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Journal of Soil Science and Environmental Management

Table of Contents: Volume 7 Number 9 September 2016

ARTICLES

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Journal of Soil Science and Environmental Management

Full Length Research Paper

Variability of soil organic carbon with landforms and land use in the Usambara Mountains of Tanzania

Joel Loitu Meliyo[1*], Balthazar, M. Msanya[2], Didas Nahum Kimaro[3], Boniface Hussein John Massawe[2], Proches, Hieronimo[3] LothS. Mulungu[4], Jozef Deckers[5] and Hubert Gulinck[5]

[1]Selian Agricultural Research Institute, P.O. Box 6024, Arusha, Tanzania.
[2] Department of Soil and Geological Sciences, Sokoine University of Agriculture, P.O. Box 3008, Morogoro, Tanzania.
[3]Department of Engineering Sciences and Technology, Sokoine University of Agriculture,
P.O. Box 3003, Morogoro, Tanzania.
[4]Pest Management Centre, Sokoine University of Agriculture, P.O. Box 3110, Morogoro, Tanzania.
[5]Department of Earth and Environmental Sciences, University of Leuven, Celestijnenlaan 200E, Leuven, Belgium.

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This study was carried out to assist in the formulation of conservation technologies for landscape sustained productivity in the Usambara Mountains, Tanzania. Conventional soil survey methods were used to develop a base map on which 55 soil profile pits were randomly located on representative landforms and land use mapping units. Soil samples were collected from topsoils for soil carbon analysis using the wet digestion method. Descriptive statistics and linear regression models were used to establish relationships between landforms, land use and soil organic carbon levels. Results showed that carbon levels ranged between 0.55 and 10.8% for bush land and forest plantations in the plain and plateau, respectively. Under cultivation, soil organic carbon (SOC) levels varied between 1.03 and 6.34% for mid-slopes and lower slopes of the plateau respectively. The average soil organic carbon in the vegetable growing valley bottoms was 4.5% while in the forest plantation was 5.5% with minimum and maximum of 0.8 and 10.8% respectively. Linear regression model analysis indicated that factors influencing variability of SOC apart from land use are: slope form, soil pH, electrical conductivity and CEC_{clay}. It was concluded that soil organic matter in the study area is mainly determined by elevation, slope form and type of land use and management. Introduction of soil erosion control measures and incorporation of crop residues to areas where soil organic matter has been depleted were recommended for sustainable crop production.

Key words: Soil quality, soil health, topographic variation, organic carbon.

INTRODUCTION

Soil organic carbon is the organic matter constituent of soil, composed of plant and animal residues synthesized by soil organisms at different stages of decay (Chan, 2008; Esmaeilzadeh and Ahangar, 2014). Soil organic

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*Corresponding author. E-mail: joelmeliyo15@gmail.com.

carbon (SOC) is of significant importance in soils because it has high cation exchange capacity (CEC) which influences plant nutrients availability, aggregate stability and microbial activity (Woomer et al., 1994; Bationo et al., 2006; Milne et al., 2006; Abera and Wolde Meskel, 2013; Liao et al., 2015).

Due to the SOC characteristics of high CEC, high water holding capacity (Liang et al., 2006; Gosain et al., 2015) and the role it plays as a source of energy to micro-organisms, SOC strongly influences soil physical, chemical and biological characteristics (Bouajila and Sanaa, 2011; Esmaeilzadeh and Ahangar, 2014). SOC degradation has negative effects mainly on cation exchange capacity, nutrient availability, aggregate stability and microbial activity (Cooperband, 2002; Bot and Benites, 2005; Gosain et al., 2015; FAO, 2015).

Extensive research works have shown that soil organic carbon content plays a crucial role in soil productivity and maintenance of soil and environmental quality (Al-Kaisi et al., 2005; Victoria et al., 2012; Drewniak et al., 2015; Banwart et al., 2015). It has long been realized that ‘worn out’ soils in which productivity has drastically declined may have resulted mainly from the depletion of soil organic matter (Magdoff and van Es, 2000; Young et al., 2015). Some scientists describe soil organic carbon as the major physical, chemical and biological indicator that significantly determines soil health (Brevik, 2012; Singh and Ryan, 2015; FAO, 2015). The stability and distribution of SOC is influenced by both biotic (abundance of faunal, microbial and plant species) and abiotic factors (temperature, moisture and soil texture) (Lorenz and Lal, 2005; Mligo, 2015), which of course are moderated by topography (elevation) and slope gradient and aspect of the landform (Sollins et al., 1996).

According to Baldock and Nelson (2000), topography in particular, elevation, slope and aspect have their influence on climate, soil properties like water content, which are largely responsible for the distribution of SOC in soils. The decrease in temperature with elevation reduces organic matter decomposition rates more than litter production, and therefore promotes the accumulation of SOC that plays a major role as sink for excess atmospheric CO_2 which is sequestered in soils as SOC (Sollins et al., 1996; Banwart et al., 2015). Carbon sequestration plays a role on reducing global warming and general climate change regulation (Singh and Ryan, 2015; Yohannes et al., 2015; FAO, 2015; Parras-Alcantara et al., 2015).

