Welemariam *et al. Agric & Food Secur (2018) 7:42*
https://doi.org/10.1186/s40066-018-0193-1

Agriculture & Food Security

RESEARCH

Open Access

Effect of community-based soil and water conservation practices on soil glomalin, aggregate size distribution, aggregate stability and aggregate-associated organic carbon in northern highlands of Ethiopia

Mengistu Welemariam[1*], Fassil Kebede[2], Bobe Bedadi[1] and Emiru Birhane[3,4]

Abstract

Background: Land degradation is a major and widespread problem causing losses of ecosystem services in Ethiopia. Extensive utilization of the land resources for centuries resulted in severe land degradation in the Tigray region of northern Ethiopia. To reverse the problem, land restoration activities have been carried out for the past three decades. This study was initiated to determine the effect of community-based soil and water conservation interventions on soil glomalin, aggregate size distribution, water stable aggregates (WSA) and aggregate-associated organic carbon.

Methods: Soil samples were collected from exclosures + terraces, exclosures alone, stone terraces and non-conserved grazing lands using systematic sampling based on slope positions.

Results: Both easily extractable glomalin and total glomalin were significantly ($p < 0.05$) higher in exclosures compared to terraces and non-conserved grazing lands. The macroaggregate fraction of all SWC measures ranged 21.91–32.41%, where the lowest was in non-conserved grazing lands, while the highest was in exclosures with terraces. The micro-aggregate fraction ranged 19.9–26.66%, where the lowest was in exclosures, while the highest was in non-conserved grazing lands. The results also indicated that exclosures had significantly ($p < 0.05$) higher percent of WSA compared to terraces and non-conserved grazing lands. Mean weight diameter (MWD) was also significantly ($p < 0.05$) higher in exclosures. The WSA and MWD decreased in the order of exclosures with terraces > exclosures alone > terracess > non-conserved communal grazing lands. Comparison of aggregate-associated organic carbon (AAOC) showed relatively higher organic carbon in macroaggregates than in micro-aggregates. Besides, both macro- and micro-aggregate-associated SOC was higher in exclosures than in terraces and non-conserved grazing lands. The AAOC of both macro- and micro-aggregates follows the order exclosures alone > exclosures + terraces > terraces > non-conserved communal grazing lands.

Conclusion: Exclosures and terraces are important strategies for rehabilitation of degraded lands through improving glomalin content, aggregate structure and stability, and aggregate-associated organic carbon.

Keywords: Aggregate stability, Glomalin, Aggregate-associated carbon, Exclosure, Terrace, Mean weight diameter

*Correspondence: mengistuwel@gmail.com
[1] College of Agriculture and Environmental Sciences, Haramaya University, P.O. Box 138, Dire Dawa, Ethiopia
Full list of author information is available at the end of the article

Background

Land degradation is a major cause of food insecurity in Ethiopia [1, 2]. Due to increasing human and livestock population pressure, large areas of the country, particularly in the northern highlands, have been exposed to land degradation [2]. Tigray, the northern part of Ethiopia, suffered from extreme land degradation [3]. The rural landscapes of the region were severely suffered from a high degree of soil degradation [4]. Soil and water conservation practices mainly exclosures and stone terraces have been implemented to reverse the land degradation process [5].

Exclosures involve excluding livestock on biophysically degraded communal grazing lands [6] by inhibiting uncontrolled cutting of trees and grass for fuel and fodder [7]. They are effective in regenerating natural vegetation and controlling soil erosion [8, 9].

Stone terraces are another important physical SWC measures to enhance plant growth by conserving moisture and retaining essential nutrients that could have been washed away by erosion [10]. Stone terraces are commonly practiced in steep sloping areas [11] with the participation of farmers. Stone terraces reduced both erosion and sediment transport [12]. Numerous soil properties including soil organic matter and soil aggregation can be improved through application of stone terraces [10].

Establishment of exclosures and construction of terraces enhanced the natural vegetation [13, 14] through improving physical and chemical properties of soils [15, 16]. Aggregate stability is soil physical property considered during restoration of degraded lands [17]. It is a measure of the ability of the soil to resist change due to environmental factors [18]. Soil organic carbon (SOC) and aggregate stability enhance vegetation growth [19]. The stability of soil aggregates influences the water holding capacity of soil and tells the susceptibility of the soil to erosion [20–22].

Change in aggregate stability is an indicator of organic matter content, biological activity and nutrient cycling in soils [15] which are essential for the functioning of ecosystems [4]. It is mainly assessed by land management and vegetation recovery [23]. Good understanding of ASD and WSA guides the management of soils against erosive and degradative factors [18]. Land management practices including physical and biological conservation measures improve soil stability to erosion and land degradation [24, 25].

Management practices are determinants in soil aggregation through glomalin [26]. Glomalin is a recalcitrant glycoprotein produced by arbuscular mycorrhizal fungi (AMF) [27, 28]. It protects hyphae during transport of nutrients from the plant to the hyphal tip and from soil to the plant [29]. Its quantification is expressed as easily extractable glomalin and total glomalin [30].

Soil glomalin forms soil aggregates and improves soil structure and stability against erosion [31, 32] as soils with stable aggregates are more resistant to erosion [33]. It is also source of active soil organic carbon [34] and contains 30–40% carbon [35]. The SOC associated with various aggregate size fractions reduces the impact of erosive forces [4] and tells the dynamics of soil organic matter [36].

Measurement of glomalin, organic carbon content and aggregate stability enable to assess the risk of soil structural degradation and function [17, 37]. Previous studies have focused on the effect of land degradation on soil fertility and productivity [9, 34]. However, studies conducted on the effect of SWC measures on soil glomalin, ASD, WSA and AAOC were lacking in the area. Thus, this research was conducted to determine the effect of two decades old CBSWC practices mainly stone terraces and exclosures on soil ASD, glomalin, WSA and organic carbon associated with soil aggregates.

The research questions answered include: Did the construction of stone terraces improved ASD glomalin, WSA and aggregate-associated SOC compared to non-terraced grazing lands? Could exclosure enhanced ASD glomalin, WSA and AAOC compared to terraces and non-conserved grazing lands? and finally could exclosures supported with terraces significantly increase soil ASD glomalin, WSA and AAOC compared to terraces, non-terraced exclosures and non-conserved grazing lands?

Methods

Description of the study area

The study was conducted in Degua Temben district, located 50 km west of Mekelle, regional capital of Tigray region, northern Ethiopia. Geographically, it is located at 13°16′23″–13°47′44″ latitude and 39°3′17″–39°24′48″ longitude (see Fig. 1). The area has rugged topography. The elevation and morphology are typical for the northern Ethiopian Highlands [39].

