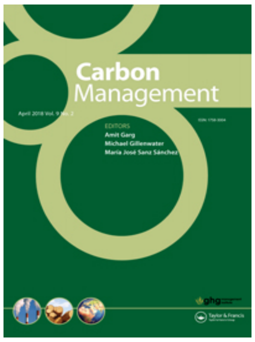

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Effects of integrated soil and water conservation measures on soil aggregate stability, soil organic matter and soil organic carbon stock of smallholder farmlands in semi-arid Northern Ethiopia

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ABSTRACT

Soil and water conservation (SWC) measures such as stone bunds and trenches integrated with fodder species (ISWC) have been implemented to tackle soil erosion in Ethiopian highlands. However, effects of ISWC measures on soil aggregate stability (SAS) and soil organic carbon stocks (SOCS) have been less studied. Fifteen disturbed composite and 15 undisturbed soil samples were collected from cropland sites treated with ISWC measures, SWC structures alone and no SWC measures (NSWC). Results revealed that mean values of stability index (SI) and stability quotient (SQ) are: 15 and 712 for sites with ISWC measures, 8 and 268 for sites with SWC structures alone and 6 and 187 for sites with NSWC measures. The SOCS (t ha-1) and SOM contents are: 12.7 and 1.7% for sites with ISWC, 8.0 and 1.2% for SWC alone and 6.3 and 0.7% for NSWC. SI, SQ SOCS and SOM content are significantly higher ($p<0.01$) for cropland sites treated with ISWC compared to those with SWC alone and NSWC. However, there are insignificant differences ($p>0.05$) in SI, SQ and SOCS, between sites with SWC alone and NSWC. This study strongly suggests that, application of ISWC measures has considerable potential to enhance SAS, SOCS and SOM content.

KEYWORDS

Soil organic matter content; soil aggregate stability; soil organic carbon stock; integrated soil and water conservation measures and cropland

1. Introduction

Land degradation in developing countries such as Ethiopia has been a serious concern for its negative implications for the livelihood of the rural community and the environment on which they largely depend. Its immediate consequence is reduced crop yield, followed by economic decline and social stress [1]. High seasonal rainfall intensity together with rugged topography and low vegetation cover caused by overgrazing and deforestation as well as low soil organic matter (SOM) content increases soil susceptibility to water erosion in the Ethiopian highlands [Haile *et al.* 2006 2; 3–5]. Soil erosion and rapid soil degradation affect soil properties, undermine agricultural production and retard the economic development of the region. Moreover, several research findings confirmed that soil degradation, especially soil erosion and associated soil nutrient depletion, is the major cause of the decline of agricultural production in Ethiopia [Nyssen *et al.* 2004 [6]; 7–9]. Hence, soil and water conservation (SWC) measures in the country aim not only to control soil erosion but also to sustain agriculture and economic development of the country at large [10].

Soil erosion by water is a severe problem in the cultivated lands of the Tigray region, Northern Ethiopia, where population density is high, climate is relatively dry 9 to 10 months in a year (semi-arid climate) and agriculture is intensive due to population pressure [11; Nyssen *et al.* 2004]. Though the reported soil loss rate varies over a wide range, the average estimated soil erosion rate from cropland of the humid central Ethiopia highlands is 42 t $ha^{-1}y^{-1}$ [10,12]. To address soil erosion challenges, the regional government of Tigray and local and international development agencies have invested in substantial resource management and in [6] promoting soil conservation practices to improve soil fertility and ensure sustainable agricultural production. Several SWC technologies with different implementation approaches such as food for work, cash for work, a safety net program and, more recently, based on free labor contribution by the local farmers have focused on the highlands of the country where the problem is more threatening to the sustainability of agriculture and the natural resources [10].

The implemented SWC measures improve soil properties such as soil aggregate stability (SAS), soil organic matter (SOM) content and soil organic carbon stock (SOCS) [13,14]. However, most of the SWC measures implemented in croplands, with a few exceptions, are only physical structures – mainly stone bunds, soil bunds and trenches in the study area.

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Most farmers invest in SWC measures for short-term benefits, while most of the implemented physical measures yield relatively long-term agricultural benefits such as increased production and environmental benefits such as restoration of soil fertility, reduced siltation and increased recharge to the ground water (Adgo *et al*. [15]).