Regardless of the crucial role SOC plays in soil health and environment (Sollins et al., 1996; Lorenz and Lal, 2005; Singh and Ryan, 2015), research (Bot and Benites, 2005) has shown that there are fluctuations leading to SOC decline to low levels in some places and these have mostly been linked to anthropogenic factors as causes and accelerators (Bot and Benites, 2005; Louwagie et al., 2009; Young et al., 2015). The factors mainly are land use changes including clearing natural vegetation for agriculture and succeeding management practices that results in large reduction in soil organic carbon levels (Guo and Gifford, 2002; Houghton et al., 2004; Bot and Benites, 2005; Chan, 2008; Groppo et al., 2015).

The dynamics in SOC upon land use change may occur due to changes in the rates of accumulation, turnover and decomposition of soil organic carbon (Liu et al., 2006; Liu et al., 2010; Poeplau et al., 2011). The type of land use system is an important factor controlling soil organic carbon levels since it influences the amount and quality of litter input, the litter decomposition rates and the processes of organic matter stabilization in soils (Römkenset al., 1999; Eaton et al., 2007).

Literature also indicates that changes of land use and management practices influence the amount and rate of soil organic carbon losses (Post and Kwon, 2000; Corsi et al., 2012; Jamala and Ok, 2013; Young et al., 2015), which is causing considerable concern that land use changes could alter soil carbon equilibrium which in turn could negatively affect soil productivity (Corsi et al., 2012; Singh and Ryan, 2015).

According to Corsi et al. (2012) and Banwart et al. (2015), loss of SOC results in soil degradation and once organic matter is lost, a major repercussion is declined production functions of the soil that can only be restored by addition of soil organic matter through amendments or by changes of management practices such as adoption of conservation tillage. Generally, land use changes and poor agronomic practices have been reported to deplete soil organic carbon thereby lowering soil productivity but, conservation tillage practices have been known to increase soil organic carbon and improves soil productivity (Al-Kaisi et al., 2005; Bot and Benites, 2005).

The burgeoning population pressure on the highlands of East Africa including the West Usambara Mountains has led to vast changes in land use patterns caused mainly by clearing natural forests for additional agricultural land for crop production and settlements. Cultivation in the area has quickly expanded since independence, such that the mountains are dominated by agriculture on steep slope lands with few conserved forest reserves. Information on soil organic carbon in the area which is an important indicator of soil health in relation to land use/cover changes and topography is lacking. This study was designed to investigate the influence of land use changes and topography on soil organic carbon in the West Usambara Mountains of Tanzania. The knowledge will help in formulation of strategies that will conserve SOC and sustainably maintain the productivity of the area.

MATERIALS AND METHODS

Description of the study area

The study area is located between UTM Zone 37, UTM 9474,965 N through 9502,586 N and 444,532E through 472,276E covering an area of about 151,000 ha. It extends from 450 m a.s.l. to about 2270 m a.s.l (Figure 1). The area receives rainfall in two seasons with slight

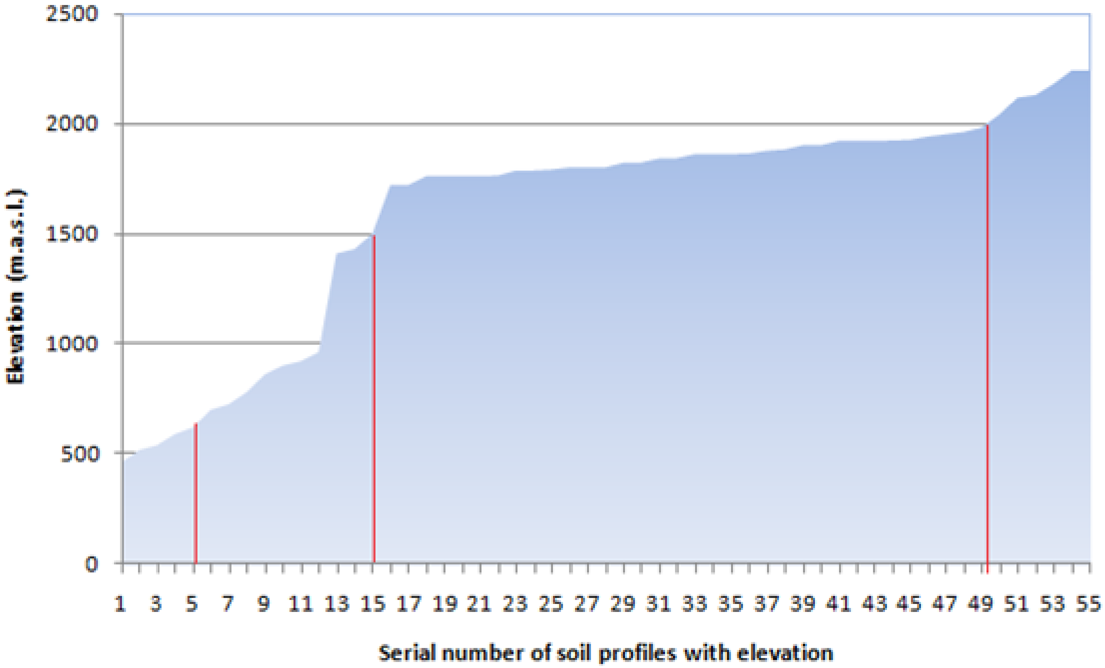

Figure 1. Topographic variation of soil organic carbon study sites in west Usambara Mountains, Tanzania.

variation from 500 to 900 mm per annum for the plains and plateau respectively. The rainfall pattern is weakly bimodal where short rains start in October to December and long rains start on March to end of May. The rainfall onset and distribution are unreliable. The area is also characterised by variable temperature regimes where annual average ranges between 26°C and 30°C for the lowland, and drops with elevation to 15 through 22°C in the plateau. The average relative humidity recorded stands at 70%.