The area receives 290–900-mm rainfall annually with an average value of 615 mm $year^{-1}$. The rainy season usually occurs between June and September. The highest rainfall is in July and August. The growing season varies between 90 and 120 days. The maximum temperatures occur in May and June.

Soils of the study sites are developed from calcium carbonate-rich parent material [40]. According to World Reference Base [41] soil classification system, *Calcaric Cambisols, Vertic Leptosols, Vertic Cambisols and Lithic Leptosols* are the dominant soil types. Water erosion is an extremely serious problem; and sheet, rill and gully erosions are observed elsewhere in the study area.

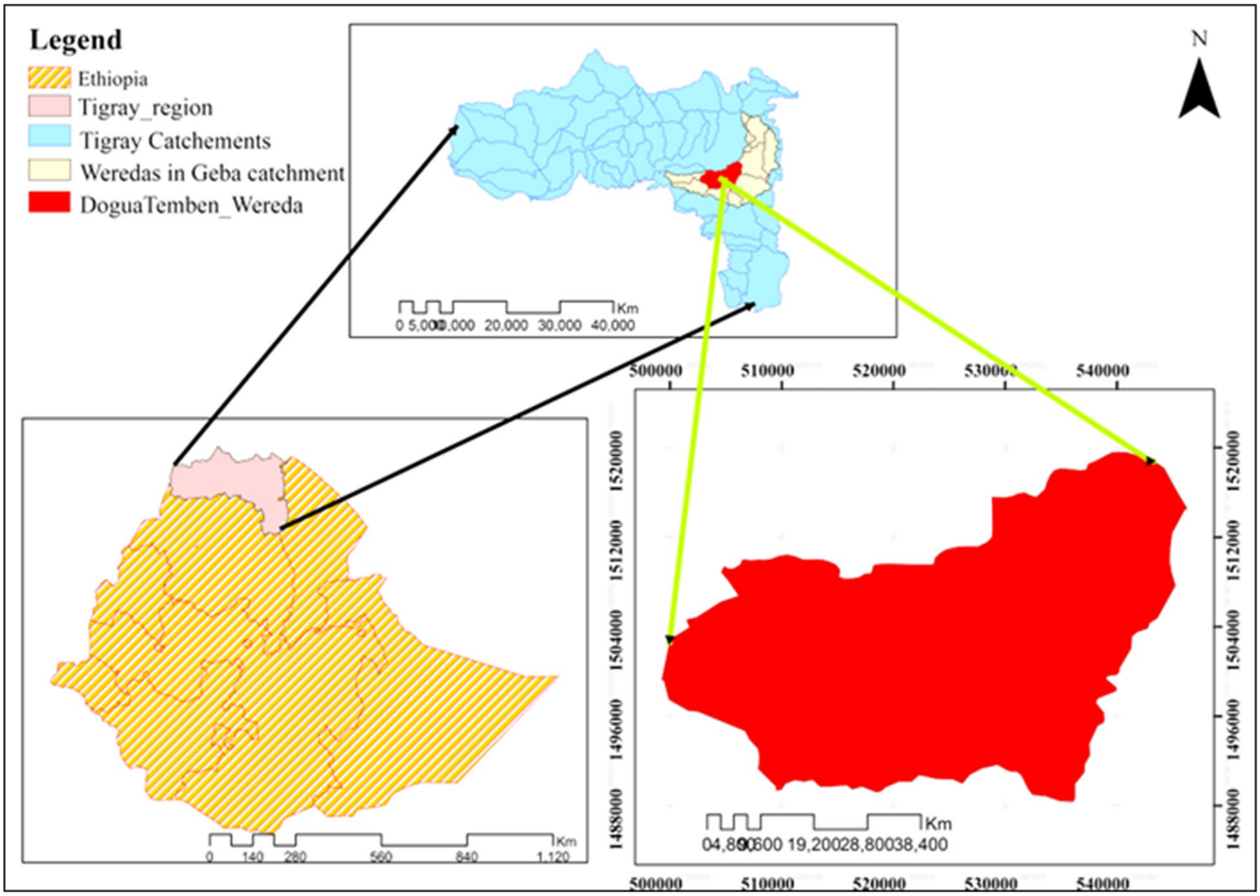

Fig. 1 Location map of the study area

Fig. 2 Major soil and water conservation measures in one site (**a** non-conserved open communal grazing land; **b** terraces; **c** exclosure + terrace; **d** exclosure alone)

Acacia etbaica, *Carissa edulis*, *Dodonea angustifolia*, *Stereospermum kunthianum*, *Rhus vulgaris*, *Senna singueana* and *Eucla racemosa* are the common woody vegetation species identified in exclosures and in communal grazing lands. Mixed farming system (crop and livestock) is the main livelihood of the study area. Major land uses include forest land, cultivated lands, exclosures and communal grazing lands.

Protection and conservation of the degraded sites involve integrated SWC practices using stone faced terraces, enforcement of grazing restrictions and plantation development [5, 9]. The most commonly 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 toward ensuring their sustainability (BoANR 2014). Before their establishment, the selected SWC measures had a 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 terraces, exclosures with terraces, exclosures alone and non-conserved open communal grazing lands (Fig. 2). The management which was classified as exclosure with terrace is restricted from the interference of animals, and both biological planting and physical structures, mainly stone terraces, were implemented. Accumulation of sediments, grasses and litter falls was observed on terraces. More woody plant species were observed compared to the other SWC measures.

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

The stone terraces in grazing lands were selected as third management unit because they are relatively more stable physical SWC measures. It was observed that terraces had better sediment deposits and vegetation cover. Besides, sheet, rill and gully erosion types were less common compared to the open non-conserved 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 very 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 ASD, WSA and AAOC were assumed to be as a consequence of terraces and exclosures establishment.

The area coverage of terraces ranged from 13.87 to 24.42 ha and that of exclosures + terraces and exclosures alone ranged 12.74–51.80 and 14.02–34.70 ha, respectively, while area of the adjacent non-conserved communal grazing lands ranged 11–34.96 ha.

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 [42].

Soil samples were collected from 0 to 30 cm at four corners and center of a 10 m × 10 m size plot using "X" sampling design from terraces, exclosure + terrace, exclosure without terraces and from non-conserved communal grazing lands. A total of 108 soil samples (i.e., four conservation measures*three slope positions*three samples*three replications) were collected for glomalin, ASD, WSA and AAOC determination.