In view of this one may ask questions related to the short-term environmental benefits of integrated soil and water conservation (ISWC) measures (a combination of physical and biological measures) being implemented together on the same cropland at the study area. ISWC measures significantly reduce the soil erosion rate [16] and thereby improve soil properties for enhanced agricultural productivity [17,18]. However, the effects of stone bunds and trenches integrated with fodder species such as *Leucaena leucocephala* and *Sesbania sesban* on soil properties in cropland is less understood in the semi-arid Tigray region of Northern Ethiopia. It is hypothesized that the implementation of ISWC measures leads to increase in SOM content, SAS and SOCS attributed to the control of wind and water erosion, enhanced inputs of SOM content, structural stability, and carbon sequestration in the form of SOCS. Therefore, this study aims to assess and better understand the effects of ISWC measures on SAS, SOM content and SOCS compared to those with SWC structures alone and without soil and water conservation measures (NSWC).

2. Methods

2.1. Study area

The study was conducted from December to June 2015 in Werie Leke district, which is located in the Tigray region of Northern Ethiopia. The district is located at 164 km from Mekelle, the capital city of Tigray region, to the north (Figure 1). It is geographically situated at 13°38′52″N (lat.) and 39°13′15″E (long.). Topography is rugged, and mountainous with an altitude that ranges from 1450 to 2350 m asl. The agro-climate of the study area is a semi-arid type locally called (*kola*) comprising about 84% and the rest is dry sub-humid (*weyna-dega*, 16%).

The annual rainfall ranges from 340 to 800 mm with an average annual rainfall depth of 570 mm and mean monthly temperature of 21 °C. Due to this high temperature, the annual potential evapotranspiration is rather large, significantly reducing crop water availability. The geologic formation of the study site is late Paleozoic–Triassic: Edaga Arbi Glacial (tillites), red Adigrat sandstone, shale and conglomerates [19,20]. The dominant soil types are Cambisol, Regosol, Luvisol, Vertisol and Arenosol [19]. The distribution of soil types is strongly influenced by topography and parent materials [21]. The largest part of the study area is covered by soils with sandy loam texture and the remaining small part is covered by soils with clay, clay loam, loamy and loamy sand textures. Topsoil is continuously

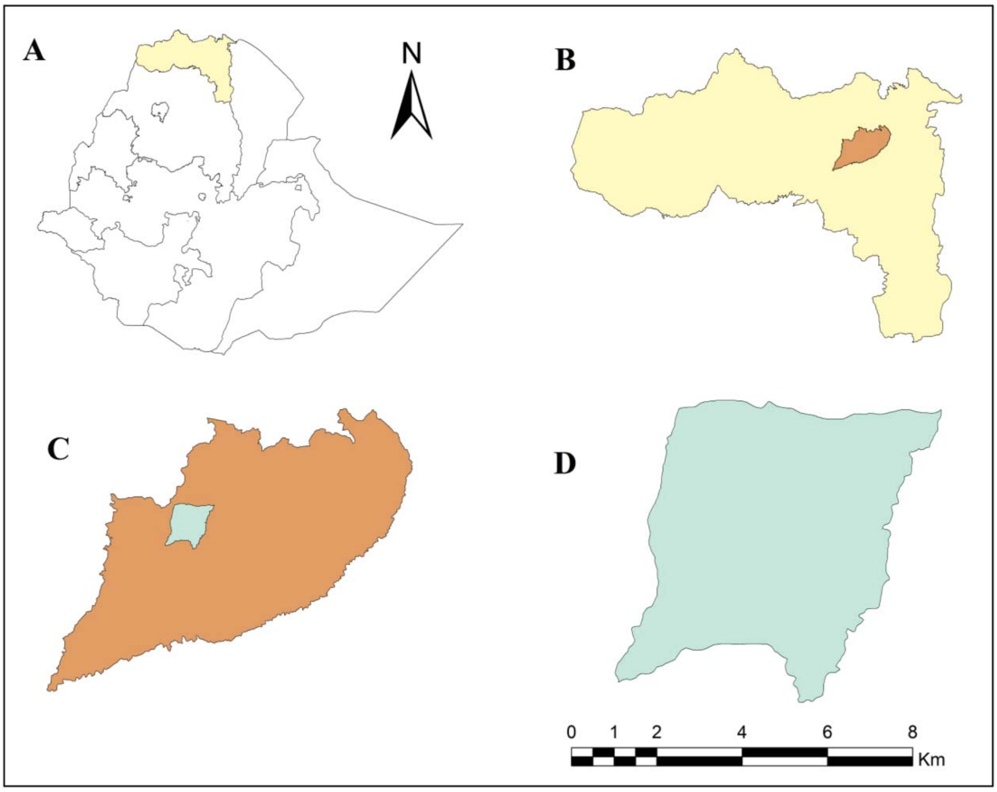

Figure 1. Location of the study area: A, Ethiopia, B, Tigray indicating Werie Leke district, C, Werie Leke indicating Zongui sub-district, and D, Zongui sub-district.

eroded, by surface runoff during the rainy season and by wind during the dry season. Steep slopes of up to 33% are common in the study area, whereas the slope of cultivated land ranges from 3 to 8%. Recently, increased population pressure and the corresponding increased demand for additional croplands are increasing the rate of land-use change, with very steep slopes and marginal areas also being brought under cultivation.

