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Sustainable land management practices and their impact on soil organic matter content and other chemical parameters, the case of Northern Ethiopia

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Land management practices have a major impact on soil chemical quality, agricultural productivity and land sustainability. Land use change and management affects soil chemical properties and resilience, which is directly related with sustainability of agriculture production. The importance of sustainable land management practices SLMPs applied in northern Ethiopia has not been evaluated in terms of their contribution for improving soil organic matter content and other soil chemical quality. The aim of this study was to compare the impacts of different SLMPs on SOM content and other chemical parameters. Six types of SLMPs (area closure AC, crop rotation CR, conventional tillage CT, grazing land GL, conservation agriculture (DER+) and fallow land FL) were selected and arranged in a randomized complete block design with three replications on Vertisols and Leptosols. Soil texture, soil organic matter, total nitrogen, available phosphorus and soil structure stability index were measured. SOM and total N were significantly higher ($p < 0.05$) on AC under both types of soil followed by CA, it was lower in GL and CR in Leptosols. In Leptosols the amount of available P were significantly higher than the rest land management. Except AC on Vertisols, which showed a value (8.99%) greater than the critical limit for soil structural degradation but the other land management in both soil types the value of soil structure stability were below the critical limit for land degradation. So soil on GL and CT needs urgent management changes in order to obtain good quality and maintain soil resilience. Generally, the importance of AC, CA and FL in improving and restoring SOM, total N, available P and, thus increasing crop productivity, land sustainability and maintaining long-term land resilience thereby avoiding further land degradation. However, the improvement in organic matter content and others chemical properties cannot seen immediately and the full benefit of AC, CA and land fallowing can only be expected after several years.

Keywords: Conservation agriculture, Soil resilience, Vertisols, Leptosols, Crop rotation, Fallow land Grazing land, Soil structural index, Soil organic matter

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INTRODUCTION

Sustainable agriculture practices are practices that meet current and future societal needs for food and fibre, for ecosystem services, and for healthy lives, and that do so by maximizing the net benefit to society when all costs and benefits of the practices are considered. Land use change and management affects soil chemical properties and resilience, which is directly related with sustainability of agriculture production (Szabolcs, 1994). Sustainability is based on the long-term maintenance of the capacity and quality of a soil to resist and recover from minor stress and disturbances that can be reduced through land management. These practices include the following, which are not the exhaustive list but could be more of that based on the culture and ancestral practices of different groups of society.

Population growth and small farming unit in the northern part of Ethiopia with intensive cultivation of the landscape caused serious natural resource degradation. As a result of human interference on natural forest, improper land management and grazing land, soil organic matter (SOM) content, total nitrogen and available P and other chemical properties has declined to low level especially in cultivated soils of the northern Ethiopia. Consequence of this soil degradation in chemical soil properties has brought low productivity of agricultural soils due to loss of nutrient through crop removal and water erosion this leads to decline in agricultural productivity, persistent food insecurity, and rural poverty (World Bank, 2008). Soil loss, nutrient depletion and decline in chemical soil quality are some of the manifestations of land degradation. The drastic effect of soil erosion on soil quality and soil organic carbon (SOC) is described in (Kimble et al., 1999) and (Lal, 2004) as the effect of high soil organic matter concentration in the top soil. Thus, the degradation of land in Ethiopia has resulted in the depletion of the carbon stock not only in biomass, but also in soils.

The main causes of soil organic matter depletion and degradation of cropland in northern Ethiopia are the conventional farming practices related to frequently ploughing the land, complete removal of crop residue at harvest, no soil cover being left and aftermath overgrazing of crop fields (Temesgen et al., 2008).

Although total organic matter and N are important for long-term assessments of sustainable land management systems and productivity (Follett et al., 1987), particulate organic C and N and biologically active soil C and N pools have been shown to be equally and sometimes more, responsive to changes in soil management, which makes them excellent indicators of soil quality (Gregorich et al., 1994b).

