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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

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Abstract

Background: Soil and water conservation measures (SWC) have a great practical significance to the restoration of arbuscular mycorrhiza (AMF). The objective of this study was to quantify the effect of decades long community-based soil and water conservation practices on arbuscular mycorrhiza fungi spore density, woody plant root colonization, and soil nutrients.

Methods: The SWC measures considered were stone terraces, exclosures + stone terraces, exclosures alone, and adjacent non-conserved open communal grazing lands. Soil and root samples were collected from the rhizosphere of matured woody plant species using systematic sampling from 10 m × 10 m plot based on slope positions. Spores were isolated using wet sieving and decanting method, while AMF fungal root colonization was done using the grid-line intersection method.

Results: The study revealed that five major genera of AMF, including *Glomus*, *Acaulospora*, *Gigaspora*, *Scutellospora*, and *Entrophospora* were identified. *Glomus* was found to be the most abundant genera, which accounted for (52%) of the total spore density, followed by *Acaulospora* (18%). Besides, exclosures had the highest total spore density (60%) being followed by stone terraces (23%), whereas the lowest (17%) spore density was recorded in the open communal grazing lands. Total root colonization among the treatments ranged from 48.6% in the open communal grazing lands to 68.7% in the exclosure with terraces. Hyphal colonization was higher than arbuscular and vesicular colonization. The total colonization was in the order of exclosure with terraces > exclosure alone > terraces > non-conserved communal grazing lands.

Conclusions: Rehabilitating the communal grazing lands with terraces and exclosure is an important approach for restoring AMF and regenerating the degraded lands.

Keywords: Arbuscular mycorrhiza, Ethiopia, Exclosure, Soil properties, Terrace

Background

Degradation of communal grazing land vegetation is a widespread problem throughout the Sub-Saharan Africa and its restoration is a challenge for the management of many semi-arid areas [1]. It is a major ecological problem in Tigray high lands northern, Ethiopia [2]. Steep slopes have been cultivated and grazed for many centuries without effective soil and water conservation measures [3]. This has accelerated the problem of land degradation [4].

Terraces and exclosures have been implemented to reverse the land degradation process [5, 6] and restore the natural vegetation [7]. Exclosures increased biomass, herbaceous cover, and vegetative regeneration

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[8]. Exclosures also improved soil nutrient status, and reduced soil erosion [6]. Terraces decreased surface erosion and improved soil conditions [4]. Soil quality was improved after installation terraces [9, 10].

Soil microbiota have been considered a vital factor for the functioning of ecosystems [11, 12]. Among the soil microbial communities, arbuscular mycorrhizal fungi (AMF) are key components [13].

Arbuscular mycorrhizal fungi are ubiquitous in natural ecosystems and form intimate symbiotic associations with the majority of terrestrial plant roots [14]. More than 80% of the terrestrial plant species are associated with mycorrhizal fungi [15]. AMF are fundamental for soil fertility enhancement [16]. They increase organic carbon content and stability, improve soil water relation, and increase phosphorus availability [17]. Mycorrhiza play a key role in regulating abiotic and biotic stresses in plants [18].

Degraded lands harbor low levels of AMF abundance and diversity [19]. Many studies found that disturbance of semi-arid ecosystems decreased mycorrhizal spore density and root colonization [20, 21]. It was also reported that livestock and human disturbances decreased AMF spore density, root colonization, and nutrient availability [22]. However, establishment of exclosures on degraded communal grazing lands significantly improved spore density and root colonization [23]. Nutrient stocks and concentrations of soil organic matter (SOM), total nitrogen (TN), and available phosphorus (AP) were found higher in areas with high AMF [21].

Notwithstanding the massive undertakings of community-based soil and water conservation practices and the enormous benefits of AMF in soil fertility restoration; so far there has been no systematic study conducted on the effect of SWC practices on AMF in the area. Therefore, this study was conducted with the objective of quantifying the effect of decades old terraces, exclosures with and without terrace on AMF spore density, root colonization, and soil nutrients.

The research questions answered include the following: did the support of free grazing lands with terrace increase AMF spore density and root colonization? Could protection of free grazing lands through exclosure increase AMF spore density and root colonization? Could exclosures supported with terrace result in significant increase in AMF spore density and root colonization? Is there any correlation between spore density, root colonization, and soil nutrients?

