ dm. $h^{-1}$ corresponds to 20.6 mg biomass-C 0.100 $g^{-1}$ dm. Thus, this factor was used to convert the $CO_2$ into MBC.

### Determination of total organic carbon, bulk density, and coarse fragment

Total organic carbon was determined by the wet digestion using potassium dichromate [44]. The microbial quotient was determined as the ratio of MBC/SOC ratio after converting the percentage of SOC carbon into mg 100 $gm^{-1}$ dry soil. Bulk density was determined by core method. Coarse fragment was determined as percentage weight of soil greater than 2 mm.

### Determination of soil organic carbon stock

The carbon held in the upper profile is often the most chemically decomposable, and the most directly exposed to natural and anthropogenic disturbances [45]. Therefore, soil organic carbon pool was estimated up to the depth of 30 cm in this study.The data for SOC pool were calculated using the following equation:

$$\text{SOC stock} = \text{SOCi} * \text{BD} * \text{di} * (1 - \text{CFi})/100, \quad (2)$$

where SOCi = soil organic carbon of a given soil depth, Mg C $ha^{-1}$; BD (Bulk density) = soil mass per sample volume, kilogram soil $m^{-3}$ (equivalent to kg $m^{-3}$); di = horizon depth or thickness of soil layer, m; CFi = % volume of coarse fragments/100, dimensionless. The rate of change of total organic carbon and SOC stock over time was computed by subtracting the stocks of free grazing land from that of terraces and exclosures and dividing it by the number of years, since the terraces and exclosures were established.

### Data analysis

The mean, minimum, maximum, standard error, and coefficient of variation (CV) were determined using descriptive analysis of the original data variables. The significance of the difference between means of each SOC, MBC, and MBC/SOC ratio variable for different SWC measures was carried out by the analysis of variance (ANOVA) using SAS 9.2 [46]. A pairwise mean comparison was done by Duncan Least Significant Difference (LSD). Pearson correlation coefficient was also used for observing any associations between the parameters.

## Results

### Soil bulk density and organic carbon concentration among the community-based soil and water conservation measures

There was a significant ($P < 0.05$) variation in SOC among the soil and water conservation measures specifically between exclosures, and grazing lands with and without terraces. The highest mean value of SOC (2.9%) was found on exclosures supported with terraces followed by exclosures without terraces (2.8%) and terraces (2.5%), respectively (Table 1). The lowest mean value of SOC (1.9%) was found in non-conserved communal grazing lands. The SOC content followed the order exclosures > stone terraces > non-conserved open communal grazing lands.

Free grazing lands and terraced land had relatively higher BD as compared to both types of exclosures (Table 1). The bulk density of the area was in the order of exclosures without terraces < exclosures with terraces < terraces alone < non-conserved communal grazing lands. The coefficient of variation (CV) for SOC and BD along the different SWC measures was between 17 and 27% for organic carbon and 10–18% for BD, respectively (Table 2). Non-conserved grazing lands had relatively higher percentage of coarse fragments, while exclosures with terraces had significantly lower percentage of coarse fragments as compared to the other soil and water conservation measures (Table 1).

### Effect of soil depth and slope position on total soil organic carbon and bulk density

Soil depth resulted in a significant variation in SOC content (Table 3). The upper soil layer (0–15 cm depth) had significantly ($P < 0.05$) higher SOC than the lower one (15–30 cm depth). Soil BD was relatively lower in the upper than lower soil depth. On the other hand, coarse fragment was relatively higher on the upper than lower soil depth. The total SOC and BD in response to soil depth had a coefficient of variation between 20 and 26% for organic carbon and 14 for BD (Table 4), which is a moderate variation. In most of the community-based SWC measures, BD and SOC showed inconsistent variation among slope positions with some increasing trend at lower slope position (Table 5).