Extraction and determination of glomalin-related soil proteins

The method described by Wright and Upadhyaya [31] was used to determine the easily extractable and total glomalin-related soil proteins. A one-gram sample of air-dried soil was placed in 8 mL 20 mM citrate, pH 7.0, and autoclaved (121 °C) for 30 min to remove the easily extractable glomalin (EEG). After centrifugation (10,000×*g*) and removal of the supernatant, 8 mL 50 mM citrate, pH 8.0, was added to the remaining soil and heated at 121 °C for 60 min to extract total glomalin (TG). Extractions continued with 50 mM citrate until the supernatant becomes straw in color, indicating that glomalin, a red-brown color, had been removed. One mL of EEG was removed, and then, the remaining supernatant containing EEG was combined with all of the supernatants from the 50 mM citrate extractions. Bradford dye-binding assay was used to determine protein with bovine serum albumin as a standard [43].

Aggregate stability determination

The method described by Kemper and Rosenau [44] was used to determine water stability of air-dried aggregates. Hundred grams of air-dried bulk soil that passed through 8-mm sieve was sieved using 5-, 2-, 1-, 0.5-, 0.25- and 0.053-mm sieves. Each fraction was pre-wetted overnight by capillary action and then transferred on the top of a nest of the same sieves immersed in water. The nest of sieves was then vertically tumbled in a column of water for 5 min, at a rate of 50 complete repetitions per minute. The mass of oven-dried particles (105 °C for 24 h) that resisted breakdown was assessed for each sieve. The respective dry masses were used to compute the mean weight diameter (MWD) and water stable aggregate (WSA) as follows:

$$\mathrm{WSA} = ((M(a+s) - \mathrm{MS})/(\mathrm{Mt} - \mathrm{Ms})) \times 100 \quad (1)$$

where $M(a+s)$ is the mass of resistant aggregates plus sand (g), Ms is the mass of resistant aggregates and Mt is total mass of soil

$$\mathrm{MWD} = \sum \mathrm{X\ iW\ i} \quad (2)$$

where MWD is the mean weight diameter of water stable aggregates, Xi is the mean diameter of each sieve fraction (mm) and Wi is the proportion of the total sample mass in the corresponding size fraction

$$\text{Stability index (SI)} = \frac{1}{(\mathrm{MWD})d - (\mathrm{MWD})w} \quad (3)$$

$$\mathrm{SQ} = \mathrm{SI} \times \text{percentage of aggregates} > 2\ \mathrm{mm} \quad (4)$$

where SQ = stability quotient.

Determination of aggregate-associated organic carbon

Soil organic carbon content was determined by Walkeley and Black [45] after sieving with 0.25-mm sieve for micro-aggregates and 2-mm sieve for macroaggregates.

Data analysis

Analysis of variance (ANOVA) was used to see for any significant differences of the parameters along the different community soil and water conservation measures using SAS 9.2. Mean comparison was carried out using Duncan's multiple range test (DMRT), and finally, correlation analysis was carried out to see the relationship between ASD, WSA, glomalin-related proteins and soil organic carbon associated with macro- and micro-aggregate fractions.

Results and discussion

Effect of CBSWC measures on soil glomalin

The content of glomalin under the different CBSWC measures showed that EEG was significantly ($p < 0.05$) higher in exclosures compared to non-conserved grazing lands. Terraces also had relatively higher EEG compared to non-conserved grazing lands. Easily extractable glomalin in exclosures was 11–27.93% higher than on terraces and 44.65–55.17% higher than that of non-conserved grazing lands. Besides, EEG on terraces was 37.79% higher than non-conserved grazing lands. The order of EEG was in the order of exclosures + terraces > exclosures alone > stone terraces > non-conserved grazing lands (Table 1). The presence of higher glomalin in exclosures could be due to the presence of high AMF root colonization as glomalin is produced by mycorrhizal fungi. It was reported that glomalin stocks are greater where AMF is more abundant [46].

Total glomalin was also significantly ($p < 0.05$) higher in exclosures compared to non-conserved grazing lands. Total glomalin in exclosures was 37–45% higher than in non-conserved grazing lands and 24.55–35.51% higher than that of terraces. Livestock grazing could be the cause for low content EEG and TG in non-conserved grazing lands. It was reported that grazing and trampling had negative effect on the amount of glomalin through decreasing vegetation cover [47, 48]. Furthermore, as glomalin is produced by AM fungi, trampling may have destroyed the aggregate of the soil and break the hyphae. It was also reported that other factors such as landscape characteristics can affect the amount of glomalin [49].

Effect of soil and water conservation practices on aggregate size distribution

The result of aggregate size distribution indicated large macroaggregates (> 2 mm) were higher than other aggregate sizes in all SWC measures. This is similar to the result of Xiao et al. [50] who found large macroaggregates (> 2 mm) represented the greatest fraction for all the land uses considered. The effect of different SWC measures on dry aggregate size distribution (Table 2) indicated that exclosures + terraces had significantly higher percentage (32.41%) in the > 2 mm fraction. This could be due to the presence of high organic carbon and low disturbances in exclosures. High organic matter from litter falls and decayed tree roots increased coarser aggregates [51]. Besides, it was reported that strong plant root systems are beneficial for soil aggregation [23]. This also agreed with the result of [36] who found higher macroaggregates in vegetated area than bare land.

Non-conserved communal grazing lands had significantly lower (21.91%) in this size class. Destruction of macroaggregates by livestock trampling and soil erosion may be the cause for the decrease in large macroaggregates in non-conserved communal grazing lands.

Table 1 Soil glomalin under the different SWC measures in mg g^{-1} soil

SWC measures	EEG	TG
Non-conserved grazing lands	3.21^{b}	9.84^{c}
Stone terraces	5.16^{ab}	11.71^{bc}
Exclosures + terraces	7.16^{a}	15.52^{ab}
Exclosures alone	5.8^{a}	18.16^{a}

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

Table 2 Percentage of dry aggregate size distribution under the different SWC measures (mean ± SEM)

SWC measures	> 2 mm	1–2 mm	0.5–1 mm	0.25–0.5 mm	< 0.25 mm
Non-conserved grazing lands	21.91 ± 2.31^{b}	19.60 ± 1.13^{b}	16.79 ± 0.78^{a}	10.41 ± 0.42^{c}	26.66 ± 3.15^{b}
Terraces	26.33 ± 1.47^{ab}	18.15 ± 0.74^{b}	16.46 ± 0.72^{a}	12.30 ± 0.46^{ab}	25.84 ± 1.32^{b}
Exclosures + terraces	32.41 ± 3.11^{a}	22.49 ± 0.73^{a}	17.72 ± 0.65^{a}	12.61 ± 0.39^{a}	13.90 ± 2.04^{c}
Exclosures alone	31.36 ± 2.28^{a}	20.56 ± 0.62^{ab}	16.59 ± 0.45^{a}	11.09 ± 0.66^{bc}	19.40 ± 2.02^{a}

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

Furthermore, clearing of the natural vegetation could be the cause for the dispersion, detachment and decrease in macroaggregates as vegetation cover protects the soil from detachment and aggregate breakdown. The order of percentage of aggregates (> 2 mm fraction) was exclosures + terraces > exclosures alone > terraces > non-conserved communal grazing lands.