The farming system of the study area is characterized as mixed, with crop production and livestock husbandry being the dominant components of the system. The interaction between the components is significant, with the crop component providing residue while the livestock component provides manure and draft power. Crop production is mainly a rain-fed and small-scale subsistence system. The majority of the croplands are cultivated to annual food crops in a rotation, including cereals such as teff (*Eragrostis tef*), barley (*Hordeum vulgare*), wheat (*Triticum* sp.) and '*Hanfets*' (a mix of wheat and barley grown together in the same field) and maize (*Zea mays*); pulses like beans and some vegetables and fruits in the irrigated land are also important components. Croplands are tilled with *ard* plow *meharesha* pulled by a pair of oxen, with tillage frequency ranging from 1 to 4 times per cropping season depending on available draft power and crop type [22].

The types of livestock in the study area are cattle, goats, sheep, equines, poultry and bee colonies. The dominant tree and shrub species are *Faidherbia albida*, *Acacia etbaica*, *Dichrostacys cihareal*, *Dodonaea angustifolia*, *Euclea schimperi*, *Ziziphus spinachristi*, *Acacia lahai*, *Croton macrostachyus*, *Luceana lucocephla* and *Sesbania sesban*. *Luceana lucocephla* and *Sesbania sesban* are common fodder species planted in the farmland integrated with SWC structures, whereas *Faidherbia albida* is grown naturally in cropland as scattered trees (parkland agroforestry).

2.2. Sampling techniques and experimental procedures

Zongui sub-district was purposely selected based on the availability of different SWC measures integrated with agroforestry fodder tree species (i.e. ISWC measures). Moreover, the selected area is best representative of different ISWC measures in the region and of SWC measures alone. A preliminary transect survey in the study area was conducted in 2015 to identify sampling plots with different treatments: plots with ISWC measures, plots with only physical SWC structures, and sites with NSWC measures implemented (Figure 2). Information regarding the history of cultivation and age of the implemented SWC measures was obtained from land users and complemented with information from Bureau of Agriculture and Natural Resources. These three sites – a site with ISWC measures, a site with SWC alone and a site with NSWC measures – are similar with respect to tillage history, fertilizer

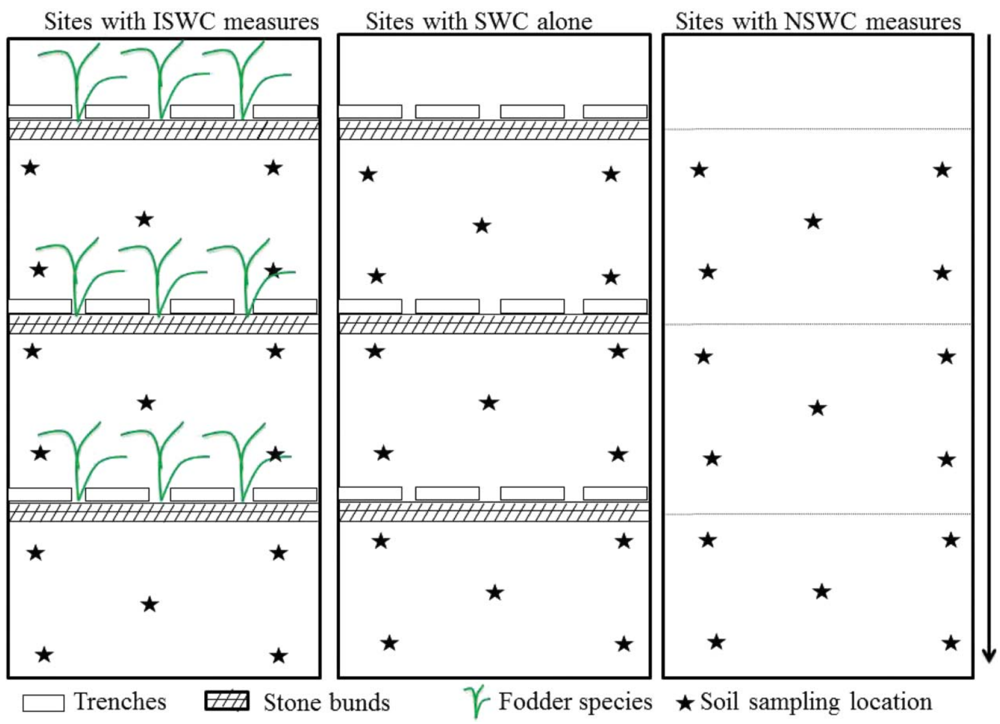

Figure 2. Illustration of experimental layout indicating a site with stone bunds and trenches integrated with fodder species (ISWC measures), a site with stone bunds and trenches alone (SWC) and cropland site with no conservation interventions (NSWC). The soil sampling locations within each soil and water conservation treatments are indicated with black stars (each group of five stars represents one composite sample) and the arrow indicates runoff direction.