SOM contributes significantly to soil nutrient resilience (Baldock and Skjemstad, 2000), renders the physical environment of soil suitable for plant growth (Cambardella et al., 2001), increases water holding capacity, erosion resistance, cation exchange capacity and reduces leaching of plant nutrients (Young, 1997). It is also an important source of inorganic nutrients for plant production in natural and managed ecosystems (Solomon et al., 2002). SOM management is envisaged to maintain soil fertility and promote sustainable agriculture (Katyal et al., 2001; Martin et al., 1990). However, unsustainable land use practices on deforested lands have resulted in extensive land degradation of serious concern in the country (Hawando, 1997; Omiti et al., 1999; Solomon et al., 2002).

A variety of land management decisions that might affect soil organic matter content, total nitrogen and available phosphorus including conventional tillage, conservation agriculture, crop rotation, grazing land, land fallowing and exclosures. Tillage, overgrazing, fallowing, crop rotation, use of inorganic fertilizers and compost can affect soil organic matter storage, and soil chemical, biological and physical quality. Soil organic matter content is an indicator of these three forms of soil quality (Shukla et al., 2006). A decrease in organic matter would cause an increase in bulk density and a decrease in porosity, thereby reducing soil infiltration, and water and air storage capacities (Celik, 2005; Franzluebbers et al., 2000; Wall and Heiskanen, 2003). Depletion of soil organic matter storage resulting in soil organic matter deficit represents an opportunity to store organic matter in the soil through a variety of land management approaches. Soil organic matter improves soil structural stability and thus, increases the infiltration of water and air, promoting water retention, and reducing erosion (Gregorich et al., 1994a). Hence, the loss of soil carbon (SC) with cultivation is usually linked to the deterioration of soil physical properties. Reducing both tillage intensity and frequency will decrease the decomposing of organic matter and this might lead to improved soil tilth, soil quality and microbial activity, resulting in soils that are less vulnerable to compaction and more resilient. In addition, reduced tillage combined with residue retention indirectly defines the species composition of the soil microbial community by improving the retention of soil moisture and modifying the soil temperature (Krupinsky et al., 2002). Soil organic carbon (SOC) and soil nutrient (N, P, and K) concentrations significantly increased with increasing fallow duration up to seven years. These increases have been attributed to the decay of above-ground and root biomass of fallow vegetation and the presence of native leguminous species among the vegetation (Samaké et al., 2005). According to Barrios et al. (1998), pre-season soil inorganic N is an effective indicator of plant-available N after different legumes, and also a simple index that relates well to maize yield on nitrogen-deficient soils.

The importance of sustainable land management practices SLMPs applied in northern Ethiopia has not been evaluated in terms of their contribution for improving soil organic matter content and other soil chemical quality. The objective of this study was to compare the impacts of different SLMPs on SOM content and other chemical parameters.

METHODOLOGY

Field site description

All field measurements were conducted at Adi-gudem, Northern Ethiopia (13°14' N and 39°32' E) located 740 km north of Addis Ababa at an altitude of 2100m a.s.l. As part of the Ethiopian highland massif, the study area has in general a cool tropical semi-arid climate. It is characterized by recurrent drought induced moisture stress. Rainfall in the study site tends to be unimodal, with more than 85% falling from July to September. The annual average rainfall is 512 mm and the intensity of the rainfall is very high with almost 60% of the rain having an intensity of greater than 25 mm h^{-1} (MU-IUC, 2007). Rainfall distribution is highly erratic and unpredictable due to the North and South oscillation of the inter-tropical convergence zone (Virgo and Munro, 1978). During the study year, a middle season drought has been observed affecting the emergence of late planted crop such as teff. The mean average temperature of the study area is 19 ºC (FAO, 2005). The average annual evapo-transpiration is estimated to be 1539 mm. Rainfall exceeds potential evapotranspiration only in July and August (Tigist et al., 2010). According to the FAO-UNESCO classification, the soil types of the study area are primarily Calcic Vertisols (Tigist et al., 2010) and the second soil Rendzic Leptosols (FAO-IGAD, 1998). Mixed farming, which includes livestock and subsistence crop production, is the main farming system in Adigudem. The main cereals grown are teff (*Eragrostis tef.*), barley (*Hordeum sp.*), wheat (*Triticum sp.*), sorghum (*Sorghum bicolor* (L) Moench), millet (*Eleusine coracana*) maize (*Zea mays L.*) and pulses. Different species of pulses are also an important part of the crop rotation (Nyssen et al., 2008). Oxen are the only source of draft power used for ploughing (Nyssen et al., 2011).