Though not significant, terraces had relatively lower percentage (18.15%) of aggregates in 1–2 mm fraction than the other SWC measures. The decrease could be due to the deposition fine sediments on terraces. However, exclosures + terraces had significantly higher (22.49%) which could be due to the presence of high organic carbon. Soil aggregation has positive and strong relation with soil organic carbon [53]. The decreasing order of percentage of aggregates (1–2 mm fraction) was: exclosures + terraces > exclosures alone > non-conserved communal grazing lands > terraces.

Exclosures with terraces had significantly ($p < 0.05$) higher percentage (12.61%) of aggregates in the 0.25–0.5 mm fraction followed by terraces. This indicated terraces in exclosures and in grazing lands decreased detachment and dispersion of soil particles by erosion. The presence of lower (10.41%) of aggregates in this size class in the non-conserved communal grazing lands could be due to soil dispersion by erosion. The decreasing order of percentage of aggregates in the 0.25–0.5 mm fraction was: exclosures + terraces > terraces > exclosures alone > non-conserved communal grazing lands. This revealed high disturbance in non-conserved grazing land has deteriorated soil structure. It was reported that soil aggregates destruction depends on the degree anthropogenic disturbances [52].

Next to the 2–5 mm size fraction, the highest percentage (26.66%) was found in the < 0.25 mm fraction (micro-aggregates). Non-conserved grazing lands had the highest percent of aggregate in the < 0.25 mm size. This could be due to dispersion of aggregates by disturbance. This could indicate soil particles are more likely to be detached in non-conserved grazing lands. In connection to this, Singh et al. [36] found higher micro-aggregates in bare land. The decreasing order of percentage of micro-aggregates (< 0.25 fraction) was: non-conserved communal grazing lands > stone terraces > exclosures alone > exclosure + terraces.

Effect of CBSWC measures on water stable aggregates

Wet aggregate stability values varied among the CBSWC measures (Table 3). It was significantly higher ($p < 0.05$) in exclosures. The presence of higher soil macroinvertebrates density and mycorrhizal association in exclosures could have improved soil aggregation in exclosures [25]. Especially, termites and earthworms are known to enrich the soil with organic materials and improve soil structural stability [27]. Mycorrhizal fungi entangle particles within the hyphae network and cement particles together [35]. Besides, the presence of high vegetation cover in exclosures increased supply of organic matter inputs and decreased soil erosion. In line with this, Fokom et al. [32] observed a decrease in WSA as forest is converted to other land uses. This supports the idea that greater stability is associated with organic matter supply [52] because

Table 3 Effect of SWC measures on aggregate stability (mean ± SEM)

SWC measures	WSA (%)	MWD	SI	SQ
Non-conserved grazing lands	51.8 ± 3.9^{b}	0.77 ± 0.04^{b}	1.65 ± 0.14^{a}	40.73 ± 3.06^{a}
Terraces	58.5 ± 2.0^{ab}	0.82 ± 0.04^{ab}	1.91 ± 0.6^{a}	50.24 ± 3.44^{ab}
Exclosure + terraces	65.6 ± 2.4^{a}	0.93 ± 0.05^{a}	2.60 ± 0.57^{a}	64.97 ± 12.46^{b}
Exclosures alone	64.8 ± 3.2^{a}	0.97 ± 0.06^{a}	2.45 ± 0.44^{a}	52.05 ± 5.43^{b}

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

organic matter improves establishment of soil structure through binding and limits soil erosion [15, 20]. Vegetation has also mulching effect to improve soil aggregation [53, 54].

Communal grazing lands had significantly ($p<0.05$) lower percent of water stable aggregates. This could be due to physical disturbance and low soil organic carbon. Grazing decreased aggregate stability [20] through dispersion of soil aggregates [15].

Conversion of communal grazing lands to exclosures resulted in 20–21% increase in percent of WSA, and conserving the open communal grazing lands with terrace resulted in an increase in WSA by 12%. The WSA decreased in the order of exclosures + terraces > exclosures alone > terraces > non-conserved communal grazing lands. The result of stability quotient also indicated soils in exclosures are 1.23–1.6 times more stable than non-conserved grazing lands. Terraces are also 1.27 times more stable than non-conserved grazing lands (Table 3). This indicated exclosure areas showed relative recovery from structural degradation. It could also indicate less soil erodibility in exclosures. Vegetation cover in exclosures protected the soil from structural disturbance [54]. However, grazing lands due to their bare surface, they receive few inputs of organic matter and are susceptible to degradation. Grazing breaks the soil apart, exposing the organic matter to microbial decomposition and facilitates soil loss by erosion. It was found that due to trampling effect, bulk density increased in free grazing lands, while aggregate stability decreased [51].

Mean weight diameter of aggregates is one measure of aggregate stability [18]. Exclosures had significantly higher ($p<0.05$) in MWD than the non-conserved communal grazing lands. The MWD of the different SWC measures follows decreasing order of exclosures alone > exclosures + terraces > terraces > non-conserved communal grazing lands. This revealed higher organic matter in exclosures stabilized the soil through aggregation. High values of MWD could indicate lower erodability of soils in exclosures. It would also imply stable aggregates are critical to erosion resistance. It was found that establishment of exclosures on degraded lands restores aggregate stability [55]. It was also reported that vegetation cover improved soil structure [15]. Mean weight diameter was found to be highly responsive to cover [56]. This indicated organic matter increased both WSA % and MWD through binding [57].

Bareness and disturbance by grazing are the causes for dispersion of soil aggregates [58], and this might be the cause for the decrease in MWD in non-conserved grazing lands. Similar study reported that the main mechanism of aggregate breakdown is by dispersion through disturbance [51]. Mean weight diameter was responsive to livestock grazing because it was reported that MWDs were lower in grazed grassland area [20].

Effect of SWC measures on aggregate-associated soil organic carbon

Soil and water conservation measures significantly ($p<0.05$) affected the soil organic carbon associated with macroaggregates (> 0.25 mm size). However, no significant variation was observed on those associated with micro-aggregates (< 0.25 mm) (Table 4).

Exclosures + terraces had significantly ($p<0.05$) higher (3.1%) organic carbon associated with macroaggregates, while non-conserved communal grazing lands had lower (2.2%) macroaggregate-associated carbon. Shrestha et al. [59] found higher amounts of associated SOC concentration under undisturbed sites. Xiao et al. [50] reported the highest SOC in large aggregates under exclosures. In our study, the conversion of communal grazing lands to exclosures resulted (17–27%) increase in SOC in macroaggregates followed by terrace (9%) as compared to non-conserved grazing lands.