Crops grown in the area vary with topography. In the lowland plains of Usambara Mountains, sisal and maize are the most common crops grown. In the plateau (high altitude areas) maize (*Zea mays*), cassava (*Manihot esculenta*), sweet potato (*Ipomoea batatas*), banana (*Musa* spp.), round potato (*Solanum tuberosum*), and various beans (*Phaesolus* spp.) are grown. Cash crops include assorted vegetables like cabbage (*Brassica* spp.), tomato (*Solanum lycopersicum*) and carrot (*Daucus carota*) and various fruits such as pears, plums and apples. Cultivation is carried out mostly on slopes and on relatively narrow U-shaped valley-bottoms where traditional irrigation is used (Lyamchai et al*.,* 1998; Meliyo et al., 2004).

Soil sample collection

Base maps were prepared indicating mapping units representing landforms, which were overlaid with land use layer. Conventional soil mapping techniques were used to collect soil sample from natural pedogenic horizons. The topography of the study area was categorised using elevation that is, lowland (<600 m. a.s.l.), escarpment (600 to 1500 m.a.s.l), plateau-I (1500 to 2000 m.a.s.l) and plateau-II (>2000 m.a.s.l) (Figure 1). Transects crossing most mapping units along the topography/landscape were made. Representative soil profiles and mini-pits were opened along selected transects and soil samples taken from the natural horizons. The depth (cm) of natural horizons, colours and soil structure were determined using FAO Guidelines for Soil Description (FAO, 2006).

Soil organic carbon determination

Soil samples were air dried and ground to pass through 2-mm sieve for chemical analysis. Standard methods of soil chemical analysis (Page et al., 1982) were used to determine soil organic carbon (%), pH, total nitrogen (%),available phosphorus (mg P/kg soil), cations exchange capacity (CEC) (cmolc/kg soil) and exchangeable bases (cmolc/kg soil). Parameters such as C/N ratio and base saturation percentage (BS %) were calculated. Texture was determined by Hydrometer method (Gee and Bauder, 1986) after destroying soil organic matter to obtain sand, silt and clay fractions.

Data analysis and interpretation

Field and laboratory data were compiled using MS-Excel and explored using both MS-Excel and R- software. Descriptive statistics (means, median StdDev., e.t.c) were used to study factors influencing soil organic carbon (SOC) in the area. Further, landforms and soil parameters influencing SOC were studied using Gaussian Generalized Regression Model (McCullagh and Nelder, 2007).

RESULTS AND DISCUSSION

Influence of topography and landforms on soil organic carbon

The influence of elevation to SOC is depicted in Table 1 and in Figures 2 and 3. The carbon levels range between0.55 and 10.8% for the bushland and forest plantation in the plain and plateau, respectively.

Under cultivation, soil organic carbon levels vary between

Table 1. Variation of SOC, pH $_{(water)}$, texture and soil depth with elevation.

Elevation (m.a.s.l)	Mean values of determined soil parameters					
	Topsoil Ap/Ah depth (cm)	Texture			pH $_{(water)}$	SOC (%)
		Sand (%)	Silt (%)	Clay (%)		
< 600	28	73	11	16	8	1
<620 -1500	18	65	8	27	7	2
< 1500-2000	20	46	13	40	6	4
>2000	13	59	13	28	6	6

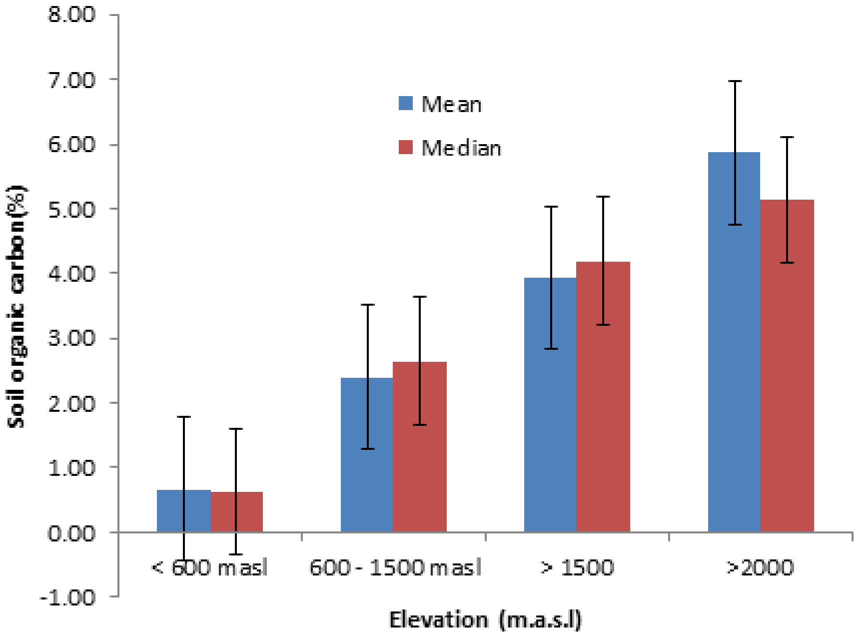

Figure 2. Influence of elevation on accumulation of soil organic carbon in West Usambara Mountains, Tanzania.