applications, range of slope gradients, cropping systems and other farm management practices. However, they differ in the type of SWC measures implemented to control soil erosion rates and restore soil fertility. The two treated sites (i.e. the site with ISWC measures and the site with SWC structures alone) were treated in the 1998 soil and water conservation campaign of the region. However, there can be some minor differences in the methods and timing with which these SWC measures are being maintained, and in the cropping sequence and rotation.

A detailed description and technical standards of the implemented SWC measures (stone bunds or stone bunds and trenches) are reported by Taye *et al.* [5]. Briefly, a description of the different SWC treatments is provided as follows: ISWC measures comprise cropland sites treated with contour stone bunds and trenches where fodder tree species are planted between consecutive trenches in a row (Figure 2). In this combination, trenches were installed immediately upslope of the stone bunds for intercepting surface runoff and sediment. SWC structures alone are cropland sites treated with stone bunds and trenches. These are similar to the sites with ISWC measures but without fodder species planted between trenches. The cropland site without soil and water conservation interventions (NSWC) is similar to the other two sites in terms of slope gradient and land use but without SWC measures applied (Figure 2).

In order to understand the effect of SWC measures with and without fodder tree species on SAS, SOM content and SOCS, five disturbed composite samples were collected based on five auguring points from the top 20 cm soil depth at each site (Figure 2). The five collected samples were mixed thoroughly and one composite sample was taken for each of the five auguring points (Figure 2). Accordingly, a total of 15 composite soil samples were collected from the three sites (ISWC, SWC and NSWC) for soil laboratory analysis. In addition, 15 undisturbed soil samples were also collected from each site to determine soil bulk density (BD) using a core sampler.

2.3. Soil laboratory analysis

2.3.1. Determination of SAS

SAS to a depth of 20 cm was determined using the dry and wet sieving methods as described by De Leenheer and De Boodt [23] and Kemper and Rosenau [24]. This is because the soil aggregate stability is different under dry and wet soil moisture conditions. The mean weight diameter (MWD) on both a dry and a wet sieving basis is used to have a good understanding of the response of the soil aggregate or its stability at different soil moisture conditions. Soil samples collected from the field were air-dried and 200 g of each was sieved using sieves with mesh sizes of 8.00, 4.0, 2.8, 2.00, 1.00, 0.50 and 0.053 mm, treating the soils with and without water to obtain the aggregate-size distribution under both dry and wet soil moisture conditions. SAS was expressed using MWD, which is given by $\mathrm{MWD} = \sum_{i=1}^{n} \mathbf{Xi} * \mathbf{Wi}$, SI; $\mathbf{SI} = \frac{1}{(\mathbf{MWD\ dry} - \mathbf{MWD\ wet}}$ and by SQ, where $\mathbf{SQ} = \mathbf{SI} * \%\ \mathbf{aggregates} > 2\mathbf{mm}$, where MWD is mean weight diameter, n is the number of size fractions, Xi is the mean diameter of each sieve fraction, given by $\mathbf{xi} = \frac{\mathbf{highest\ diameter} + \mathbf{smaller\ diameter}}{2}$, Wi is the proportion of the total sample weight occurring in the i^{th} size fraction (Wi = weight of sample in each sieve to total sample weight ratio), SI is the stability index and SQ is the stability quotient.

2.3.2. Determination of soil SOM content

Soil organic carbon content was determined by the Walkley and Black method through wet oxidation of organic carbon with potassium dichromate ($K_2Cr_2O_7$) in sulfuric acid [25]. The percentage of SOM content was obtained by multiplying the percentage of organic carbon by a factor of 1.724 [26] which is based on the assumption that organic carbon constitutes 58% of the soil organic matter.