The highest (2.8%) organic carbon associated with micro-aggregate was found in exclosures + terraces, while the lowest (1.8%) was found in non-conserved communal grazing lands. Conversion of communal grazing lands to exclosures resulted in 19–34% increase in SOC in macroaggregates, while terrace construction resulted in 17% increase in macroaggregate carbon as compared to non-conserved grazing lands. The low aggregate carbon in non-conserved communal grazing lands could be due to low biomass input caused by livestock grazing and human disturbances.

Soil organic carbon associated with macroaggregates was higher than SOC associated with micro-aggregates. This indicated macroaggregate structures are important in physical protection of soil organic carbon. In line with this, Gelaw et al. [4] in Mandae watershed, northern Ethiopia, found higher SOC in macro- than micro-aggregates. Many other authors also reported that organic carbon

Table 4 Aggregate-associated organic carbon under the different SWC measures (mean ± SEM)

SWC measures	SOC in macroaggregates (%)	SOC in micro-aggregates (%)
Non-conserved grazing lands	2.2 ± 0.2^{b}	1.8 ± 0.2^{b}
Terraces	2.5 ± 0.2^{b}	2.2 ± 0.2^{b}
Exclosures + terraces	3.1 ± 0.2^{a}	2.8 ± 0.2^{a}
Exclosures alone	2.7 ± 0.1^{ab}	2.3 ± 0.1^{ab}

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

in coarse aggregates was higher than in fine aggregates [17, 50, 60]. This was due to high rate of decomposition in micro-aggregates [61]. This suggested that micro-aggregate stability could be a better indicator of potential soil erosion hazards [36]. A large decrease in SOC from macro- to micro-aggregate (16%) was observed in exclosure with terraces followed by non-conserved communal grazing lands (16%) and exclosures with terraces (12%), while the lowest (5%) was observed in terraces.

The SOC associated with both macro- (>0.25 mm) and micro-aggregates (<0.25 mm) follows the order exclosures + terraces > exclosures alone > terraces > non-conserved communal grazing lands. This showed the deposition and turnover of litter fall, stump and roots of matured trees maintained SOC in exclosures. This implied that higher SOC content would further contribute to soil aggregate stability in the restoration of grazing lands [62].

Relationship between soil glomalin, organic carbon fractions, MWD and aggregate stability

This study found positive and significant ($p < 0.05$) relationship between EEG and water stable aggregates. Easily extractable glomalin and total glomalin explained about 43 and 40% of the variation in percent of water stable aggregates, respectively (Fig. 3). The relationship between TG and % WSA was also positive and significant. In line with this, a study by Sirinikorn et al. [49] and Hontoria et al. [63] found positive relationship between soil aggregate stability and glomalin content. Similarly, Wright et al. [64] reported that glomalin-related soil protein increased as aggregate size increased. This indicated both EEG and TG are important for soil aggregation and enhance stability. This could be due to the cementing and recalcitrant properties of glomalin. It was reported that glycoprotein, produced by AMF hyphae, has a cementing capacity to maintain soil particles together [29]. It also has relatively slow turnover in soil, contributing to lasting effects on aggregation [27].

The relationship between EEG and % SOC and TG with SOC was positive and significant. Easily extractable glomalin and TG explained 23 and 21% of the variation in % SOC, respectively (Fig. 4). These positive and significant relationships indicated that EEG and TG contribute to SOC storage. Zhang et al. [65] reported glomalin-related soil proteins are used for preserving and accumulating SOC. Glomalin contains approximately 30–40% of carbon and forms small soil clumps. This granulated material binds carbon in the soil [59].

The positive relationship between aggregate-associated soil organic carbon and water stable aggregates (Figs. 5, 6) indicated SOC is necessary in soil aggregation. This agreed with the result of Dorji et al. [53] in a montane ecosystem of Bhutan and Gelaw et al. [4] in Mandae watershed of the northern highlands of Ethiopia. This