### Distribution of soil organic carbon stock along the community-based soil and water conservation measures

The SOC stock (Mg $ha^{-1}$) in exclosures was significantly higher ($P < 0.05$) as compared with the other SWC measures (Table 1). Exclosures with terraces had the highest

**Table 1 Effect of community-based soil and water conservation measures on soil properties (Mean ± SEM)**

| Soil properties | Non-conserved grazing lands | Terraces | Exclosures + terraces | Exclosures alone |
|---|---|---|---|---|
| SOC (%) | $1.9 \pm 0.1^c$ | $2.5 \pm 0.1^b$ | $2.9 \pm 0.1^a$ | $2.8 \pm 0.1^a$ |
| Bulk density (kg $m^{-3}$) | $1280 \pm 32^a$ | $1260 \pm 28^a$ | $1240 \pm 21^a$ | $1220 \pm 48^a$ |
| Coarse fragment (%) | $57.6 \pm 0.2^b$ | $53.2 \pm 0.2^b$ | $47.4 \pm 0.2^a$ | $54.4 \pm 0.2^b$ |
| SOC stock (Mg $ha^{-1}$) | $16.0 \pm 1.0^c$ | $21.0 \pm 1.3^b$ | $29.0 \pm 1.4^a$ | $24 \pm 1.3^b$ |

Means followed by the same letter along each column do not differ significantly at $P \leq 0.05$

**Table 2 Summary of statistics for SOC, bulk density, and SOC stock in response to SWC measures**

| SWC | Variable | Mean | Median | Minimum | Maximum | Std Error | CV | Skewness | Kurtosis |
|---|---|---|---|---|---|---|---|---|---|
| Non-conserved grazing land | Organic carbon (%) | 1.9 | 2.1 | 0.7 | 3.2 | 0.1 | 27 | − 0.4 | 0.2 |
| | Bulk density (kg $m^{-3}$) | 1284 | 1362 | 770 | 1497 | 25 | 14 | − 0.9 | 0.0 |
| | SOC stock (Mg $ha^{-1}$) | 16 | 16 | 3 | 31 | 1.0 | 45 | 0.2 | − 0.7 |
| Terracing | Organic carbon (%) | 2.5 | 2.5 | 1.3 | 3.6 | 0.1 | 17 | 0.0 | 0.5 |
| | Bulk density (kg $m^{-3}$) | 1260 | 1288 | 850 | 1485 | 21 | 12 | − 0.9 | 0.4 |
| | SOC stock (Mg $ha^{-1}$) | 21 | 21 | 6 | 40 | 1.0 | 37 | 0.1 | 0.0 |
| Exclosure + terracing | Organic carbon (%) | 2.9 | 2.9 | 1.3 | 3.8 | 0.1 | 20 | − 0.4 | 0.4 |
| | Bulk density (kg $m^{-3}$) | 1244 | 1250 | 1011 | 1579 | 18 | 10 | 0.3 | − 0.4 |
| | SOC stock (Mg $ha^{-1}$) | 29 | 29 | 9 | 43 | 1.0 | 27 | − 0.3 | − 0.5 |
| Exclosure | Organic carbon (%) | 2.8 | 2.8 | 1.5 | 3.8 | 0.1 | 18 | − 0.4 | 0.1 |
| | Bulk density (kg $m^{-3}$) | 1220 | 1308 | 690 | 1491 | 30 | 18 | − 0.9 | − 0.1 |
| | SOC stock (Mg $ha^{-1}$) | 24 | 23 | 8 | 52 | 1.0 | 39 | 0.7 | 0.6 |

SOC stock (29 Mg $ha^{-1}$) followed by exclosures without terraces (24 Mg $ha^{-1}$).

Stone terraces had significantly ($P < 0.05$) higher SOC stock (21 Mg $ha^{-1}$) than non-conserved communal grazing lands (16 Mg $ha^{-1}$). Comparison of the effect of soil depth on soil organic carbon stock (Table 3) also showed significantly higher (24 Mg $ha^{-1}$) in the upper (0–15 cm) and was lower (20 Mg $ha^{-1}$) in the lower (15–30 cm) soil depth.

Soil organic carbon stock in the different soil and water conservation measures (Table 2) had a coefficient of variation ranging from 27 to 45% which lies under the moderate variability category. The CV for soil organic carbon stock ranged between 38 and 43% in the upper and lower depths, respectively (Table 4), which is also considered to be moderate variation in response to soil depth.

### Distribution of soil microbial biomass carbon along the community-based soil and water conservation measures

Exclosures had significantly higher MBC than terraces and non-conserved communal grazing lands (Table 6). The highest value of MBC (640 mg $kg^{-1}$ dry soil) was found in exclosures without terraces followed by exclosures with terraces (570 mg $kg^{-1}$ dry soil) and terraces (440 mg $kg^{-1}$ dry soil), respectively (Table 6). The lowest MBC (370 mg $kg^{-1}$ dry soil) was recorded in non-conserved communal grazing lands. The microbial biomass was in the order of exclosures without terraces > exclosures with terraces > terraces > non-conserved communal grazing lands.