2.3.3. SOCS estimation

SOCS is dependent on the content of organic carbon, BD, coarse fragment percentage and soil depth [27]. To calculate SOCS, the proportion of the coarse fragment ($\phi > 2$ mm) content was determined by weighing the coarse fragments remaining on a sieve [28]. Hence, the total SOCS of each studied cropland plot was determined using measured soil depth (i.e. 20 cm), BD (g cm^{-3}), organic carbon (%) and the sampled soil excluding the coarse fragment, as follows:

$$\mathrm{SCS}\left(\mathrm{t\ ha}^{-1}\right) = d * \mathrm{BD} \times \mathrm{SOC} * (1 - \text{proportion of coarse fragment})$$

where d is sampling depth (i.e. 20 cm), BD is soil bulk density (g cm^{-3}), SOC is soil organic carbon (%), and the proportion of coarse fragment was calculated by dividing the coarse fragment weight (g) by the total weight of the sample (g) multiplied by 100. The coarse fragment has little or no contribution to the binding and retention of SOM content; hence, its proportion was excluded from the calculation of SOCS.

2.4. Data analysis

Statistical analyses of the data were conducted using SPSS software (IMB SPSS statistics version 20) to test the influence of ISWC and physical SWC measures on the selected soil properties compared to the contribution without SWC measures. The differences among cropland sites treated with ISWC, SWC and NSWC with respect to soil aggregate size distribution, SAS, SOM content and SOCS were assessed using multiple comparisons of variance. Significance differences between treatment means were separated using Least Significant Difference (LDS) test at ($p < 0.05$) significance level. The Pearson correlation test was also used to analyze the relationship among soil aggregate size distribution, BD, SAS, SOM content and SOCS.

3. Results and discussion

3.1. Soil texture

Though there are differences in proportions of sand, silt and clay, soil textural classes of the cropland sites treated with different SWC measures (i.e. ISWC, SWC and NSWC) were found to be the same (Table 1). The results indicate that there is no significant difference in the proportion of soil separates (% sand, % silt and % clay; $p > 0.09$) among the cropland sites treated with ISWC, SWC and NSWC measures. This is also due to the fact that cropland sites were situated on the same geological unit and slope gradients (i.e. 3–8%), which put them in the same soil textural classes. This suggests that the different SWC measures did not have effects on the soil texture of the study area. Since texture is an inherent soil property derived from the parent material, it is not surprising to see no influence of land management practices such as SWC treatments on soil texture in such a short period of time. However, the highest percentage of silt and clay were recorded for sites treated with ISWC, compared to cropland sites treated with SWC alone and NSWC. This is due to the absence of selective removal of fine particles by overland flow and to the accumulation of silt and clay in cropland sites treated with different SWC measures. The results (Table 1) show greater sand contents in the fine earth for the cropland site with NSWC measures compared to sites with ISWC and SWC, which is due to selective removal of clay, silt and organic matter by overland flow from the site where no conservation measures are installed. Similarly, Tibebu *et al.* (2017) [29] reported high clay and silt content in soils of cropland sites compared to the contents in pasture and forested areas.

3.2. Soil BD

Though there is no significant ($p > 0.61$) difference in soil BD among the cropland sites treated with different SWC measures, higher mean BD values are recorded for the cropland sites treated with SWC alone and sites treated with NSWC measures (Table 2). The lowest BD, of the cropland site treated with ISWC measures, is due to the presence of fodder species which modify soil BD through increased addition of organic matter, and also to the increased soil porosity due to root actions. This study is similar to that of Tadesse *et al.* [30] who reported mean BD values of 1.21 g cm^{-3} for cropland treated with ISWC measures, 1.34 g cm^{-3} for cropland treated with SWC structures alone and 1.37 g cm^{-3} for cropland with NSWC measures in the same geology and slope gradient. Moreover, the results of the study conducted by Demelash and Karl [31] in South Gonder, northwestern highlands of Ethiopia, foud lower soil BD values for croplands treated with ISWC and SWC measures than for the cropland site with NSWC activities. This is attributed to the reduced soil erosion rate and increased SOM and clay contents of the soil.

Table 1. Proportion of sand, silt and clay as well as corresponding soil textural classes: L is loam, SL is sandy loam, SCL is sandy clay loam, LS is loamy sand for the three sites: (ISWC measures -is cropland site treated with integrated soil and water conservation measures, SWC structures -is cropland site treated with soil and water conservation structures alone and NSWC measures -is cropland site with no soil and water conservation measures).

	ISWC measures				SWC structures				NSWC measures			
Plots	Sand %	Silt %	Clay %	Textural class	Sand %	Silt %	Clay %	Textural class	Sand %	Silt %	Clay %	Textural class
1	54	33	13	SL	59	29	12	SL	65	23	12	SL
2	53	26	21	SL	73	17	10	SL	75	15	10	SL
3	56	22	22	SCL	71	21	8	SL	59	23	18	SL
4	69	21	10	SL	62	24	16	SL	81	11	8	LS
5	49	32	19	L	57	22	21	SCL	72	15	13	SL
Mean	56.2	26.8	17	SL	64.4	22.8	13.2	SL	70.4	17.4	12.2	SL

Table 2. Topsoil (0–20 cm depth) properties: soil organic matter content (SOM) content, bulk density (BD), mean weight diameter (MWD) dry sieving, mean weight diameter (MWD) wet sieving, SI (Stability index), SQ (Stability quotient) and SOCS (Soil organic carbon stock) for the three sites with different SWC measures (mean ±S.E.) where S.E. is standard error.