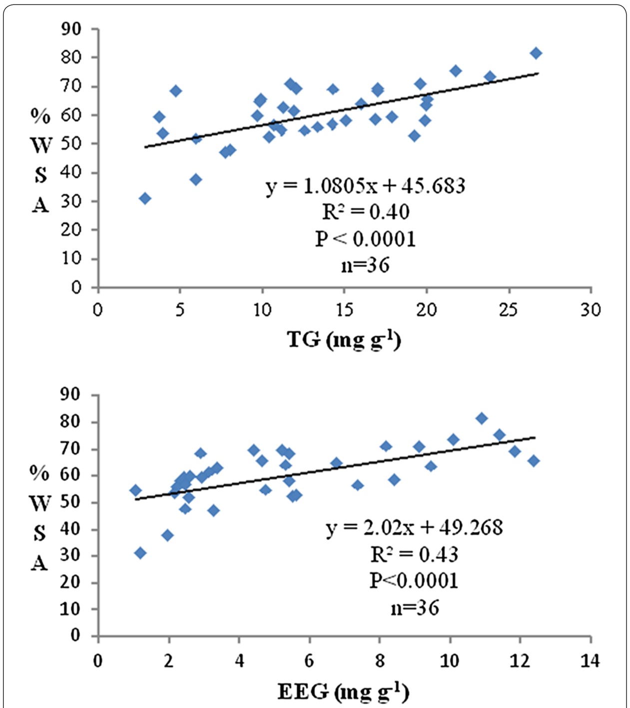

Fig. 3 Relationship of %WSA with EEG and TG

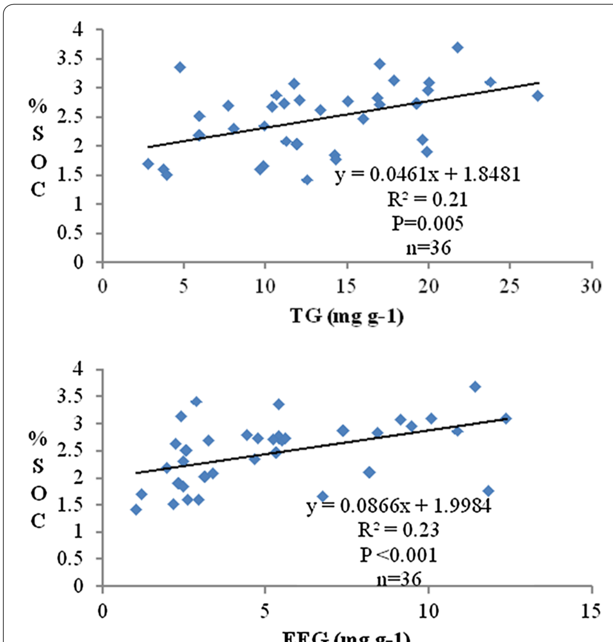

Fig. 4 Relationship of % SOC with EEG and TG

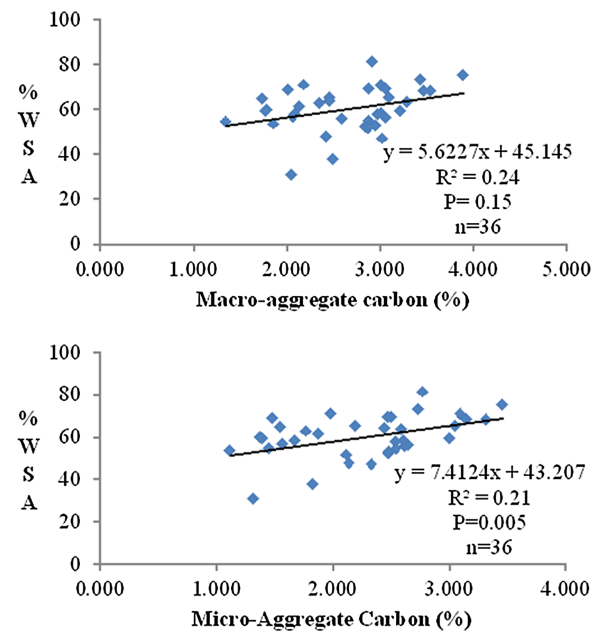

Fig. 5 Relationship of %WSA with micro- and macroaggregate carbon fractions

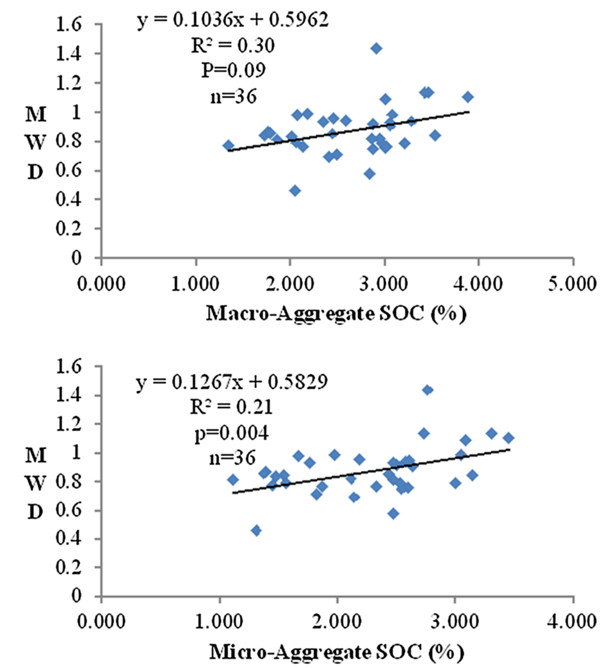

Fig. 6 Relationship of MWD with micro- and macroaggregate carbon fractions

could be due to the cementing and recalcitrant properties of glomalin which significantly enhance the stability of soil aggregates through SOC sequestration [27, 64, 66] and slowing its turnover [40]. It was reported that glomalin is glycoprotein nature and hydrophobic characteristics; therefore, it is a very stable biomolecule, with a half-life in soil between 6 and 42 years, and prevents nutrients losses [67].

Conclusions

Identifying sustainable soil and water conservation practices is necessary to solve land degradation. The application of exclosures and terraces increased soil aggregate stability. Soils with high glomalin content had high organic carbon and water stable aggregates. Larger proportions of macroaggregates were found in exclosures followed by terraces, while large proportions of microaggregate fractions were found in non-conserved communal grazing lands. Aggregate stability increased with organic matter content. Macroaggregates contain higher SOC than micro-aggregates. Significantly higher water stable aggregates were found in exclosures compared to terraces and non-conserved grazing lands. Implementation of exclosures and terraces should be expanded to enhance the aggregate stability of the soil and organic carbon associated with aggregates and finally to rehabilitate soil structure degradation.

Abbreviations

ASD: aggregate size distribution; MWD: mean weight diameter; WSA: water stable aggregates; SOC: soil organic carbon; CBSWC: community-based soil and water conservation; EEG: easily extractable glomalin; TG: total glomalin; AAOC: aggregate-associated organic carbon.

Authors' contributions

MW 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.

Author details

[1] College of Agriculture and Environmental Sciences, Haramaya University, P.O. Box 138, Dire Dawa, Ethiopia. [2] Ethiopian Agricultural Transformation Agency, P.O. Box 708, Addis Ababa, Ethiopia. [3] Department of Land Resources Management and Environmental Protection, Mekelle University, P.O. Box 231, Mekelle, Ethiopia. [4] Faculty of Environmental Sciences and Natural Resource Management, Norwegian University of Life Sciences, P.O. Box 5003, 1432 Ås, Norway.

Acknowledgements

The authors would like to thank Ministry of Education for providing scholarship to the principal investigator to study his PhD at Haramaya University, Ethiopia.

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
Not applicable.

Ethics approval and consent to participate
The authors declare that this study does not involve human subject's material and human data.

Funding
This study was funded by the ministry of education of Ethiopia through Haramaya and Wollega University. It was also partly supported by the steps toward sustainable forest management with the local communities in Tigray, northern Ethiopia (ETH 13/0018) project funded by NORAD/NORHED.

Publisher's Note
Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Received: 11 May 2018 Accepted: 8 June 2018
Published online: 28 June 2018