Experimental layout

Ten treatments were considered in this study, including conventional tillage (CT), conservation agriculture (CA) (derdero+ system, DER+), fallow land (FL), crop rotation (CR), grazing land (GL) and area closure (AC) on Vertisols and conventional tillage (CT), crop rotation (CR), grazing land (GL) and area closure (AC) on Leptosols. The experimental treatments were described in table 1.

All fields were rainfed and managed by local smallholder farmers. The experimental layout was arranged as a randomized complete block design with three replications for all parameters. One plot represents one replication and on each treatment three plots were used. Plots considered were 5m width and 6m long, except for the conservation and conventional tillage on Vertisols, where plot size was 5m x 9m. Prior to field sampling, soil and crop management practices were recorded through semi-structured interviews with the farmer responsible for each field. The questionnaire was developed to collect necessary information regarding the management regime at each site including, type and duration of current and previous management, soil fertility management, type and rotation of crops and annual yield.

Soil sampling and analysis of soil properties

Soil samples were collected from 0-15 cm depth in the first week of July 2014. From each plot, five soil samples were taken at fixed distances along a randomly located transect. The five samples were mixed thoroughly in a large bucket to form a composite soil sample, which was transported to the laboratory for further processing. The samples were air-dried and grinded to pass through a 2 mm sieve for all the chemical soil parameters to be studied, except for total nitrogen and organic carbon, which was passed through 0.5 mm sieve to remove the coarser materials.

Organic carbon was determined using the wet oxidation method (Walkley and Black, 1934), where the carbon was oxidized under standard conditions with potassium dichromate in sulfuric acid solution. Finally, the organic matter (OM) content of the soil was calculated by multiplying the percent OC by 1.724. The Kjeldahl procedure was followed for the determination of total nitrogen as described by Van Ranst et al. (1999). Available phosphorus was determined by the Olsen procedure. In the Olsen procedure, the soil samples were shaken with 0.5M sodium bicarbonate at nearly constant pH of 8.5 in 1:20 of soil to solution ratio for half an hour and the extracts were obtained by filtering the suspension (Olsen et al., 1954). The hydrometer method outlined by the simplified procedure of Day (1965) was used to determine soil particle size distribution. Hydrogen peroxide (H_2O_2) was used to destroy the organic matter and sodium hexa-metaphosphate ($NaPO_3$) was used as dispersing agent. Finally, soil textural names were determined following the textural triangle of USDA system as described by Rowell (1994).

Soil structure stability index(in %) was estimated from SOC and texture as using (Pieri, 1992)

$$\mathrm{SSI} = \frac{1.724\, SOC(\%)}{clay(\%)+silt(\%)} 100 (1)$$

Table 1. Land use types, soil types, land management practices and soil texture of the study area.

Soil type	Treatments	Land management practices	Soil texture
Vertisols	AC	15 years area closure	Clay
	CR	Four years rotation (teff–broad beans–wheat–barley)	Clay
	CT	Experimental field	Clay
	GL	Communal grazing land	Clay
	CA-based DER+	Conservation agriculture plots	Clay
	FL	One year fallow	Clay
Leptosols	AC	15 years area closure	Clay Loam
	CR	Four years rotation (teff–wheat–chicken pea–wheat)	Clay Loam
	CT	Farmer field	Clay Loam
	GL	Communal grazing land	Loam

AC, area closure; CR, crop rotation; CT, conventional tillage; GL, grazing land; CA, conservation agriculture; DER+, derdero; FL, fallow land.

where and (Clay + Silt) is the soil's combined clay and silt content, and SOC (%) is soil organic carbon content and. An SSI >9% indicates stable structure, 7%<SSI ≤9% indicates low risk of structural degradation, 5%< SSI ≤7% indicates high risk of degradation, and SSI ≤5% indicates structurally degraded soil. However, SSI is based on SOC and texture and it is directly related to resilience of the structure but not to the porosity aspects of soil structure yield data collection.