		Conservation practice		
Variable	Slope gradient (%)	ISWC Measures	SWC structures	NSWC measures
SOM content (%)	3-8	1.73±0.12a	1.16±0.12b	0.66±0.11c
Bulk density (g cm^{-3})	3-8	1.43±0.05a	1.56±0.05a	1.56±0.05a
MWD dry sieving(mm)	3-8	2.28±0.14a	1.78±0.13b	1.47±0.13b
MWD wet sieving (mm)	3-8	2.22±0.14a	1.62±0.12b	1.27±0.13b
SI	3-8	15.01±2.15a	8.06±1.95b	6.12±1.96b
SQ	3-8	712.46±99.64a	267.53±90.18b	186.93±90.77b
SOCS (ton ha^{-1})	3-8	12.67±0.62a	8.04±0.58b	6.26±0.552b

Note: - Means within a row followed by different letters are significantly different p $<$ 0.05 for the cropland sites with different SWC treatments.

3.3. Aggregate size distribution and SAS

The MWD values of the aggregate for both dry and wet sieving are presented in Table 2. These results show that aggregate size distribution is significantly different for mean dry sieving ($p < 0.05$) and for mean wet sieving ($p < 0.01$) in cropland sites treated with ISWC measures (Table 2). However, a non-significant difference in aggregate-size stability distribution for dry-sieving ($p > 0.09$) and for wet-sieving ($p > 0.05$) was observed between the cropland sites treated with SWC alone and NSWC (Table 2). The dry MWD of the soil from cropland sites treated with ISWC measures, SWC alone and NSWC ranges from 2.05 to 2.42 mm, from 1.67 to 1.90 mm, and from 0.84 to 1.96 mm, respectively. In contrast, the wet MWD of the soil from cropland sites treated with ISWC measures, SWC alone and NSWC ranges from 2.03 to 2.37 mm, from 1.49 to 1.80 mm and from 0.68 to 1.77 mm, respectively (Table 2). The MWD in both dry and wet sieving indicated that aggregate size distribution for cropland sites treated with ISWC measures is the highest among the three cropland sites followed by the cropland site treated with SWC structures alone. Though the results for MWD of both dry and wet sieving in this study are very similar, considering the MWD of the soil in both dry and wet conditions helps to create a good understanding of the response of the soil aggregate at different moisture conditions. Wet aggregate stability shows the resistance of soils against raindrops and water movement in the soil such as erosion and infiltration, whereas the dry aggregate stability shows the resistance of soils against external forces such as wind erosion and compaction [32].

The results showed that the SI and SQ for sites treated with ISWC measures are significantly higher ($p < 0.01$) than for the cropland sites treated with SWC alone and NSWC. However, a non-significant difference ($p > 0.76$) for SI and ($p > 0.80$) for SQ was found between cropland sites treated with SWC and cropland sites with NSWC measures (Table 2). The SAS of cropland sites treated with ISWC is the highest among the three sites, followed by the cropland site treated with SWC structures alone. This high SAS proves that soils from cropland sites treated with ISWC measures are more stable compared to soils of cropland sites treated with SWC alone or NSWC measures. This better soil aggregation for sites treated with ISWC measures is due to the relatively high SOM content of the topsoil from the planted fodder species, and the lower soil BD (Table 2). The results of this study are similar to the results reported by Lee *et al.* [33], who suggested that SOM content is important in soil aggregation, soil aggregate-size distribution and aggregate stability because of its cohesive and binding properties. Moreover, the higher clay content of soils from the cropland site treated with ISWC measures (Table 1) provided potential for the stabilization of the soils by association and binding effects of organic materials with clay minerals, and the formation and stabilization of organic materials within aggregates [34]. In contrast, the lower soil aggregation for the soils in cropland sites with NSWC is due to the high proportion of sandy texture, water erosion, low vegetation cover, low SOM content and high soil compaction.