between 1.03 and 6.34% for mid-slopes and lower slopes of the plateau respectively, with an average of 3.73%. The mean soil organic carbon in the vegetable growing valley bottoms was 4.5% while it was 5.5% in the forest plantation with minimum and maximum values of 0.8 and 10.8%, respectively. It was observed from these results that the SOC increases with increasing elevation from the plains to the high altitude plateau of West Usambara Mountains depicting significant differences in the distribution of SOC with elevation (Figure 2).

Soil organic carbon increased with elevation from an average of 1 to 6% (Table 1). The observed results may be attributed to variation of rainfall which is low (500 mm) in the lowlands compared to the moderate (> 900 mm) in the high altitude plateau. The observed rainfall variation correlates with establishment of different vegetation types and biomass in both areas. Due to influence of rainfall, there are marked differences of vegetation across the topography. While there are thorny and other drought resistant vegetation such as *Acacia spp.,* and *Cactus spp.,* in the low altitude plains, there are diverse woody and herbaceous vegetation in the high altitude plateau.

The difference in SOC between the topographic positions could also be due to differences in temperatures which play a major role in decomposition of deposited plant and animal residues. There are higher temperatures in low altitude plains of up to over 30°C compared to 15 to 22°C in the high altitude plateau. These results may also be attributed to longer vegetative growing periods in the high plateau than in the low altitude plains. This implies that the different topographic positions affect differently vegetation growth and biomass build up and micro- and macro-organisms which in turn add up soil organic carbon as plant and animal residues. Several authors reported similar results in their studies which indicated increases of tree biomass and soil organic carbon with elevation (Alveset al., 2010; Atkins et al., 2015; Sheng-Xuan et al., 2015).

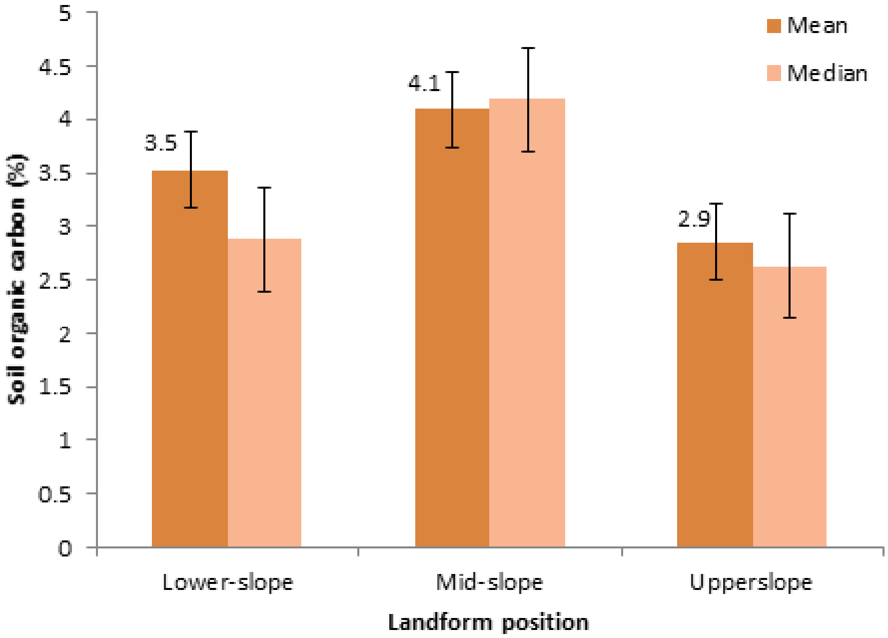

Figure 3. Influence landform position soil organic carbon in West Usambara Mountains, Tanzania.

Furthermore, Liu et al. (2010) indicated that the sensitivity of soil microbial biomass carbon (MBC) also do vary with elevation and topographic position. The team noted that there was greater built up of MBC in the lower than upper slopes and the topographic difference effect was larger in drier years, leading to stronger temporal variability of soil microbial biomass carbon at the upper than lower slope (Liu et al., 2010). These results agreed with several authors who indicated that natural factors which influence SOC include temperature, topography, vegetation and biomass production (Bot and Benites, 2005; FAO, 2015; Atkins et al., 2015).

In this study, it was also observed that comparably, large vegetation biomass builds up in the plateau, accompanied with low rate of decomposition due to low temperature hence the soil microbes which are decomposers are less active compared to those in the low altitude plains, a situation which agrees with a report by Liu et al. (2010). Additionally, results indicated in Figure3 may also be explained from the anthropogenic point of view, an account which was also reported by Bot and Benites (2005). Most of the hills and mountains in the plateau are characterised by shallow soils in the upper slopes which support poor vegetation establishment, while the middle slope in many areas are covered with woodlots and/or long time fallows. The lower slopes are where most human activities are taking place including settlements. In the lower slopes, cultivation of crops such as round potato (*Solanum tuberosum)* is done using appreciable amounts of farmyard manure which add up SOC.