Methods

Description of the study area

The study was conducted in Degua Temben district, which is located at 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 area is characterized by rugged topography with some flat areas. The elevation and morphology are typical for the northern Ethiopian highlands [3].

The lithology of the study area comprises mesozoic sedimentary rocks and tertiary basalt. Soils of the study sites developed from calcium carbonate-rich parent material of the Agula shale formation, which consists mainly of marble and limestone [24]. According to World Reference Base [25] soil classification system, *Calcaric Cambisols*, *Vertic Leptosols*, *Vertic Cambisols*, and *Lithic Leptosols* are the dominant soil types in the study area.

The annual rainfall ranges from 290 to 900 mm year^{-1} with an average value of 615 mm year^{-1}. The main rainy season starts in June, peaks in July and August, and trails off in September, with a growing period of between 90 and 120 days. All the study sites are classified with in mid-altitude according to the traditional agro-climatic classification system, which is used in Ethiopia.

The vegetation type of the area is open woodland and the most common woody vegetation species identified in exclosures and in communal grazing lands include *Acacia etbaica*, *Carissa edulis*, *Dodonaea angustifolia*, *Stereospermum kunthianum*, *Rhus vulgaris*, *Senna singueana,* and *Euclea racemosa*. The understory vegetation is also dominated by a diverse assemblage of grasses and herbs including *Aristida*, *Eragrostis, Cenchrus, Hyparrhenia*, and *Sporobolus* which are used to feed livestock via cut and carry system.

Mixed farming system (crop and livestock) is the livelihood in the study area. Major land uses in the study area were forest lands, cultivated lands, exclosures, and communal grazing lands.

As almost all the accessible land is over-cultivated or used intensively for grazing, protection, and conservation of these degraded sites through integrated soil and water conservation practices (ISWC) such as stone-faced terraces, enforcement of grazing restrictions and plantation development efforts are commonly practiced [3, 4]. These activities increased woody plant regeneration, density, diversity, and abundance [26].

The most commonly accepted and applied soil and water conservation measures (i.e., terraces and exclosures with and without terraces) were established since 1997 by the community. Before their establishment, the selected SWC measures had similar history in terms of grazing with the non-conserved communal grazing lands.

Each of the three selected sites was categorized into four management units described as terrace, exclosure + terrace, exclosure alone, and non-conserved open communal grazing lands (Table 1). There was no significant difference between spatial heterogeneity

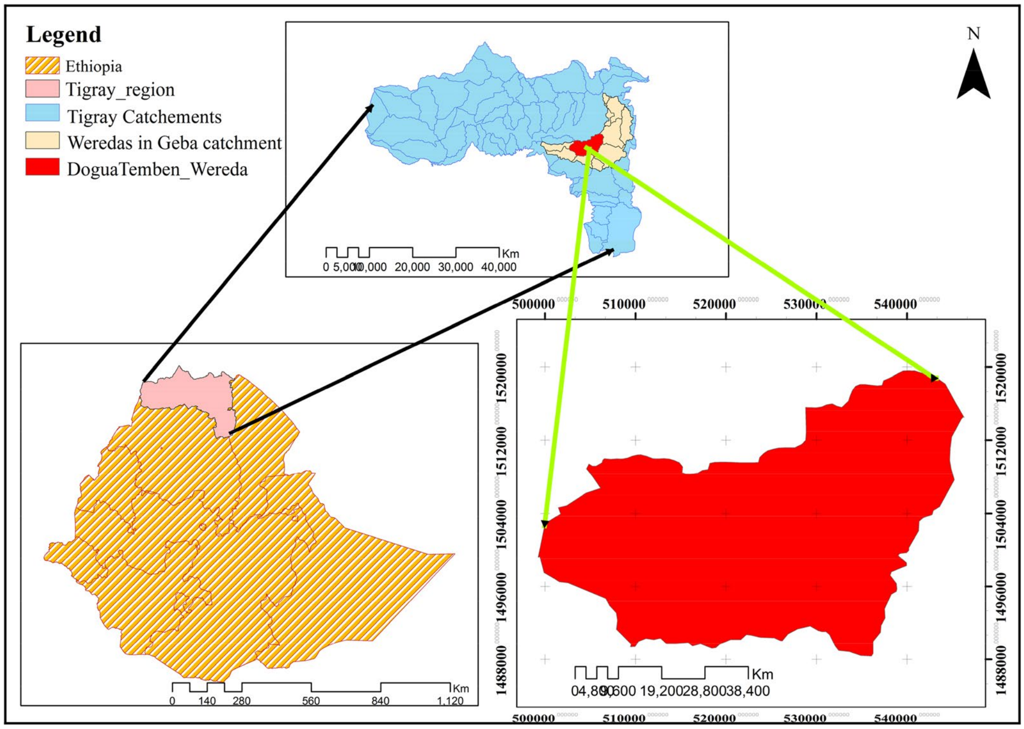

Fig. 1 Location map of the study area

(topography, soil type, vegetation, and livestock and human disturbances) among the selected sites.