Statistical analysis

The different land management types were used as independent variable (factor) and the soil chemical parameters as dependent variable. The significance difference of soil chemical properties with land management types was tested using analysis of variance (ANOVA). The Tukey procedure was used to separate the means of the soil chemical properties at ($p < 0.05$). Normal distribution and homogeneity of variances for each parameter were tested using the Kolmogoroff–Smirnoff and Levene test respectively.

RESULT

Soil chemical properties

A significant difference ($p<0.05$) in soil organic matter (SOM) content was observed among the treatments in both types of soils (figure 1). The highest values of organic matter content were exhibited on AC in Vertisols (6.56%) followed by AC on Leptosols, CA on Vertisols and GL on Vertisols, with SOM values of 3.64%, 3.20% and 3.05%. respectively. The lowest organic matter contents were observed on GL (1.32%) and CR (1.86%) of Leptosols. No significant difference in SOM was observed between CA and GL on Vertisols ($p >0.05$).

The N content in Vertisols and Leptosols was significantly different between different land use and management practices ($p<0.05$) (figure 2). Highest amounts of total N were obtained in AC on Vertisols (0.426%) and CA on Vertisols (0.197%). The value of total N in AC on Leptosols (0.184%) was relatively higher than the rest of land use and management practices even though it was smaller than AC in Vertisols. A significant low amount of total N was observed on CT (0.10%) and GL (0.083%) in both Vertisols and Leptosols. In contrast, no significant total N differences were observed between GL, CT and FL ($p >0.05$), and CA and CR ($p >0.05$) on Vertisols.

Substantial statistical differences ($p<0.05$) were found in available P between different land use and management treatments (figure 3). Significantly greatest amount of available P was retained under CR in Leptosols (10.49ppm) and higher values were observed on AC (7.83ppm) and CA on Vertisols (7.42ppm). Low available P was measured on FL on Vertisols (1.57ppm) and AC Leptosols (1.79ppm). However, differences in available P between GL and CR and among AC, CT and GL were not significant ($p>0.05$) on Vertisols.

Soil structural stability index (SSI) was not influenced by the type of land use and land management, with no significant differences among treatments under both type of soil, except AC on Vertisols, which showed a value (8.99%) greater than the critical limit for soil structural degradation (figure 4).

Grain and straw yield

There was a significant difference ($p<0.05$) between the land use and management practices in terms of wheat yield. The mean grain and straw yield of wheat on CR and CT of Leptosols was 3.4 t $ha^{-1}$and 11.5t ha^{-1}, and 2.7t ha^{-1} and 6.7 t ha^{-1}respectively.

Teff yields in CT were remarkably lower than in CA on Vertisols (with crop failure under CT, whereas CA showed 0.7 t ha^{-1} grain yield and 3.0 t ha^{-1} straw yield). (table 2)