Results of this study further revealed that, in the high altitude plateau, positions and slope forms (concave, convex and straight) of the hills, mountains and ridges had influence on soil organic carbon (Figures 3 and 4). The results have shown that the SOC mean values are 3.5, 4.1 and 2.9 for lower, middle and upper slopes respectively (Figure 3). Our study results show that there are statistically significant differences of SOC between middle and upper slope positions. The observed results in the plateau could also be attributed to soil properties particularly texture and topsoil horizons (Ap/Ah) depth (in cm) which shows that (Table 1) in the elevation range between 1980 and 2000 m a.s.l., the topsoil horizons are thicker and are more clayey than other topographic segments of the plateau. When studying the natural factors that influence SOC, Bot and Benites (2005) indicated that soil texture and moisture were among the important factors in some areas, while on the other hand litter decomposition rate and soil organic carbon build up was dependent on vegetation cover and soil drainage (Certini et al., 2015).

Therefore, variability of SOC observed in the high altitude plateau of West Usambara Mountains, is also attributed to the landform slope form and position (Figures 4 and 5) which also has influence on soil properties including soil depth and moisture. The complex-concave slopes are water collecting slopes hence had deeper and moist soils which encourage good vegetation biomass production that is reflected in the SOC (Figure 5). The convex slopes are water distributing characterrised with shallow, sometimes gravelly soils which have

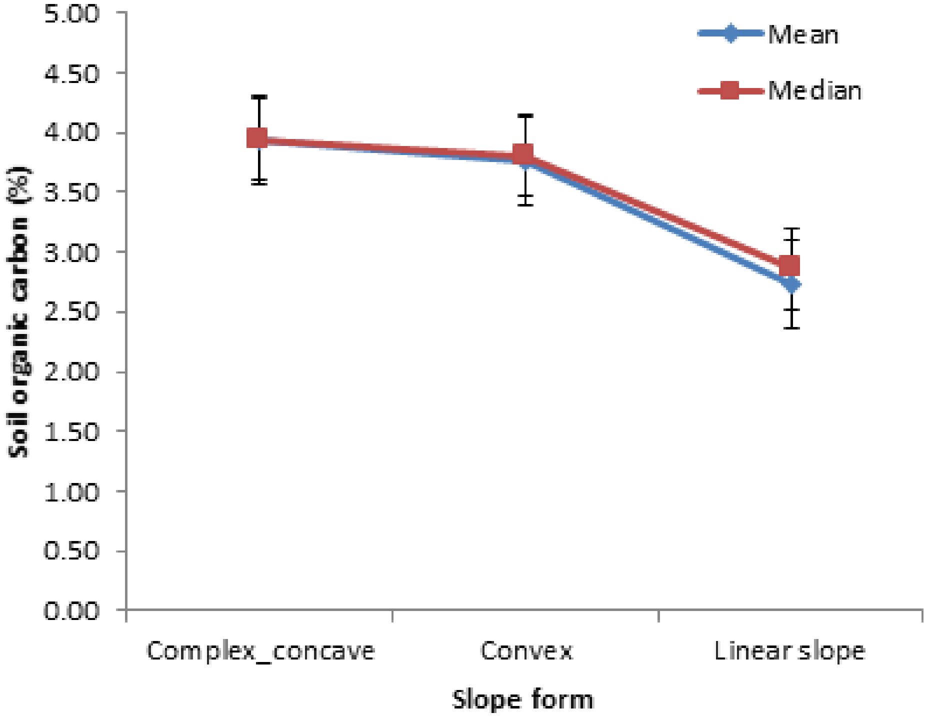

Figure 4. Influence of landform slope forms on soil organic carbon accumulation in West Usambara Mountains, Tanzania.