References
1. Shiferaw A, Hurni H, Gete Z. Long-term changes in soil-based ecological services at three sites in Ethiopia. J Environ Microbiol. 2013;1(1):136–44.
2. World Food Program (WFP). Scaling up an integrated watershed management approach through social protection programmes in Ethiopia: the MERET and PSNP schemes. Hunger. Nutrition climate justice. Case studies: policy responses, local to national. Dublin; 2013.
3. Mekuria W, Veldkamp E, Mitiku H, Kindeya G, Muys B, Nyssen J. Effectiveness of exclosures to control soil erosion and local community perception on soil erosion in Tigray, Ethiopia. Afr J Agric Res. 2009;4(4):365–77.
4. Gelaw AM, Singh BR, Lal R. Soil quality indices for evaluation of tree-based agricultural land uses in a semi-arid watershed in Tigray, Northern Ethiopia. Sustainability. 2014;7:2322–37.
5. Nyssen J, Poesen J, Moeyersons J, Deckers J, Haile M, Lang A. A Human impact on the environment in the Ethiopian and Eritrean highlands, a state of the art. Earth Sci Rev. 2004;64:273–320.
6. Descheemaeker K, Muys B, Nyssen J, Poesen J, Raes D, Haile M, Deckers J. Litter production and organic matter accumulation in exclosures of the Tigray highlands, Ethiopia. For Ecol Manag. 2006;233:21–35.
7. Yayneshet T, Eik LO, Moe SR. Seasonal variations in the chemical composition and dry matter degradability of exclosure forages in the semi-arid region of northern Ethiopia. Anim Feed Sci Technol. 2009;148:12–33.
8. Baudron F, Mamo A, Tirfessa D, Argaw M. Impact of farmland exclosure on the productivity and sustainability of a mixed crop-livestock system in the Central Rift Valley of Ethiopia agriculture. Ecosyst Environ. 2015;207:109–18.
9. Gebremeskel G, Gebremicael TG, Girmay A. Economic and environmental rehabilitation through soil and water conservation, the case of Tigray in northern Ethiopia. J Arid Environ. 2017;151:113–24.
10. Rashid M, Rehman O, Alvi S, Kausar R, Akram MI. The effectiveness of soil and water conservation terrace structures for improvement of crops and soil productivity in rainfed terraced system. Pak J Agric Sci. 2016;53:241–8.
11. Gebre-egziabher T, Nyssen J, Govaerts B, Getne F, Behailu M, Haile M, Deckers J. Contour furrows for in situ soil and water conservation, Tigray, Northern Ethiopia. Soil Tillage Res J. 2009;103:257–64.
12. Sawadogo H. Using soil and water conservation techniques to rehabilitate degraded lands in northwestern Burkina Faso. Int J Agric Sustain. 2017;9(1):120–8.
13. Gebrehiwot T, Veen A. The effect of enclosures in rehabilitating degraded vegetation a case of Enderta District, northern Ethiopia. For Res. 2014. https://doi.org/10.4172/2168-9776.1000128.
14. Yimer F, Alemu G, Abdelkadir A. Soil property variations in relation to exclosure and open grazing land use types in the Central Rift Valley area of Ethiopia. Environ Syst Res. 2015;4:17.
15. Carballas T, Villar MC, Petrikova V. Changes in soil microbial biomass and aggregate stability following burning and soil rehabilitation. Geoderma. 2004;122:73–82.
16. Welemariam M, Kebede F, Bedadi B, Birhane E. The effect of community-based soil and water conservation practices on abundance and diversity of soil macroinvertebrates in the northern highlands of Ethiopia. Agronomy MDPI. 2018;8:56.
17. Boogar AM, Jahansouz MR, Reza M. Soil aggregate size distribution and stability following conventional-till, minimum-till and no-till systems. Int J Farming Allied Sci. 2014;3:512–7.
18. Igwe CA, Obalum SE. Microaggregate stability of tropical soils and its roles on soil erosion hazard prediction. Adv Agrophys Res. 2013. https://doi.org/10.5772/52473.
19. Bird SB, Herrick JE, Wander MM, Wright SF. Spatial heterogeneity of aggregate stability and soil carbon in semi-arid rangeland. Environ Pollut. 2002;116(3):445–55.
20. An SS, Darboux F, Cheng M. Revegetation as an efficient means of increasing soil aggregate stability on the Loess Plateau (China). Geoderma. 2013;209–210:75–85.
21. Hobley E, Willgoose GR, Frisia S, Jacobsen G. Stability and storage of soil organic carbon in a heavy-textured Karst soil from south-eastern Australia. Soil Res. 2014;52(5):476–82.
22. Belaid H, Habaieb H. Soil aggregate stability in a Tunisian semi-arid environment with reference to fractal analysis. J Soil Sci Environ Manag. 2015;6:16–23.
23. Zhao PS, Han FZ, Yang XH, Feng GH, Ren GX. Soil structure and carbon distribution in subsoil affected by vegetation restoration. Plant Soil Environ. 2014;60(1):21–6.
24. Njira KOW, Nabwami J. Soil management practices that improve soil health: elucidating their implications on biological indicators. Rev Paper J Animal Plant Sci. 2013;18(2):2750–60.
25. Welemariam M, Kebede F, Bedadi B, Birhane E. Effect of community-based soil and water conservation practices on arbuscular mycorrhizal fungi types, spore densities, root colonization, and soil nutrients in the northern highlands of Ethiopia. Chem Biol Technol Agric. 2018;5:9.
26. Borie F, Rubio R, Rouanet JL, Morales A, Borie G, Rojas C. Effects of tillage systems on soil characteristics, glomalin and mycorrhizal propagules in a Chilean Ultisol. Soil Tillage Res. 2006;88:253–61.
27. Rillig MC. Arbuscular mycorrhizae, glomalin, and soil aggregation. Can J Soil Sci. 2004;84:355–63.
28. Wang Q, Lu H, Chen J, Hong H, Liu J, Li J, Yan C. Spatial distribution of glomalin-related soil protein and its relationship with sediment carbon sequestration across a mangrove forest. Sci Total Environ. 2018;613–614:548–56.
29. Singh PK. Role of glomalin related soil protein produced by arbuscular mycorrhizal fungi: a review. Agric Sci Res J. 2012;2(3):119–25.
30. Wright SF, Upadhyaya A. Extraction of an abundant and unusual protein from soil and comparison with hyphal protein of arbuscular mycorrhizal fungi. Soil Sci. 1996;161:575–86.
31. Wright SF, Upadhyaya AA. survey of soil for aggregates stability and glomalin, a glycoprotein produced by hyphea of arbuscular mycorrhizal fungi. Plant Soil. 1998;198:97–107.
32. Fokom R, Teugwa MC, Nana WL, Ngonkeu MEL, Tchameni S, Nwaga D, Rillig CM, Amvam Zollo PH. Glomalin, carbon, nitrogen and soil aggregate stability as affected by land use changes in the humid forest zone in south Cameroon. Appl Ecol Environ Res. 2013;11(4):581–92.
33. Ćirić V, Manojlović M, Nešić L, Belić M. Soil dry aggregate size distribution: effects of soil type and land use. J Soil Sci Plant Nutr. 2012;12:689–703.
34. Rillig MC, Rmsey PW, Morris S, Paul EA. Glomalin, an arbuscular-mycorrhizal fungal soil protein, responds to land-use change. Plant Soil. 2003;253:293–9.
35. Bedini S, Avio L, Argese E, Giovannetti M. Effects of long-term land use on arbuscular mycorrhizal fungi and glomalin-related soil protein. Agr Ecosyst Environ. 2007;120:463–6.
36. Singh MK, Singh S, Ghoshal N. Impact of land use change on soil aggregate dynamics in the dry tropics. Restor Ecol. 2017;25:962–71.
37. Burri K, Graf F, Böll A. Revegetation measures improve soil aggregate stability: a case study of a landslide area in Central Switzerland. For Snow Landsc Res. 2009;60:45–60.