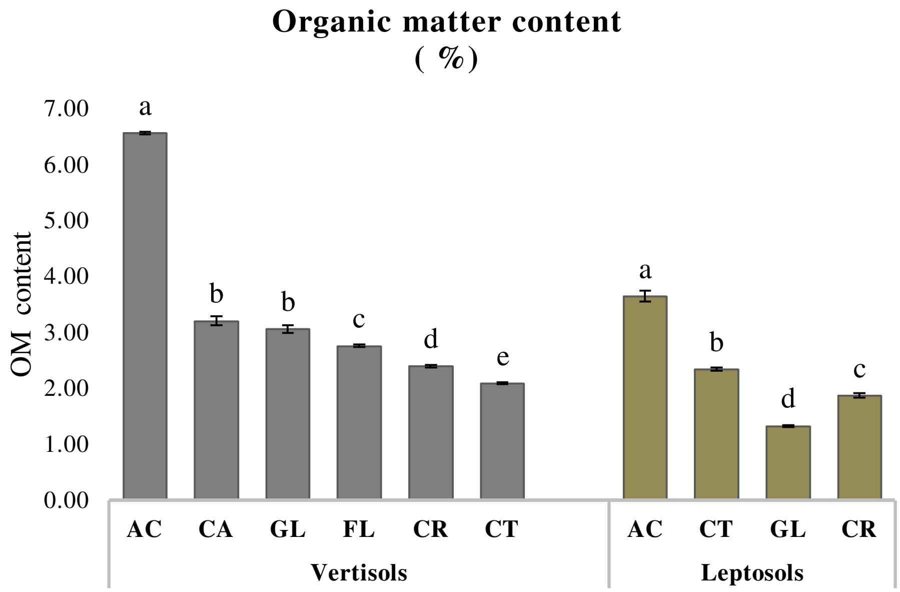

Figure 1. Effect of land management practices on organic matter content, AC, area closure; CR, crop rotation; CT, conventional tillage; GL, grazing land; CA, conservation agriculture; FL, fallow land; OM, organic matter; +,standard error of mean. (Means with the same letters are not significantly different at p<0.05 according to Turkeys'multiple range tests).

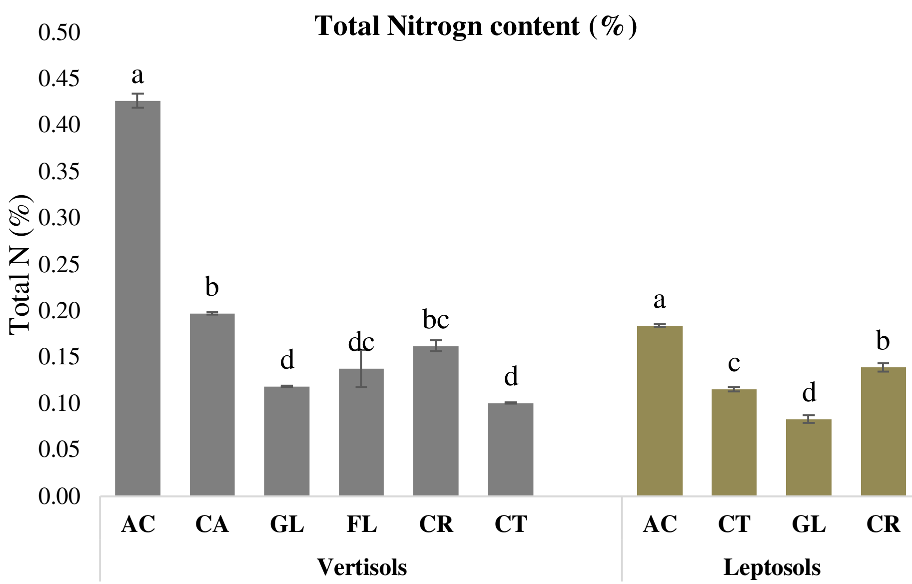

Figure 2 Effect of land management practices on total nitrogen, AC, area closure; CR, crop rotation; CT, conventional tillage; GL, grazing land; CA, conservation agriculture; FL, fallow land, +,standard error of mean. (Means with the same letters are not significantly different at p<0.05 according to Turkeys'multiple range tests).