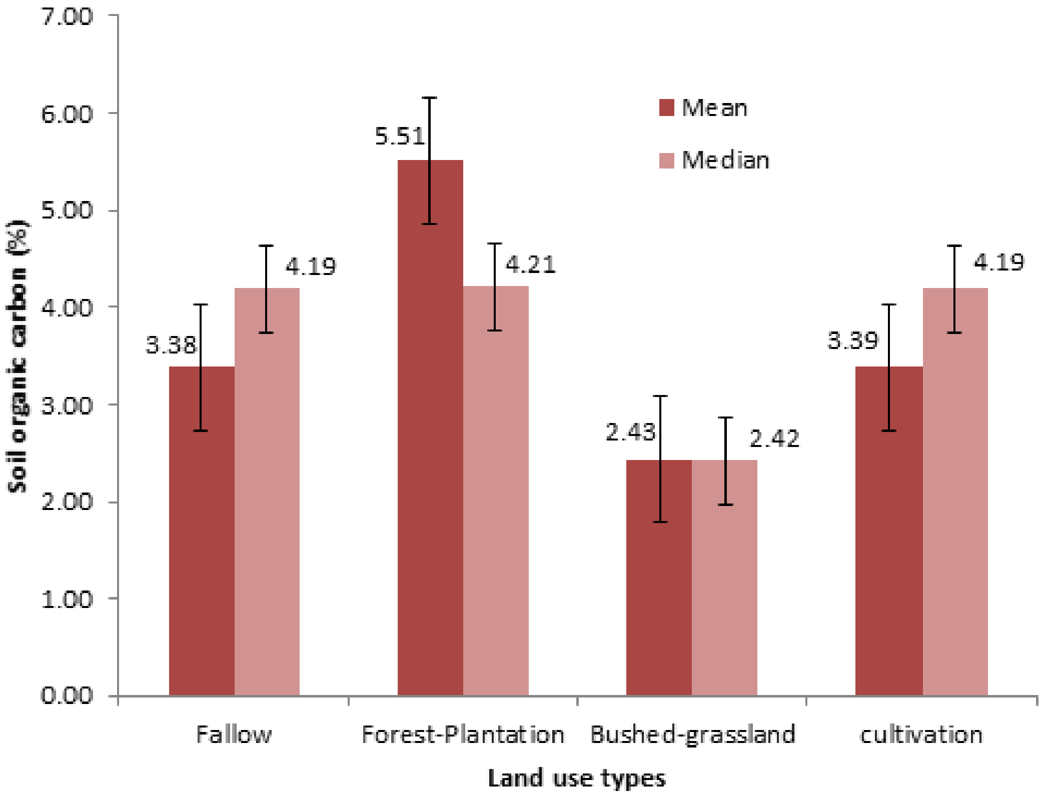

Figure 5. Influence of land use/cover on soil organic carbon in West Usambara Mountains, Tanzania.

Table 2. Variation of SOC with land use types.

Statistics	Cultivated	Fallow	Forest/Forest plantations	Bushed-grassland
Mean	3.39	3.38	5.51	2.43
Standard error	0.44	0.79	0.78	0.39
Median	4.19	4.19	4.21	2.42
Standard deviation	1.453	1.76	2.33	1.62
Sample variance	2.110	3.08	5.42	2.63
Range	4.870	4.40	7.06	5.66
Minimum	1.026	0.55	3.73	0.63
Maximum	5.897	4.94	10.79	6.29
Count	11	5	9	17
Confidence level (95.0%)	0.9758	2.1808	1.7893	0.8344

which have less vegetation biomass compared to complex-concave slopes.

Influence of land use on soil organic carbon

The spatial distribution of SOC within and between studied land use/cover types and their influence on SOC is depicted in Table 2 and Figure 5. Though the SOC median values on forest plantation, cultivated and fallow were similar, there was a significant difference of SOC between forest plantations, fallow and cultivated lands. This implies that short time fallows, do not have influence on SOC compared to the cultivated land. Forest plantation has significantly higher SOC compared to fallow and cultivated ones. The results further show that bushed-grassland which is mostly located in the low altitude plain had the lowest SOC compared to the rest of tested land use/cover. This could be attributed to the type of vegetation and cover (thorny and scanty) with limited litter addition on the surface of the soil, resulting into little addition of SOC. The results agree with many research works which have shown that land use change like clearing forests for cultivation, depletes SOC (Römkenset al., 1999; Post and Kwon, 2000; Al-Kaisi et al., 2005; Bot and Benites, 2005; Eaton et al., 2007; Corsiet al., 2012; FAO, 2015; Dengiz et al., 2015; Drewniak et al., 2015).

Influence of landform and soil characteristics on soil organic carbon

The results on the influence of landform characteristics on SOC showed that elevation and slope form were significant factors ($P < 0.001$) (Table 3). Soil parameters which influence SOC are texture (sand % and silt %), pH, total N, C/N ratio, available phosphorus and soil CEC (Table 3). The observed results suggest that apart from topographic, landforms and anthropogenic factors there are soil born factors which significantly influence SOC dynamic in soils in West Usambara Mountains. Figure 6 indicate error analysis showing the goodness fit of the model.

Our results are in agreement with several authors who reported that soil physical properties (texture, drainage) (Bot and Benites, 2005; Certini et al., 2015; Mishra and Riley, 2015), and soil chemical properties (total N, available P, CEC soil, CEC Clay, exchangeable K) do significantly influence soil organic carbon (Bouajila and Sanaa, 2011; Esmaeilzadeh and Ahangar, 2014; Aytenew, 2015; Tian et al., 2016). Furthermore, they are in agreement with the account made by several authors that soil organic carbon deposition is influenced by a complex interaction of landforms, vegetation and inherent physical and chemical soil characteristics along the topographic gradient (FAO, 2015; Sheng-Xuan et al., 2015; Atkins et al., 2015) and that land use/cover management has been among anthropogenic factors contributing to accelerated soil organic carbon depletion (Liu et at., 2006; Edmondson et al., 2014; Minase et al., 2015; Drewniak et al., 2015; FAO, 2015).

However, it has been documented further that agricultural management practices which restore soil organic carbon have resulted to improved soil quality in degraded areas and hence restored soil productivity (Corsi et al., 2012; Lal, 2015; FAO, 2015).

CONCLUSIONS

Results of this study have shown that influence of both land use changes and topographic variation had great influence on soil organic carbon. There was a significant increase of SOC with elevation, and there was higher soil organic carbon in forest plantation compared to lower levels in bushed grassland. In the plateau, the landform positions and slope types had significant influence on soil organic carbon. There was higher SOC in the middle slopes than in the lower and upper slopes.

RECOMMENDATIONS

Low SOC levels are attributed to poor land use practices,

Table 3. Factors influencing soil organic carbon in West Usambara Mountains, Tanzania.