3.4. SOM content

The results presented in Table 2 show that mean SOM content is significantly ($p < 0.01$) different among the cropland sites treated with ISWC, SWC alone, and NSWC measures. The highest value of SOM content (1.73%) is found in the cropland site treated with ISWC, followed by the cropland sites treated with SWC alone (1.16%) and with NSWC (0.66%) (Table 2). The higher SOM content is due to the consequences of ISWC measures that involve the addition of organic matter from the planted fodder tree species. The percentage of SOM content in the cropland site treated with ISWC measures increased by 49% compared to the corresponding cropland site with SWC alone. Similarly, for the cropland site treated with ISWC measures, the SOM content increased by 162% compared to the cropland site with NSWC measures, whereas the SOM content for the cropland site treated with physical SWC measures alone increased by 76% compared to the cropland site with NSWC measures. Litter fall from the planted fodder plant species together with the physical SWC measures have the best effect in enhancing SOM content. This result is in line with previous results of Amezketa [35] and Tadesse *et al.* [30] who reported a mean SOM content of 2.13% for cropland treated with integrated soil bund, 1.47% for cropland treated with only soil bund and 0.85% for cropland without SWC measures.

Although there is a significant difference among the soils of the different experimental sites with respect to SOM content, all the experimental sites have low SOM content which is below the optimum level proposed by Barber [36]. The results indicate a moderately low mean SOM content in cropland sites treated with ISWC (1.73%) and SWC structures alone (1.16%), and a low mean SOM content in the NSWC site (0.66%) (Table 2). The low SOM content for the cropland site treated with ISWC is due to long-term cultivation, soil erosion before the conservation measures were implemented, the short time period after implementation of ISWC measures, and poor soil fertility management practices such as less manure and compost application and free stubble grazing after harvest. The low mean SOM content of the cropland site treated with SWC structure alone is also due to the lack of plant litter decomposition, and poor soil fertility management practices such as low manure and compost application and free stubble grazing after harvest. In contrast, the very low mean values of SOM content of cropland sites with NSWC measures may be due to the lack of plant litter addition, leaching of decomposed materials, poor soil fertility management practices, free stubble grazing and lack of deposition of materials coming from upland areas.

The significant difference and relatively high mean SOM content in the cropland treated with ISWC is due to litter fall and decomposition of dead roots from the planted fodder species, which adds organic matter to the soil continuously and causes the accumulation of sediments near the ISWC structures. This finding agrees with Amézketa [35] who reported that SOM content results from litter fall, and dead root decomposition is an indicator of recovery from degradation of soil and ecosystem. Once the SOM is depleted, soil productivity declines because of the degraded soil structure and depletion of nutrients; this causes poor soil aggregation and soil compaction [37].

3.5. Soil organic carbon stock

The SOCS in the topsoil (0–20 cm) of the studied cropland sites treated with ISWC is significantly higher ($p < 0.01$) than in the cropland sites treated with SWC structures alone or NSWC. However, a non-significant difference ($p > 0.08$) is observed between the cropland sites treated with SWC alone and NSWC measures (Table 2). The SOCS ranges from 10.21 to 15.50 t ha^{-1} for the cropland site treated with ISWC, from 7.30 to 9.72 t ha^{-1} for the cropland site treated with SWC alone, and from 5.82 to 7.21 t ha^{-1} for the cropland site with NSWC measures (Table 2). The highest mean value of SOCS in the cropland was found in the site treated with ISWC and the lowest was found in the cropland site with NSWC.

The SOCS in the soil of the cropland site treated with ISWC was improved through appropriate land management practices that integrate fodder species with physical SWC measures. This integrated intervention also increased the conservation of SOM content through reduced erosion rates, which helps to sequester more carbon and plant nutrients and recycle them into the soil through decomposition of plant residues. This finding is in line with Li *et al.* [38] who suggested both concentration and stocks of carbon are significantly higher in croplands with agroforestry species than in cropland sites without agro-forestry. Tadesse *et al.* [30] found a mean SOCS of 12.48 t ha^{-1} for a cropland site treated with integrated soil bund, 10.47 t ha^{-1} for a cropland site treated with soil bund alone, and 4.7 t ha^{-1} for cropland without SWC measures. In general, the low carbon sequestration in soils of the cropland with NSWC measures is due to erosion and low organic matter addition to the soil by the farmers for fertility management and free stubble grazing after harvest.

3.6. Relationships among BD, SOM content, soil aggregate-size distribution, SAS and SOCS

Soil BD is negatively correlated with SOM content, SI and SQ (Table 3), with a significant correlation ($p < 0.01$). However, BD has a weak correlation with dry aggregate size, wet aggregate size and SOCS (Table 3). These results agree with those reported by Tadesse *et al.* [30] that suggested BD is negatively correlated with SOM and SOCS, based on studies using cropland soils of Tigray, North Ethiopia. This is because increased soil organic matter content and related biological activities in the soil reduce soil compaction, contributing toward aggregate stability and increasing the macroporosity of the soils. It is important to consider management conditions that maintain the stability of the soil structure, porosity and a good distribution of pore size, which are crucial for soil water, air and nutrient dynamics [39].