Experimental design

The study was conducted in three nearby sites (*Kerano*, *Tesemat*, and *Alasa* within the district) and having all the SWC measures. In each SWC measure, three transects separated at a minimum distance of 75 m were established. The 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.

Three sampling plots or quadrats of 10 m*10 m size (50 m apart from each other) were delineated in each slope position. Soil and root samples were collected from the rhizosphere of matured woody plant species (i.e., *Acacia etbaica*, *Carissa edulis*, *Dodonaea angustifolia*, *Stereospermum kunthianum*, *Rhus vulgaris*, *Senna singueana*, and *Euclea racemosa*) commonly found in all soil and water conservation measures.

Isolation, enumeration, and identification of AMF spores

Spores were isolated from soil samples that were collected from each corner (i.e., 0–15 cm from the stem) of the same and matured woody plant species in each SWC measure. Spores were isolated using 25 g soils by wet sieving and decanting method in a nest of three soil sieves with different mesh sizes (i.e., 300, 100, and 50 μm) and sucrose density centrifugation [27]. The residues on the sieves were washed into beaker with water and filtered through filter papers. Each filter paper was spread on petri dish and spores were counted using a dissection microscope at 40 × magnification. A sporocarp was counted as one unit.

Spore identification

A compound microscope was used to identify the quantified spores to their respective genera. The identification or characterization was based on morphological characters such as spore size, color, surface ornamentation, wall structure as well as presence and absence of subtending hyphae with reference to the descriptions provided by Schüßler and Walker [28].

Estimation of AMF root colonization

The rhizosphere of each matured woody plant species was excavated up to 30 cm depth around all corners (i.e., 0–15 cm distance from the stem of the plant) at the end

Table 1 Characteristics of the community-based soil and water conservation measures

SWC measures	Characteristics
Non-conserved communal grazing land	Low vegetation cover High proportion of bare soil Coarse fragment (57%) Sheet, rill, and gully erosion very common Relatively low organic carbon (1.9%) Moisture content (8.6%) Bulk density (1290 kg m^{-3}) Area (11–34.96 ha)
Stone terraces	Relatively more stable and durable than other physical SWC measures Soil organic carbon (2.5%) Moisture content (9.6%) Bulk density (1260 kg m^{-3}) Coarse fragment (53%) High sediment deposit Area (13.87–24.42 ha)
Exclosure + terrace	Closed from the interference of humans and livestock Enrichment planting common Supported with terraces High organic carbon (2.9%) Sheet, rill, and gully formation are less common Moisture content (10.06%) Bulk density (1240 kg m^{-3}) Coarse fragment (46%) Area (12.74–51.80 ha)
Exclosures alone	Closed from humans and livestock interference No enrichment planting No physical SWC measures High organic carbon (2.8%) Moisture content (8.7%) Bulk density (1220 kg m^{-3}) Coarse fragment (51%) Sheet, rill, and gully formation are less common Area (14.02–34.7 ha)

of rainy season (during October). Only fine and live root samples were collected and put into plastic jar, and filled with 97% ethanol to preserve the roots until processing.

In the laboratory, the root samples were washed thoroughly in tap water, cut it to approximately 1 cm and cleared in 10% KOH for 20 min at 120 °C, acidified with 3% HCl, and stained with trypan blue. The stained root samples were mounted on microscope slides in polyvinyl lacto glycerol (PVLG) and examined for AMF colonization under light microscope. Root lengths with mycorrhizal colonization in the form of arbuscules, vesicles, and hyphae in 100 root segments from each plant species were estimated using the gridline intersection method of [29]. Finally, the average AMF root colonization of woody plant species of each plot across slope position within each SWC measure were considered to calculate and analyze AMF root colonization. Calculation was done as follows