Paremeter	Df	Sum Sq.	Mean Sq.	F value	Pr (>F)	-
Landform Position	1	0.038	0.038	0.4123	0.5311766	-
Elevation	1	69.457	69.457	752.1192	1.44E-13	***
Slope gradient	1	0.023	0.023	0.2455	0.6279761	
Slope form	1	1.689	1.689	18.2845	0.0007684	***
Land use type	1	0.259	0.259	2.8088	0.1159288	-
Depth_cm	1	0.223	0.223	2.4192	0.1421681	-
Sand (%)	1	4.063	4.063	43.9975	1.13E-05	***
Silt (%)	1	6.68	6.68	72.3391	6.67E-07	***
pH water	1	0.738	0.738	7.9963	0.0134257	*
Total N(%).	1	42.277	42.277	457.799	4.30E-12	***
C/N ratio	1	17.278	17.278	187.0929	1.71E-09	***
Avail.P mg/kg soil	1	1.169	1.169	12.6542	0.003155	**
CEC cmolc/kg soil	1	3.703	3.703	40.0989	1.85E-05	***
CECclay cmolc/kg soil	1	3.703	3.703	40.0989	1.85E-05	***
Cacmolc/kgsoil	1	0.414	0.414	4.485	0.0525721	.
Mgcmolc/kgsoil	1	0	0	0.0004	0.9837584	
Kcmolc/kgsoil	1	1.539	1.539	16.6617	0.0011211	**
Nacmolc/kgsoil	1	0.079	0.079	0.8585	0.3698602	-
TEBcmolc/kgsoil	1	0.253	0.253	2.7426	0.1199404	-
BS (%)	1	0.279	0.279	3.0204	0.1041582	-
Residuals	14	1.293	0.092	-	-	-

Significant codes: $p < 0.001$ = ***, $p < 0.01$ = **, $p < 0.05$ = * and $p > 0.05$ =ns: Residual standard error: 0.3039 on 14 degrees of freedom; Multiple R^2: 0.96, Adjusted R^2: 0.94; F-statistic: 77.94 on 22 and 14 DF, p-value: 4.137e-11.

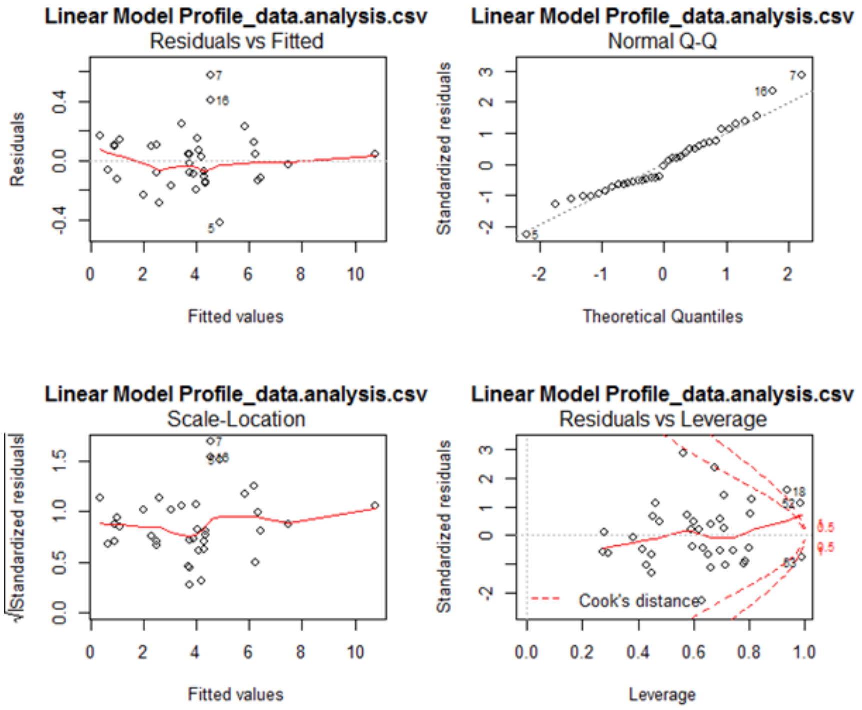

Figure 6. Model validation using residual analysis indicating that analysed data fitted well though there were outliers.

and this requires immediate restoration efforts for sustainable crop production and environment protection. It is recommended that a policy for proper land use management (conservation agriculture) that considers factors affecting SOC and its distribution in specific landform position, slope forms and position along the landscape (lowland and high altitude) should be set up. Additionally, conservation measures for increasing soil organic carbon and improvement of soil fertility and productivity should take into consideration the slope forms, landform positions and the differences in vegetation and land uses between lower and high altitude elevations for successful interventions.

Conflict of interests

The authors have not declared any conflict of interests.

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Sulphate sorption and desorption characteristics of selected Malawi soils

J. H. A. Maida* and P. C. Nalivata

Department of Crop and Soil Sciences, Lilongwe University of Agriculture and Natural Resources, P.O. Box 219, Lilongwe. Malawi.