38. Nyssen J, Munro N, Haile M, Poesen J, Descheemaeker K, Haregeweyn N, Decker J. Understanding the environmental changes in tigray: a photographic record over 30 years. Tigray Livelihood Papers. 2007;3:82.
39. Mekuria W, Veldkamp E, Haile M, Nyssen J, Muys B, Gebrehiwot K. Effectiveness of exclosures to restore degraded soils as a result of overgrazing in Tigray Ethiopia. J Arid Environ. 2007;69(2):270–84.
40. Beyth M. Paleozoic–mesozoic sedimentary basin of Mekele outlier. Am Assoc Pet Geol Bull. 1972;56:2426–39.
41. World Reference Base (WRB). A framework for international classification, correlation and communication FAO, Rome Italy. 2006.
42. Mekuria W, Aynekulu E. Exclosure land management for restoration of the soils in degraded communal grazing lands in northern Ethiopia. Land Degrad Dev. 2013;24:528–38.
43. Wright SF, Upadhyaya A. Extraction of an abundant and unusual protein from soil and comparison with hyphal protein of arbuscular mycorrhizal fungi. Soil Sci. 1996;161:575–85.
44. Kemper WD, Rosenau RC. Aggregate stability and size distribution. In: Klute A, editor. Methods of soil analysis. part 1, SSSA book ser. 5. 2nd ed. Madison: American Society of Agronomy; 1986. p. 425–42.
45. Walkeley A, Black I. An examination of Degtjareff methods for determining soil organic matter and a proposed modification of the chromic acid titration method. Soil Sci. 1934;37:29–38.
46. Treseder KK, Turner KM. Glomalin in ecosystems. Soil Sci Soc Am J. 2007;71:1257.
47. Wright SF, Starr JL, Paltineanu IC. Changes in aggregate stability and concentration of glomalin during tillage management transition. Soil Sci Soc Am J. 1999;63:1825–9.
48. Bai H, Bao X, Sun X, Jiang S. The effect of stocking rate on soil glomalin under traditional and mixed grazing systems in a temperate steppe. Procedia Environ Sci. 2011;11:817–23.
49. Sirinikorn SA, Susingsa P, Maungjai PN. Glomalin-related soil protein influence on soil aggregate stability in soils of cultivated areas and secondary forests from Northern Thailand. In: 19th world congress of soil science, soil solutions for a changing world. 2010.
50. Xiao S, Zhang W, Ye Y, Zhao J, Wang K. Soil aggregate mediates the impacts of land uses on organic carbon, total nitrogen, and microbial activity in a Karst ecosystem. Sci Rep. 2017;7:1–10.
51. Gurmessa B, Demissie A, Lemma B. Susceptibility of soil to wind erosion in arid area of the Central Rift Valley of Ethiopia. Environ Syst Res. 2015;4:10.
52. Gajic B, Dugalic G, Djurovic N. Comparison of soil organic matter content, aggregate composition and water stability of gleyic fluvisol from adjacent forest and cultivated areas. Agron Res. 2006;4(2):499–508.
53. Dorji T, Odeh IA, Field DJ. Effects of land use/land cover on aggregate fractions, aggregate stability, and aggregate-associated organic carbon in a montane ecosystem. In: Global symposium on soil organic carbon, Rome; 2015.
54. Demenois J, Carriconde F, Rey F, Stokes A. Tropical plant communities modify soil aggregate stability along a successional vegetation gradient on a Ferralsol. Ecol Eng. 2017;109:161–8.
55. Delelegn YT, Purahong W, Blazevic A, Yitaferu B, Wubet T, Göransson H, Godbold DL. Changes in land use alter soil quality and aggregate stability in the highlands of northern Ethiopia. Sci Rep. 2017;7:1–12.
56. Stavi I, Ungar ED, Lavee H, Sarah P. Soil aggregate fraction 1–5 mm: an indicator for soil quality in rangelands. J Arid Environ. 2011;75:1050–5.
57. Karami A, Homaee M, Afzalinia S, Ruhipour H, Basirat S. Organic resource management: impacts on soil aggregate stability and other soil physico-chemical properties. Agric Ecosyst Environ. 2012;148:22–8.
58. Six J, Paustian K. Aggregate-associated soil organic matter as an ecosystem property and a measurement tool. Soil Biol Biochem. 2014;68:A4–9.
59. Shrestha BM, Singh BR, Sitaula BK, Lal R, Bajracharya RM. Soil aggregate-and particle-associated organic carbon under different land uses in Nepal. Soil Sci Soc Am J. 2007;71:1194.
60. Cleide JOR, Forestieri EG, Carlos AG-R, Carlos JP, Cele RM, Baligar VC. Content in density fractions of whole soil and soil size fraction under cacao agroforestry systems and natural forest in Bahia, Brazil. Environ Manag. 2011. https://doi.org/10.1007/s00267-011-9642-3.
61. John B, Yamashita T, Ludwig B, Flessa H. Storage of organic carbon in aggregate and density fractions of silty soils under different types of land use. Geoderma. 2005;128:63–79.
62. Zhu G, Shangguan Z, Deng L. Soil aggregate stability and aggregate-associated carbon and nitrogen in natural restoration grassland and Chinese red pine plantation on the Loess Plateau. CATENA. 2017;149:253–60.
63. Hontoria C, Velásquez R, Benito M, Almorox J, Moliner A. Soil biology & biochemistry bradford-reactive soil proteins and aggregate stability under abandoned versus tilled olive groves in a semi-arid calcisol. Soil Biol Biochem J. 2009;41:1583–5.
64. Wright SF, Green VS, Cavigelli MA. Glomalin in aggregate size classes from three different farming systems. Soil Tillage Res. 2007;94:546–9.
65. Zhang J, Tang X, Zhong S, Yin G, Gao Y, He X. Recalcitrant carbon components in glomalin-related soil protein facilitate soil organic carbon preservation in tropical forests. Sci Rep. 2017. https://doi.org/10.1038/s41598-017-02486-6.
66. Perez AB. Extraction of glomalin and associated compounds with two chemical solutions in cultivated tepetates of mexico. Commun Soil Sci Plant Anal. 2012;43:28–35.
67. Wu QS, Xin HH, Ming QC, Ying NZ, Shuang W, Yan L. Relationships between glomalin- related soil protein in water-stable aggregate fractions and aggregate stability in citrus rhizosphere. Int J Agric Biol. 2013;15(3):603–6.