$$\text{Total intersection points } (G) = (p + q + r + s + t + u)$$

$$\text{Total root colonization} = [(G - P)/G] * 100$$

$$\text{Hyphal colonization (HC)} = [(G - (q + r + s) - p)/G] * 100 \text{ or } (q + r + s + t)/G * 100$$

$$\text{Arbuscular colonization (AC)} = (q + s)/G * 100$$

$$\text{Vesicular colonization (VC)} = (r + s)/G * 100,$$

where p is the intersection where no fungal structures are seen, q intersection is where arbuscules is seen, r intersection is where mycorrhizal vesicles are seen, s intersection is where arbuscules and mycorrhizal vesicles are seen, t intersection is where mycorrhizal hyphae but no arbuscules or mycorrhizal vesicles are seen, u intersection is where mycorrhizal hyphae is not seen is connected to arbuscules or mycorrhizal vesicles.

Determination of soil physical and chemical properties

Soil samples were collected from the top (0–30 cm) soil depth at a distance of 0 to 15 cm from the stem of the plants. In the lab, soil samples of each woody plant species were air dried and a composite soil sample was formed from each woody plant of the same species found in each SWC measure.

Soil samples were sieved through 2 mm mesh to remove stones, roots, and large organic residues. Soil texture was determined using a hydrometer [30], soil pH by using a combined glass electrode pH meters in 1:2.5 soil–water [31], soil organic (OC) by wet combustion [32], total nitrogen according to [33], and soil available P was determined by Olsen method [34].

Data analysis

The mean spore density, root colonization, and soil nutrients was tested using ANOVA and comparison of means was made based on Duncan's multiple range test (DMRT) using SAS 9.2. Pearson correlation coefficient was calculated to see for any correlation between the AMF spore density and root colonization and soil nutrients.

Results and discussion

Effect of community-based soil and water conservation measures on total AMF spore density

The study identified five genera of AMF that include *Glomus*, *Acaulospora*, *Gigaspora*, *Scutellospora*, and *Entrophospora*. Total spore density was significantly ($P < 0.05$) affected by the community-based soil and water conservation measures (Table 2). *Glomus* was the most abundant (52%) genus, followed by *Acaulospora* (18%). This could be due to the resistance of these genera to disturbances. Arbuscular mycorrhiza fungi species that

Table 2 Effect of SWC measures on total spore density (mean ± SEM)

Spore type	Non-conserved grazing lands	Terraces	Exclosures + terraces	Exclosures alone
Glomus	436.7 ± 72[b]	587.8 ± 58[ab]	754.4 ± 86[a]	815.5 ± 97[a]
Acaulospora	142.2 ± 22[b]	230.0 ± 42[ab]	276.7 ± 33[a]	257.8 ± 29[a]
Gigaspora	104.4 ± 18[b]	152.2 ± 18[ab]	181.1 ± 14[a]	196.7 ± 30[a]
Scutellospora	125.6 ± 18[a]	142.2 ± 21[a]	193.3 ± 27[a]	188.9 ± 18[a]
Entrophospora	16.6 ± 8[b]	42.2 ± 9[ab]	83.3 ± 25[a]	58.9 ± 13[ab]
Grand total	825.6 ± 121[b]	1154.0 ± 103[ab]	1489.0 ± 112[a]	1518.0 ± 158[a]

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

belong to the genera *Glomus* and *Acaulospora* are resistant to soil disturbances and altered ecosystems [18, 21, 35]. They are also not host-specific and might be found to be associated with various plants in the same locality [36].

Scutellospora accounted only for 13%, *Gigaspora* for 12.7%, and *Entrophospora* about 4% of the total spore density (Table 2). *Glomus* was the most abundant due to the fact that it is also sporageous, while *Entrophospora* was found to be the least abundant genus because it is sensitive to disturbances. In line with this, *Glomus* was abundant in *Boswellia papyrifera*-dominated woodlands of northern Ethiopia [8]. Likewise, Wubet et al. [37] reported that *Glomus* was abundant in indigenous trees in dry Afromontane forests of Ethiopia.

Basically, AMF spore densities are affected by soil erosion and mechanical disturbance due to livestock grazing. Due to this reason, the lowest spore density which accounted for 16.5% (Table 2) was found in non-conserved communal grazing lands. In connection, Muleta et al. [21] found that soil disturbance has reduced AM fungi spore densities. Particularly, AM fungi *Entrophospora* is sensitive to human disturbance and soil erosion. Scarcity of *Entrophospora* in the rhizosphere of woody plant species is attributed to the disruption of the extraradical hyphae [21].