**Table 3 Effect of soil depth on total SOC, bulk density, coarse fragment, and SOC stock (Mean ± SEM)**

| Soil parameters | Depths (cm) | |
|---|---|---|
| | 0–15 cm | 15–30 cm |
| Organic carbon (%) | 2.8 ± $0.1^{a}$ | 2.2 ± $0.1^{b}$ |
| Bulk density (kg $m^{-3}$) | 1244 ± $23^{a}$ | 1258 ± $25^{a}$ |
| Coarse fragment (%) | 55 ± $1.0^{a}$ | 52 ± $2.0^{a}$ |
| Soil carbon stock (Mg $ha^{-1}$) | 24 ± $1.0^{a}$ | 20 ± $1.0^{b}$ |

Means of each soil parameter followed by the same letter along each column do not differ significantly at $P \leq 0.05$

The microbial quotient was higher in exclosures than terraces and non-terraced communal grazing land (Table 6). It was higher in exclosures without terraces than exclosures with terraces.

Microbial biomass contents were inconsistent and not significant along the three slope positions of the SWC measures. However, the highest (720 mg $kg^{-1}$) MBC was found at foot slope in exclosures without terraces, while the lowest (370 mg $kg^{-1}$) was found at upper slope in non-conserved communal grazing lands (Table 7). As indicated in (Table 8), the CV value for MBC in response to SWC ranged 15–43% which is a moderate variability

## Discussion

Exclosures with terraces had significantly higher SOC as compared to the other SWC measures, which could be due to low disturbance, better vegetation cover, and deposition of soil materials. Stone terraces when supported with vegetation enhance soil organic matter accumulation as compared to non-supported ones [47]. Returns of biomass and reduced erosion in exclosures enhanced SOC concentration in arid environments [43, 48].

The presence of significantly lower SOC concentration in non-conserved grazing lands could be due to the fact that grazing reduces vegetation cover and primary production, which in turn exposes the soil to increased erosion losses and reduced carbon inputs [41]. Grazing lands

**Table 4 Summary of statistics for total SOC, bulk density, and SOC stock in response to soil depth**

| Depth (cm) | Variable | Mean | Median | Minimum | Maximum | Std error | CV | Skewness | Kurtosis |
|---|---|---|---|---|---|---|---|---|---|
| 0–15 | Organic carbon (%) | 2.8 | 2.8 | 1.3 | 3.8 | 0.1 | 20 | 0.0 | – 0.5 |
| | Bulk density (kg $m^{-3}$) | 1258 | 1275 | 740 | 1579 | 17 | 14 | – 1.0 | 1.0 |
| | SOC stock (Mg $ha^{-1}$) | 24.2 | 23.2 | 5.8 | 52 | 0.1 | 38 | 0.3 | -0.3 |
| 15–30 | Organic carbon (%) | 2.3 | 2.3 | 0.7 | 3.7 | 0.1 | 26.2 | 0.4 | 0.0 |
| | Bulk density (kg $m^{-3}$) | 1247 | 1260 | 690 | 1483 | 17 | 14 | – 0.7 | 0.1 |
| | SOC stock (Mg $ha^{-1}$) | 20 | 21 | 3 | 42 | 1.0 | 43 | 0.2 | – 0.4 |