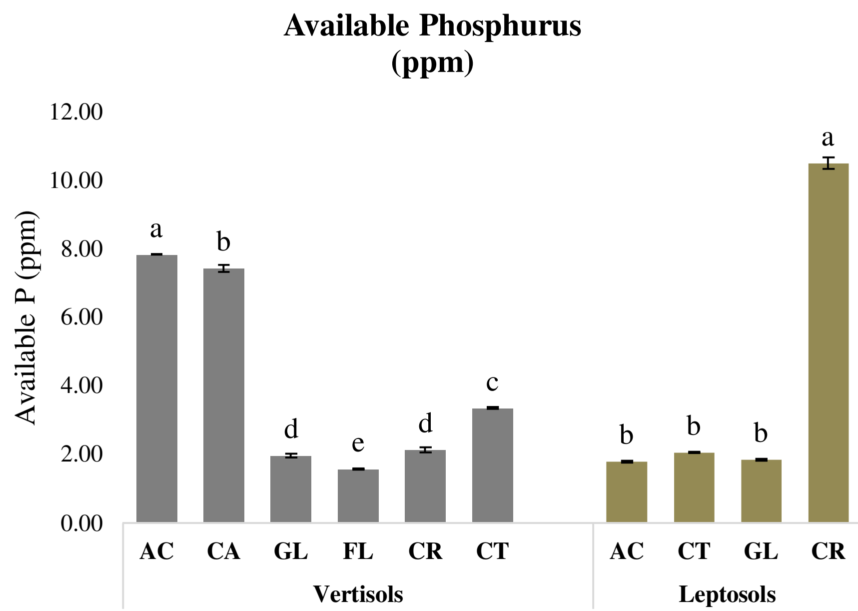

Figure 3. Effect of land management practices on available phosphorus, AC, area closure; CR, crop rotation; CT, conventional tillage; GL, grazing land; CA, conservation agriculture; FL, fallow land; OM, organic matter; SSI, structural stability index; +,standard error of mean. (Means with the same letters are not significantly different at p<0.05 according to Turkeys'multiple range tests).

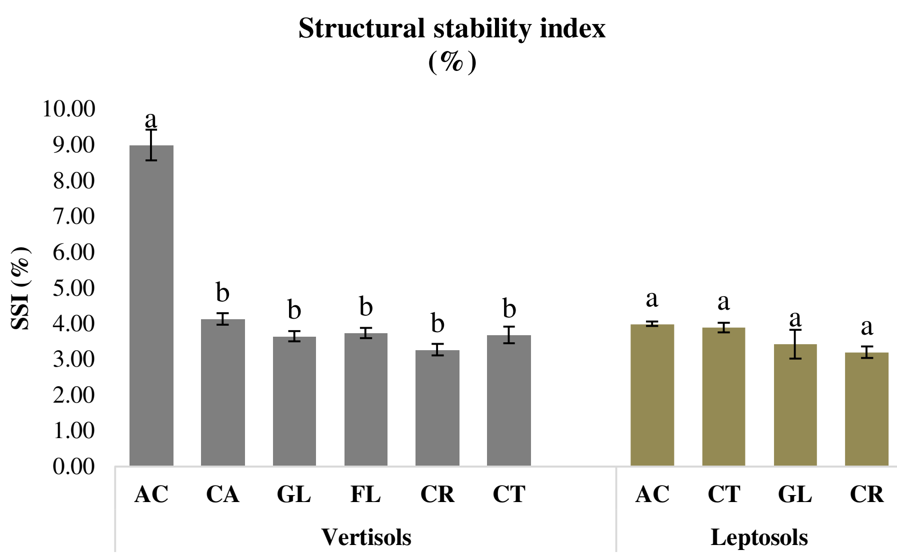

Figure 4. Effect of land management practices soil structural stability index, AC, area closure; CR, crop rotation; CT, conventional tillage; GL, grazing land; CA, conservation agriculture; FL, fallow land; SSI, structural stability index; +,standard error of mean. (Means with the same letters are not significantly different at p<0.05 according to Turkeys'multiple range tests).

Table 2. Grain and straw yield on different land use and management practices on Vertisols and Leptosols in Adi-gudem, Ethiopia.

Soil type	Crop type	Treatments	Grain yield t ha^{-1}	Sd Error	Straw yield t ha^{-1}	Sd error
Vertisols	Teff	CA	0.7b	0.07	3b	0.04
	Barley	CR	2.6a	0.02	5.3a	0.01
	Teff	CT	0c	0	0c	0
Leptosols	Wheat	CT	2.7b	0.10	6.7b	0.09
	Wheat	CR	3.4a	0.08	11.5a	0.05

CA, conservation agriculture; CT, conventional tillage; CR, crop rotation; Sd error, standard error of the mean; (Means with the same letters are not significantly different at p<0.05 according to Turkeys' multiple range tests).