Total spore density in the exclosures ranged from 1488.9 to 1517.8 spore 100 g^{-1} of dry soil while stone terraces accounted 1154 spores 100 g^{-1} of dry soil. Both exclosures also had significantly ($P < 0.05$) higher spore density than free grazing lands without SWC structure. This may be due to the presence of favorable environment such as high organic carbon content in exclosures. Similarly, Birhane et al. [22] found up to 2980 spores 100 g^{-1} dry soil in exclosures. Terraces had higher mean total spore density than free grazing land without any SWC structures (Table 2). Non-conserved open communal grazing lands had the lowest mean total AMF spore density (825 spores 100 g^{-1} dry soils). In this study, it is witnessed that community-based soil and water conservation (CBSWC) practices had brought significant change in spore density. Exclosures had brought about 45.6% increment in spore density as compared to the non-conserved communal grazing lands and 28.5% against the stone terraces. Besides, a stone terrace has resulted in 24% increment in spore density as compared to the non-conserved communal grazing lands. Spore density of the different CBSWC measures was in the order of exclosures alone > exclosures + terraces > terraces > non-conserved communal grazing lands.

Effect of slope position on total AMF spore density

The highest spore density was found at foot slope as compared to the middle and upper slope positions (Table 3). The highest spore density (i.e., 1616 spores 100 g^{-1} dry soil) was recorded at the foot slope in exclosures without terraces, whereas the lowest total spore density (i.e., 723 spores 100 g^{-1} dry soil) was found at the upper slope position in non-conserved communal grazing lands (Table 3). The variation could be due to displacement of spores by erosion from the upper to down slope position. This is in agreement to Birhane et al. [23] who found significantly higher spore density at the foot than the middle and upper slope positions. Large variations in spore density between slope positions could also be due to the properties of the soils, host relations, and the differential survival strategies of AMF [22].

Effect of community-based soil and water conservation measures on AMF root colonization

Root colonization by AMF is characterized by the presence of hyphae, arbuscules and vesicles. In this study, it was found that the different CBSWC measures had brought a significant ($P < 0.05$) variation in the total AMF root colonization. The total percent of AMF root colonization was the highest (68.7%) in the exclosures + terrace. The lowest (48.6%) total percent of AMF root colonization was recorded in the non-conserved communal grazing lands (Table 4). This indicated grazing decreased AMF root colonization. Grazing by herbivores decreased colonization by AMF [38]. Earlier studies reported that disturbance generally had the greatest impact on biological properties, including symbiotic fungal populations [39, 40].

Table 3 Effect of slope positions on total spore density

Slope position	Non-conserved grazing lands	Terraces	Exclosures + terraces	Exclosures alone
Foot slope	903.3^{ab}	1210.0^{ab}	1603.3^{a}	1616.6^{a}
Middle slope	850.0^{ab}	1066.6^{ab}	1466.6^{ab}	1506.6^{ab}
Upper slope	723.3^{b}	1186.6^{ab}	1396.6^{ab}	1430.0^{ab}

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

Table 4 Effect of SWC measures on root colonization (mean ± SEM)

Root colonization types	Soil and water conservation measures			
	Non-conserved communal grazing lands	Terraces	Exclosures + terraces	Exclosures alone
Total (%)	48.6 ± 3^{c}	60.5 ± 2^{b}	68.7 ± 2^{a}	67.8 ± 4^{a}
Hyphal (%)	21.2 ± 3^{b}	28.2 ± 4^{b}	45.3 ± 4^{a}	41.1 ± 3^{a}
Arbuscular (%)	7.1 ± 2^{b}	7.6 ± 2^{b}	18.5 ± 1^{a}	15.9 ± 3^{a}
Vesicular (%)	4.3 ± 1^{b}	8.9 ± 3^{a}	12.4 ± 1^{a}	12.9 ± 2^{a}

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

There was no significant difference in total percent of root length colonization between the two exclosure types (Table 4). However, exclosures had significantly ($P < 0.05$) higher total AMF root colonization than terraces. Besides, exclosures and terraces had significantly ($P < 0.05$) higher total AMF colonization than non-conserved communal grazing lands (Table 4). Total root colonization by AMF was in the order of exclosures + terraces > exclosures alone > terraces > non-conserved grazing lands. The presence of high organic carbon and lower disturbance in exclosures (Table 1) could resulted in high AMF root colonization compared to terraces and non-conserved grazing lands.