**Table 5 Effect of slope position on SOC concentration, SOC stock, and soil bulk density (Mean ± SEM)**

| SWC measures | Soil parameter | Slope positions | | |
|---|---|---|---|---|
| | | Foot slope | Middle slope | Upper slope |
| Non-conserved grazing lands | SOC (%) | $1.9 \pm 0.1^{c}$ | $2.1 \pm 0.1^{ce}$ | $1.7 \pm 0.1^{c}$ |
| | Bulk density (kg $m^{-3}$) | $1199 \pm 40^{bcd}$ | $1310 \pm 40^{ad}$ | $1315 \pm 40^{a}$ |
| | SOC stock (Mg $ha^{-1}$) | $18 \pm 2^{ac}$ | $15 \pm 2^{c}$ | $15 \pm 2^{c}$ |
| Terraces | SOC (%) | $2.6 \pm 0.1^{abd}$ | $2.4 \pm 0.1^{bd}$ | $2.4 \pm 0.1^{de}$ |
| | Bulk density(kg $m^{-3}$) | $1262.9 \pm 40^{abcd}$ | $1276.6 \pm 40^{acd}$ | $1240.8 \pm 40^{abcd}$ |
| | SOC stock (Mg $ha^{-1}$) | $22 \pm 2^{ab}$ | $20 \pm 2^{ac}$ | $22 \pm 2^{ab}$ |
| Exclosures + terraces | SOC (%) | $2.9 \pm 0.1^{a}$ | $2.8 \pm 0.1^{a}$ | $2.9 \pm 0.1^{a}$ |
| | Bulk density(kg $m^{-3}$) | $1218 \pm 40^{abcd}$ | $1233 \pm 40^{abcd}$ | $1231 \pm 40^{abcd}$ |
| | SOC stock (Mg $ha^{-1}$) | $31 \pm 2^{de}$ | $26 \pm 2^{bde}$ | $30 \pm 2^{e}$ |
| Exclosures alone | SOC (%) | $2.7 \pm 0.1^{a}$ | $2.7 \pm 0.1^{ab}$ | $2.8 \pm 0.1^{ab}$ |
| | Bulk density (kg $m^{-3}$) | $1315 \pm 40^{a}$ | $1162 \pm 40^{b}$ | $1184 \pm 40^{bc}$ |
| | SOC stock (Mg $ha^{-1}$) | $25 \pm 2^{bd}$ | $22 \pm 2^{ab}$ | $23 \pm 2^{ab}$ |

Means of each soil parameter followed by the same letter do not differ significantly at $P \leq 0.05$

**Table 6 Effect of community-based SWC measures on total values of MBC and MBC/SOC ratio (Mean ± SEM)**

| SWC measures | MBC (mg $kg^{-1}$ soil) | MBC/SOC (%) |
|---|---|---|
| Non-conserved grazing lands | $370 \pm 10^{b}$ | $1.9 \pm 0.1^{a}$ |
| Terraces | $440 \pm 30^{b}$ | $1.8 \pm 0.2^{a}$ |
| Exclosures with terraces | $570 \pm 40^{a}$ | $2.1 \pm 0.1^{a}$ |
| Exclosures without terraces | $640 \pm 50^{a}$ | $2.3 \pm 0.2^{a}$ |

Means followed by the same letter across each row do not differ significantly at $P \leq 0.05$

**Table 7 Effect of slope position on microbial biomass carbon (mg $kg^{-1}$ soil) (Mean ± SEM)**

| SWC measures | Slope positions | | |
|---|---|---|---|
| | Foot slope | Middle slope | Upper slope |
| Non-conserved grazing lands | $380 \pm 70^{bc}$ | $350 \pm 70^{b}$ | $370 \pm 70^{bc}$ |
| Terraces | $460 \pm 70^{abc}$ | $450 \pm 70^{abc}$ | $400 \pm 70^{abc}$ |
| Exclosures + terraces | $550 \pm 70^{acd}$ | $560 \pm 70^{ad}$ | $580 \pm 70^{ad}$ |
| Exclosures without terraces | $720 \pm 70^{d}$ | $560 \pm 70^{ad}$ | $640 \pm 70^{d}$ |

Means followed by the same letter do not differ significantly at $P \leq 0.05$

with terraces had higher SOC than non-conserved communal grazing lands. This could show that terraces store more organic carbon from the materials that they trap during deposition. Amdemariam et al. [49] reported high SOC in conserved fields compared to non-conserved fields in north western part of Ethiopia. Similarly, Hishe et al. [50] found higher SOC in conserved land scape than non-conserved landscape in Suluh valley of northern highlands Ethiopia. These results indicated practicing soil conservation measures improved soil organic carbon [49].

Non- conserved grazing lands had relatively higher bulk density as compared to exclosures and terraces. This is in line with the result reported by Mekuria and Veldkamp [49], where non-conserved fields exhibit higher mean BD than the conserved fields. This could be due to low soil organic carbon and high soil compaction by livestock grazing in non-conserved open communal grazing lands. The results of other studies also clearly showed the important role of organic matter for rehabilitating degraded soils by improving other soil properties [51, 52]. The BD decreased 1.28–1.26 g $cm^{-3}$ due to terrace