SOM content is positively correlated with dry aggregate size (r = 0.85**), wet aggregate size (r = 0.87**), SI (r = 0.70**), SQ (r = 0.78** and SOCS (r = 0.75**); Table 3), with significant correlation ($p < 0.01$). This is because increasing SOM content increases SAS as organic matter and its decomposition products are binding agents during the genesis of soil structure. This is in line with the findings of Tisdall and Oades [40], Graham *et al.* [41] and Lee *et al.* [33] who also reported a positive correlation among SOM content, SAS and SOCS. The SOCS is also strongly correlated

Table 3. Pearson correlation among soil bulk density (BD), soil organic matter content (SOM) content, soil aggregate stability (SAS) and soil organic carbon stock (SOCS) for the different cropland sites treated with Integrated soil and water conservation (ISWC) physical soil and water conservation measures alone (SWC) and with no soil and water conservation (NSWC) measures.

	BD	MWD dry sieving	MWD wet sieving	SI	SQ	SOCS
SOM content	−0.62**	0.85**	0.87**	0.70**	0.78**	0.75**
BD		−0.39	−0.42	−0.67**	−0.67**	−0.35
MWD dry sieving			0.99**	0.54*	0.66**	0.77**
MWD wet sieving				0.63**	0.73**	0.83**
SI					0.96**	0.75**
SQ						0.81**

**Correlation is significant at the 0.01 level.
*Correlation is significant at the 0.05 level.

with dry aggregate size (r = 0.77**), wet aggregate size (r = 0.83**), SI (r = 0.75**) and SQ (r = 0.81**) (Table 3), with significant correlation ($p < 0.01$).

In general, the higher carbon sequestration potential of the soils of cropland sites treated with ISWC measures is due to a continuous addition of organic matter from litter fall, roots and plant residue of the fodder tree species and SOM accumulated by the ISWC due to reduced erosion which also enhanced the SAS of the site. This strong relationship of SOCS and soil aggregation is an indicator of the different land management roles that enhance productivity, water and nutrient holding capacity, and the overall ecosystem health. The SOCS in the topsoil achieved through conservation of nutrients and planting of trees helps to enhance SOM content through addition and conservation mechanisms. This finding implies that ISWC enables the incorporation of organic matter into the soil. As a result, these effects contribute to enhanced SOM content, improved SOCS and aggregate stability. These effects are similar to those found by Tadesse *et al.* [30], who suggested that soil organic carbon increased due to the addition of organic matter, and conservation. They are also in line with Zhou *et al.* [42] who reported that physical SWC integrated with biological measures has positive effects on preventing soil degradation through modifying soil properties, thereby inducing positive effects on soil aggregation. The organic materials of the fodder plant species added to the soil also promote good soil aggregate formation [43,44]. Soil and water conservation measures implemented in Tigray region significantly reduce the soil erosion rate [5,17,18]. This study also reported that ISWC measures significantly increase SOM content and SOCS, which in turn contribute toward soil quality improvement and reduction of soil erosion, and enhance agricultural productivity.

4. Conclusion

In this study, we evaluated the effects of integrated soil and water conservation measures (physical soil and water conservation integrated with fodder tree species) on soil aggregate stability, soil organic matter content and soil organic carbon stocks of smallholder farmlands in a semi-arid area of Ethiopia. The results revealed that soil organic matter content, soil aggregate stability and soil organic carbon stocks are significantly affected by integrated soil and water conservation measures, whereas soil texture and soil bulk density are not significantly affected by integrated soil and water conservation measures. Soil organic carbon content is significantly increased as a result of soil and water conservation measures alone. However, though there is no significant difference in soil aggregate stability and soil organic carbon stocks between the cropland site treated with SWC alone and the cropland site treated with NSWC measures, higher values were found in cropland treated with SWC measures alone. Soil organic matter content is positively correlated with soil aggregate stability and soil organic carbon stock. This study strongly indicates that integrated soil and water conservation measures have a remarkable potential to increase soil organic matter content, soil aggregate stability and soil organic carbon stock. Even though restoration of degraded soils is a very slow process in dry-land environments, this study has shown that soil and water conservation measures that integrate physical soil and water conservation with fodder tree species contribute significantly to soil quality improvement. Carbon sequestration in degraded soils has double advantages: primarily it enhances food security though increased agricultural productivity; and it also sequesters carbon, contributing toward mitigating the build-up of atmospheric carbon. Therefore, this study provides insight for improved land management in dry lands of the study area and other similar environments.

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