Exclosures resulted about 29% increase in total root colonization as compared to non-conserved communal grazing lands and 12% increase as compared to terraces, while terraces resulted in 20% increase in total root colonization compared to non-conserved communal grazing lands. Hyphal colonization was the highest in all conservation measures followed by arbuscular colonization but vesicular colonization was the lowest (Table 4). In many studies, it was also found that Hyphal root colonization > arbuscular > vesicular colonization [8, 21, 22].

Effect of community-based soil and water conservation measures on soil physicochemical properties

Soil and water conservation had brought significant ($P < 0.05$) variation on most rhizosphere soil nutrients. Most of the rhizosphere soil nutrients were higher in exclosures and followed by terraces; and the lowest was found in non-conserved communal grazing lands (Table 5). Significant ($P < 0.05$) variation in soil organic carbon content was found between the CBSWC measures. Similarly, Demelash and Stahr et al. [41] reported that soil and water conservation measures increased the soil organic carbon content. The highest organic carbon content was found in the exclosures + terraces being followed by the exclosures alone (Table 1). The lowest was obtained in the non-conserved open communal grazing lands. Organic matter content of the CBSWC measures was in the order of exclosures + terraces > exclosures alone > terraces > non-conserved grazing lands.

The pH content of all the soil and water conservation measures is classified as moderately alkaline [42]. This indicates the soils have calcium carbonate. pH was significantly ($P < 0.05$) lower in exclosures than terraced and non-terraced open communal grazing lands (Table 5). This could be due to the presence of high organic matter in exclosures. Many studies showed that ungrazed lands had high SOC but low pH than grazed sites [3, 25]. The pH of the CBSWC measures was in the order of non-conserved communal grazing lands > terraces > exclosures + terraces > exclosures alone.

Available phosphorus in terraced and non-terraced open communal grazing land is rated as medium, whereas it is classed as high in case of both exclosures [42]. Available potassium is rated as medium in case of terraced and non-terraced open communal grazing lands (Table 5), where as it is rated as high in case of both exclosures [43].

The total nitrogen in case of terraced and non-terraced open grazing lands is classed as high while those of both types of exclosures is rated as very high [42]. In conformity, other researchers also reported significantly higher total soil nitrogen and available potassium in exclosures than in the grazed areas [44] and on terraced than non-terraced lands [41].

Table 5 Effect of SWC measures on rhizosphere soil physicochemical properties

Physicochemical properties	Soil and water conservation measures			
	Non-conserved grazing lands	Terraces	Exclosures + terraces	Exclosures alone
pH	8.22^{b}	8.21^{b}	8.1^{a}	7.9^{a}
Ec (cS/M)	0.13^{a}	0.12^{a}	0.12^{a}	0.11^{a}
TN (%)	0.21^{c}	0.24^{bc}	0.28^{ab}	0.31^{a}
Avail. P (ppm)	4.13 ± 1^{a}	4.60 ± 1^{a}	5.70 ± 1^{a}	6.99 ± 1^{a}
Avail. K cmol (+)/kg	0.49^{b}	0.59^{b}	0.61^{b}	0.8^{a}
Sand (%)	36.48 ± 3^{a}	31.43 ± 2^{b}	28.67 ± 2^{b}	32.57 ± 2^{ab}
Silt (%)	29.81 ± 1^{a}	31.33 ± 1^{a}	29.81 ± 1^{a}	32.38 ± 2^{a}
Clay (%)	33.71 ± 3^{b}	37.24 ± 1^{ab}	40.29 ± 2^{a}	35.14 ± 2^{b}

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

AvaP available phosphorus, *AvaK* available potassium, *OC* organic carbon, *TN* total nitrogen, *Ec* electrical conductivity

Table 6 Pearson correlations between rhizosphere soil properties and AMF spore densities and root colonization