**Table 8 Summary statistics on analysis of MBC (mg $kg^{-1}$ soil) in response to SWC measures**

| SWC | Mean | Median | Minimum | Maximum | Std error | CV | Skewness | Kurtosis |
|---|---|---|---|---|---|---|---|---|
| Non-conserved grazing lands | 370 | 370 | 210 | 460 | 10 | 15 | −1 | 1 |
| Terraces | 440 | 450 | 170 | 790 | 30 | 35 | 0.6 | 0.8 |
| Exclosures + terraces | 560 | 520 | 250 | 1250 | 40 | 38 | 1 | 2.5 |
| Exclosures without terraces | 640 | 630 | 210 | 1250 | 50 | 43 | 0.3 | −0.5 |

construction and 1.28–1.22 g $cm^{-3}$ due to exclosure establishment. Mureithi et al. [32] found that, on average, exclosures lowered the BD of top soil from 1.48 to 1.19 g $cm^{-3}$ in range lands of Kenya. Mean value for BD varied from 1.12 g $cm^{-3}$ (in exclosure) to 1.34 g $cm^{-3}$ (in grazing land) in nearby site [4].

Soil organic carbon and BD had CV values 17–27% and 10–18%, respectively. This indicated that they have moderate variation in response to the SWC measures. Because CV of less than 10% has weak variability, CV between 10 and 100% is considered as moderate variability, while CV with higher than 100% is considered as strong variability [53].

The upper soil depth (0–15 cm) had significantly higher SOC than lower (15–30 cm) soil depth. This could indicate the presence of easily decomposable biomass in the upper soil depth. It was found that high SOC at surface soil is due to the input of organic matter from above-ground biomass [34]. Other studies reported that soil organic carbon is mainly formed by the decomposition of plant materials in the soil surface. Soils of Bale Mountains in southeastern Ethiopia showed similar results [54].

A rough and non-consistent increase in SOC was observed at foot slope which could be due to removal of materials from upper slope position and deposition in lower slope positions. Similarly, Mekuria and Veldkamp [48] in northern highlands of Ethiopia and Amare et al. [51] in Anjeni Watershed in central highlands of Ethiopia found higher SOC in lower and depositional zone than upper and loss zones.

Though not consistent in all the SWC measures, a lower bulk density was observed at the foot slope position. This is probably due to increase in SOC down slope. Increase in SOC is one cause for decrease in bulk density [50].

Soil organic carbon stocks are a function of the concentration SOC, soil thickness considered, soil BD, and coarse fragment. The coarse fragment was included as a correction factor to exclude materials that are assumed to have no soil organic carbon. Soil organic carbon stock decreased with increasing depth due to decrease in organic carbon concentration and gravel content. Gravel content and SOC affect SOC stock [34, 55]. The total SOC for the whole 30 cm soil depth was 44 Mg C $ha^{-1}$. Similarly, a total of 74 Mg C $ha^{-1}$ SOC stock was reported in the top 40 cm in exclosure in a nearby site, which indicated the importance of such restoration measures in addressing SOC depletion in the area [4].

Conversion of free grazing lands to exclosures and supporting with terraces increased SOC stock by 64%, exclosures without terraces by 37% and terraces by 25%. Exclosures increased SOC stock by more than 50% [41]. Protected grasslands contributed to significant carbon sequestration [56]. Increased SOC stock is related to the restoration of natural vegetation, which enhances above-ground and below-ground litter inputs [9, 57]. It was observed in both exclosures types, the canopy of shrubs and under-story vegetation has been restored, and the soil surface is, therefore, protected from erosion [58]. Vegetation restoration and litter accumulation in exclosures significantly increased plant–soil system carbon storage and sequestration [57].

The presence of significantly higher MBC in exclosures could be due to fewer disturbances, which encouraged enrichment of the microbial biomass carbon. The existence of better vegetation cover in exclosures protects the soil from erosion to maintain favorable conditions for microbial growth [27]. High MBC indicated high efficiency of carbon utilization and increase in ecosystem maturity and vice versa [42]. High MBC can also be used as bio-indicator for the recovery of degraded soils [27]. Thus, high MBC in exclosures indicate that they had the potential for the restoration of soil quality [32].

The low MBC in non-conserved communal grazing lands indicates that there is inefficient utilization of carbon by microbes, which could be due to stress such as grazing and soil compaction by livestock. It was also found that erosion had a more severe disturbance to soil microbial biomass [59]. This caused for the loss of carbon in the form of carbon dioxide [60]. Similarly, Gelaw et al. [61] in a nearby site found that environmental disturbance was the main cause for the decrease in microbial biomass carbon.