DISCUSSION

Impact of sustainable land management on chemical soil properties

Sustainable land management practices have great impacts on soil chemical properties. Our results show that AC and CA increase organic matter content, total N and available P significantly as compared with the other of land uses and management practices, with increases being most pronounced under AC. This is related to the restoration of natural vegetation, which increased aboveground and belowground litter inputs and possibly litters quality and nutrient cycling.

In a study conducted on effectiveness of exclosures to restore degraded soils as a result of overgrazing in Tigray, Ethiopia, significantly higher organic matter content, total N and available P were found in area closure land management than grazing land (Mekuria et al., 2007). Similar results were found on exclosures established within the last twenty years in the central highlands and northern Ethiopia. Mamo (2008) observed an increase of 0.67% organic matter and 8.85 mg kg^{-1} available P after 9 years of exclosures establishment, whereas after 20 years of exclosures establishment Tsetargachew (2008), found increases in organic matter and total soil N of 2.33% and 0.08%, respectively. Our results are in line with those of Verdoodt et al. (2009) in Kenya who found significantly higher organic matter content and total N in area closure as compared with communal and private grazing land.

The relative high value of organic matter, total N and available P under CA was most probably due to the contribution of plant residue from the previous season and minimum soil disturbance by tillage operation, which attributed to good chemical soil quality and higher soil aggregate stability. Our results coincided with those of Tigist et al. (2010), Araya (2012) and Thierfelder and Wall (2012), who found significantly higher organic matter content and total N in CA as compared with CT. Both Tigist et al. (2010) and Gebreegziabher et al. (2009) concluded that stubble retention and the incorporation of straw increased organic carbon on conservational fields. Our results thus indicate the potential of area closure and conservation agriculture for land restoration, rehabilitation and to maintain soil resilience from degradation.

This study indicated that continuous grazing on Leptosols resulted in less vegetation cover and litter accumulation resulting in very low organic matter and total N concentrations. Due to continuous grazing and frequent trampling by sheep and cattle, the ground surface at the GL site became bare and exposed to wind and water erosion. The reduced vegetation cover and litter accumulation accelerated wind and water erosion. On Vertisols, organic matter content and total N was greater for GL than CR, CT and FL. The possible reason is not well understood but continuous supply of animal faeces on the field, incorporation of dead plant root with soil and no soil disturbance could increase soil organic matter as compared to that of CR and CT.

Different studies confirmed that a land-fallowing system could improve soil fertility in terms of chemical soil quality for degraded land. Abu (2013) found significant increases in organic matter under natural fallowing as compared to continuous cultivation. In this study, we found a slight increase in soil organic matter and total N, but no significant effect was observed in terms of soil organic matter, total N and available P compared with CA and AC. Fallowing period and type of vegetation during fallowing has significant impact on soil chemical quality. According to Aguilera et al. (2013), the length of fallow has a significant impact on restoration of important soil elements, such as soil organic C and N. In south-western Nigeria, Salako et al. (1999) found an increase in soil organic carbon content as fallow length increased from 1 to 3 years. For the same region, Aweto (1981) observed an increase in soil organic matter accumulation as natural fallow increased until the 10th year of fallow.

The overall decrease of organic matter and total N in CT,CR and GL on both soil types may have resulted from a combination of lower C inputs because of less biomass C return on harvested land and greater C losses because of aggregate disruption, increased aeration by tillage, crop residue burning, accelerated water erosion and livestock grazing (Girma, 1998; Mueller-Harvey et al., 1985).

Generally, the amount of organic matter and total N was greater on Vertisols than on Leptosols which is probably due to textural and mineralogical difference between the two soil classes. Leptosols are characterized by shallow soil with continuous hard rock within 25 cm from the surface and weakly developed soil structure. This leads to less vegetation and making them highly susceptible to soil erosion. This could explain the lower in organic matter content and total N in Leptosols in all land use and management practices. According to Greenland (1981), our organic matter content was only above the “critical limit on soil under AC, whereas it felt in the rest of the land use and management practices below the “critical limit” (2.3 wt.%) at which tillage-induced loss of structure may occur in fine-textured soils.