Soil properties	pH	EC	TN	P	K	OC	Sand	Silt	Clay	Total spore	TRC	HC	AC	VC
pH	1													
EC	0.31**	1												
TN	−0.04^{ns}	0.40***	1											
AvaP	−0.05^{ns}	0.14^{ns}	0.40***	1										
AvaK	−0.34**	−0.13^{ns}	0.46***	0.48***	1									
OC	−0.01^{ns}	−0.21*	0.16^{ns}	0.04^{ns}	0.26*	1								
Sand	−0.15^{ns}	0.01^{ns}	0.19^{ns}	0.07^{ns}	0.05^{ns}	−0.07^{ns}	1							
Silt	0.05^{ns}	−0.14^{ns}	−0.22*	0.10^{ns}	0.04^{ns}	−0.06^{ns}	−0.26*							
Clay	0.10**	0.05^{ns}	−0.05^{ns}	−0.12^{ns}	−0.07^{ns}	0.12^{ns}	−0.83**	−0.31^{ns}	1					
Total spore	0.05^{ns}	0.16^{ns}	0.46***	0.25*	0.33***	0.21*	0.21*	−0.11^{ns}	−0.15^{ns}	1				
TRC	0.26*	0.25*	0.23*	0.16^{ns}	0.05^{ns}	0.38*	−0.09^{ns}	0.22*	−0.03^{ns}	0.36*	1			
HC	0.21^{ns}	0.25*	0.28**	0.12^{ns}	0.06^{ns}	0.30**	−0.10^{ns}	0.13^{ns}	0.03^{ns}	0.30*	0.86*	1		
AC	0.09^{ns}	0.12^{ns}	0.21*	0.17^{ns}	0.10^{ns}	0.11^{ns}	−0.01^{ns}	0.25*	−0.14^{ns}	0.20*	0.51*	0.69^{ns}	1	
VC	0.29**	0.18^{ns}	0.08^{ns}	−0.03^{ns}	−0.01^{ns}	0.27*	−0.16^{ns}	0.09^{ns}	0.11^{ns}	0.01^{ns}	0.67*	0.81^{ns}	0.45^{ns}	1

* Correlation is significant at 0.05 levels (pair wise). ** Correlation is significant at 0.01 levels (pair wise). *** Correlation is significant at 0.001 ns. Correlation is not significant at $P < 0.05$

Relationship between AMF spore density, root colonization, and soil nutrients

Correlation of arbuscular mycorrhizal fungal spore density and percent of total root colonization were positive and significant ($P < 0.05$). Spore density and total root colonization (TRC) were significantly ($P < 0.05$) and positively related. Total root colonization was significantly correlated with pH total nitrogen, organic carbon, and electrical conductivity, while total spore density was significantly correlated with total nitrogen, available phosphorus, available potassium and organic carbon (Table 6). Unlike silt and clay fraction, a positive correlation between spore density and total root colonization (TRC), and sand fraction was observed. Belay et al. [45] found a positive correlation of spore density with sand fraction under acacia species in central highlands of Ethiopia. Sand fractions is known to have many macropores and this indicated the need of macropore spaces for increased AMF density. Spore density and root colonization were also positively related [22, 46]. In contrast, a study by Alghamdi and Jais [47] in Saudi Arabia found a negative correlation of AMF with sand proportions but positive and strong correlation of AMF with silt and clay under *Juniperus procera*. This could be due to variation in the nature of the soil, climate, and the plant considered.

A positive correlation between AMF spore density and available phosphorus was observed. In line with this, Ong et al. [48] found positive correlation between spore count and soil available P due to the fact that the P concentration in the soil was low, thus allowing the enhancement of mycorrhizal sporulation. This finding is also in agreement with Muleta et al. [21] but in contrast to [22, 49] who found negative correlation between AMF and available phosphorus. This could be due to variation in root property of woody plants, climatic factors, and the phosphorus status of the plant.

Conclusions

The different soil and water conservation measures resulted in significant variation in AMF and soil nutrients. Slope position also brought relative variation in spore count and root colonization and need to be considered in the design of AMF and soil nutrient study of degraded landscapes. Exclosure management and supporting open grazing lands with terrace enhanced AMF spore density root colonization and soil nutrients. Therefore, community-based soil and water conservation practice is a dependable rehabilitation or restoration approach, which helps to boost the arbuscular mycorrhizal fungi and soil nutrients in degraded lands.

Abbreviations

Avail. P: available phosphorus; Avail. K: available potassium; OC: organic carbon; TN: total nitrogen; Ec: electrical conductivity; ARC: average root colonization.

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 of results, and drafted the manuscript. FK and BB as supervisors participated in reviewing the manuscript. EB was supervisor and participated in designing the field experiment and reviewed the manuscript in depth. 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 the 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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