The MBC/SOC ratio represents the contribution of microbial biomass to organic carbon in soil and is a more useful assessment index for soil health than either MBC or SOC [62]. The MBC/SOC was low in exclosures and terraces than non-conserved communal grazing lands. However, this is in contrast to the report of Anderson and Domsch [42] who found high MBC/SOC in fields with high total organic carbon. This could be due to woody biomass and litter in exclosures with terraces and terraced grazing lands, which is relatively resistant microbial decomposition. In a similar study, the MBC/SOC ratio at 0–15 cm decreased with increasing woody plant stand from 6% in grasslands to 4% in older woodlands, suggesting that woody litter may be less suitable as a microbial substrate compared with grassland litter [63]. Decline of MBC/SOC meant the decrease of available organic matter in soils [64]. Thus, the contribution of MBC to soil organic carbon was relatively lower in exclosures with terraces compared to exclosures without terraces; and in terraced grazing lands than non-conserved communal grazing lands.

### Relationship among soil properties

The strong and significant ($P<0.01$) correlation between SOC stock, SOC concentration, and coarse fragment indicated SOC concentration and coarse fragment (Table 9) are important factors that affect SOC stock. Strong and significant ($R^2=0.87$, $P<0.01$) correlation was found between MBC and MBC/SOC, which indicated that MBC has good contribution to SOC concentration and SOC stock. However, SOC was negatively correlated with bulk density. This is in line with similar study done in south Gonder, northwestern highlands of Ethiopia, [47] and in Middle Sulluh Valley, northern Ethiopia [50]. Soil organic carbon was also negatively and significantly ($R^2=-0.1$, $P<0.01$) correlated with MBC to SOC ratio. This could be either the soil organic matter source is resistant or poor quality or the microbes are weak to decompose the organic matter source.

**Table 9 Correlation coefficient between the soil properties (n = 108)**

| | MBC | SOC | MBC/SOC | BD | Coarse fragment |
|---|---|---|---|---|---|
| MBC | 1 | | | | |
| SOC | 0.39** | 1 | | | |
| MBC/SOC | 0.87** | $-0.1^{ns}$ | 1 | | |
| BD | $-0.11^{ns}$ | − 0.19* | − 0.02 | 1 | |
| Coarse fragment | $0.21^{ns}$ | $0.11^{ns}$ | 0.19 | $-0.03^{ns}$ | 1 |
| SOC stock | 0.32** | 0.56** | $0.07^{ns}$ | 0.26** | 0.76** |

*ns* correlation is not significant

* Correlation is significant at $P \leq 0.05$

** Correlation is significant at $P \leq 0.01$ confidence interval

## Conclusion

The different SWC measures had brought a significant impact on the ability of the soil to sequester SOC and microbial biomass carbon. Exclosures had higher soil organic carbon stock and MBC compared to terraces and non-conserved open communal grazing lands. Soil depth is an important factor that affects SOC concentrations, because it was observed that upper soil depth had higher SOC than lower soil depth, which could be due to the fact that biotic processes like biomass production, decomposition, and above-ground litter are higher in upper soil depth. Soil organic carbon concentration, bulk density, and percentage of coarse fragment had also brought a significant variation in the SOC stock. Establishment of exclosures and construction of terraces in the open communal grazing lands had a positive impact in terms of SOC stock and microbial biomass carbon storage.

#### Abbreviations

SOC: soil organic carbon; MBC: microbial biomass carbon; CBSWC: community-based soil and water conservation; BD: bulk density; Mg C ha$^{-1}$: mega gram carbon per hectare; CF: coarse fragment.

#### Authors' contributions

MW was a Ph.D. student in soil science and participated in proposing the study, ran and managed all experiments, conducted all laboratory analyses performed statistical analyses and interpretation results, and drafted the manuscript. FK and BB as supervisors participated in guiding and reviewing the manuscript. EB was supervisor and participated in designing the field experiment and reviewed the manuscript. All authors read and approved the final manuscript.

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#### Competing interests

The authors declare that they have no competing interests.

#### Availability of data and materials

Additional data may be available on request to the authors; please contact corresponding author.

#### Consent for publication

The other authors in this study were supervisors to the corresponding author and provided their consent to publication of this work.

#### Ethics approval and consent to participate

The authors declare that this study does not involve human subject's material and human data.

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