The soil structural stability index (SSI) is a measure of structural degradation in soils. A SSI ≤ 5% is indicative of a structurally degraded soil while, SSI of 5-7% indicates high risk of structural degradation due to insufficient organic carbon (Reynolds et al., 2007). Results of SSI obtained in this study showed that all soils under various land use and management practices were structurally degraded except AC (8.99%). This kind of soil quality assessment might however not be perfect for fine textured soil. Even though we obtained high amounts of organic matter content due to the high clay and silt content relative to sand fraction, our SSI felt under degraded soil structure. Degradation was more pronounced on soils with CT, CR and GL on Vertisols and Leptosols. Ogunwole et al. (2014) found very small SSI values under continuous cropping with high clay and silt texture soil.

Soil aggregation and aggregate stability are influenced largely by soil organic carbon and to some extent, clay (Shukla et al., 2006),which consequently affects the soil’s water storage, water movement and activities of soil biota (Ogunwole et al., 2014), and complex interactions exist between organic carbon storage and aggregate stability.

Impact of land management on crop yield and yield component

Sustainable land management had a great impact on crop yield and yield components. We obtained significant differences between the treatments on both soil types. Grain and straw yield in CR was better than CT on Leptosols. Berzsenyi et al. (2000) suggested that yield under (maize–spring barley–peas–wheat) crop rotation was significantly higher than that of a cereal (wheat-maize) rotation systems. They found yield increments on maize and wheat under rotations as compared to cereal rotation and reduced pathogen impact especially on wheat fields. Another study done on tropical legume crop rotation showed that maximum grain yield (6.03–6.84 t ha^{-1}) was produced by rice after winged bean in both years. However rice in rotation with corn grown produced comparatively lower yield (2.93–3.49 t ha^{-1}) than rice with winged bean (Rahman et al., 2014).

Grain and straw yield under Vertisols was significantly greater on CA than CT, but still yield was lower from the expected one on both fields. The low teff yield might be related to the occurrence of dry spells during germination time on conservation and conventional field. Yield reduction was more pronounced on CT than CA, with CT showing complete crop failure. Crop residue from the previous growing season and absence of soil disturbance could preserve soil moisture from evaporation. That might be the reason why no complete yield failure was observed on CA fields. Mkoga et al. (2010) reported that conservation tillage practices where surface crop residue is used are much more effective in mitigating dry spells and increasing productivity. They found significantly higher yield under ripping with crop residue treatment yielding 3.8 t ha^{-1}as compared to 1.7 t $ha^{-1}$for conventional tillage treatment. Araya et al. (2015) suggested that conservation farming systems were effective in improving water productivity thereby increasing in rainwater harvesting, and improving green water availability and crop yield, hence reducing dry spell effects.

The results of this research suggest that use of crop residue and minimum soil disturbance under CA fields can help in conserving soil moisture needed for enhancing germination, maintaining good plant population and having higher yield compared with conventional tillage practice. Abrecht and Bristow (1996) argue that maintenance of soil cover in close proximity to the emerging seedling slows soil drying, thereby improving water availability to the seedling, delaying the onset of high soil impedance and reduces maximum soil temperature.

CONCLUSION

From this study, we conclude that land use and management has an impact on soil chemical properties resilience and restoration. Fifteen years area closure brings significant changes on soil chemical quality as compared to grazing land and other land management types. It had high soil organic matter, total N, and SSI. CA practices are important to ameliorate soil chemical properties. Comparatively, good chemical soil quality was observed on CA in comparison with the rest of the land use and management practices except AC. Agronomic yields were highly affected by land use and management treatment and climate condition. Appropriate land use and management is important for soil and water conservation as well as dry spell management in dry land environment in order to provide reasonable agronomic yield.

Generally, this study demonstrated the importance of CA, CA and FL in improving and restoring chemical soil quality and thus increasing crop productivity, land sustainability and maintaining long-term land resilience thereby avoiding further land degradation. However, the improvement in chemical properties is not immediate and the full benefit of area closure, conservation agriculture and land fallowing can only be expected after several years.

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