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The soils selected for this study represented major soil types in Malawi. They exhibited a wide range of physical and chemical properties. Their pH values ranged from 4.7 to 6.7 and their contents of clay fraction (<0.002 mm) ranged from 170 to 500 g kg^{-1}, organic matter from 6.7 to 39.3 g kg^{-1}, free Fe_2O_3 from 18.9 to 44.7 g kg^{-1}, and free Al_2O_3 from 17.8 to 45.6 g kg^{-1}. The soils varied widely in their SO_4 sorption behaviour. Soil pH was negatively and significantly correlated (P<0.05) with the bonding energy (*k*) of SO_4 by the soil, Langmuir sulphate sorption maximum (*b*) and maximum buffering capacity (MBC). Soil organic matter was positively and significantly related with *k*, *b* and MBC at the same level of significance (*P*<0.05). Free Al_2O_3 and Fe_2O_3 were positively and significantly related (*P*<0.001) with *b* and MBC. Free Fe_2O_3 and Al_2O_3 were positively and significantly correlated with *k* at *P*<0.01 and *P*<0.001 respectively. About 90 and 91% of the total variations in the sulphate sorption maxima were accounted for by free Al_2O_3 and Fe_2O_3 respectively.

Key words: Sulphate, sorption, desorption, Langmuir, hysteresis, affinity.

INTRODUCTION

Because crop yields were widely observed to be related to levels of N and P bioavailability in soils, these two elements featured prominently in mineral fertilisers used by smallholder farmers prior to the early 1980s. Among the fertilisers smallholder farmers in Malawi were then advised to use were single superphosphate [$Ca(H_2PO_4)_2.CaSO_4$] or 20:20:0 granular fertilizer as a basal dressing, and low analysis fertilisers including ammonium sulphate [$(NH_4)_2SO_4$] as a topdressing. During this period, some crop responses to S additions were observed only in few parts of the country where soils were coarse-textured and highly weathered (Jones, 1977).

Early reports about S deficiencies observed in some parts of Malawi are those reviewed by Bolle-Jones (1964). Bolton and Bennett (1974) observed crop responses to fertiliser S applications in the South Rukuru Valley, the Mzimba Hills, Kasungu Plain, Dzalamanja Hills, and Dedza Hills. The crop responses to S supplementation were observed on newly opened land with course-textured soils and on smallholder farmers' fields that had not received dressings of S-containing

*Corresponding author: E-mail: zjagi@ewimax.mw.

fertilizers. Jones (1977) observed that the soils that were coarse-textured and highly weathered were low in their total and available S contents and that maize (*Zea mays*), groundnut (*Arachis hypogaea* L.) and tea (*Camellia sinensis*) grown on these soils showed variations in their responses to fertiliser S applications. Severe S deficiency symptoms on maize were also observed by MacColl (1984) from investigations conducted on land that had been acquired from smallholder farmers by the Department of Crop and Soil Sciences, Lilongwe University of Agriculture and Natural Resources, Malawi.

Workers in other parts of the sub-Saharan Africa (SSA) also observed crop responses to S additions. Increases in crop yields ranging from 12 to 20% due to S additions, for example, were observed during this period by Kang and Osiname (1976) in Nigeria, Shenkalwa (1986) in Tanzania, and Grant and Rowell (1976) in Zimbabwe. The S deficiencies in the SSA, however, were not widely observed on smallholder farmers' fields and this can be ascribed to several reasons principal amongst which are three. First, N and S deficiency symptoms are similar. Sulphur deficiency symptoms can therefore be easily confused with those of N symptoms. Secondly, S might have been supplied following the biodegradation of soil organic matter during the growing season of the crop. The mineralisation of organically bound S serves as a source of S which plants manage to use to meet their nutritional demands when effective S concentration is too low to meet such demands. Ester sulphates, for example, which are not as likely to become bonded covalently to humic compounds as is C-bonded S (McGill and Cole, 1981), are mineralised more easily than C-bonded S, thus releasing S that can be used by growing plants. Soil microorganisms and plant roots are able also to hydrolyse ester sulphates when S is needed to meet immediate nutritional demands (McGill and Cole, 1981).

The third possible reason for the absence of S deficiency symptoms then observed on smallholder farmers' fields is the incidental supply of S following the supplementation of single superphosphate [$Ca(H_2PO_4)_2.CaSO_4$] as basal dressing and ammonium sulphate [$(NH_4)_2SO_4$] as topdressing. The fortuitous supply of 24% S and 12% S following the application of $Ca(H_2PO_4)_2.CaSO_4$ and $(NH_4)_2SO_4$ could have counteracted S deficiencies in the plant. These three reasons may explain why S received very little attention from agronomists during the period when low-analysis fertilisers were used by smallholder farmers. Following the introduction of high-analysis fertilizers such as urea and diammonium phosphate (DAP), however, some S deficiency symptoms started to be widely observable in Malawi.

Sulphur is one of the elements that are essential for plant growth and crop production. It is essential for nodule development in legumes and for fruiting in some of the other crops (Tandon, 1991). Plants take up sulphur as SO_4^{2-} ions, and the availability of the sulphate ions for crop nutrition causes crop yields to increase; the quality of cereals for milling and baking to improve; both the quality and quantity of protein in cereals, oilseeds, pulses and tubers to improve; the quality, colour, and uniformity of vegetable crops to improve; the content of oilseeds and other oil-producing crops to increase; and an increase in the content of, and a decrease in the N:S ratio and nitrate levels in, forages. As the S deficiencies are becoming more widespread with the increasing use of high-analysis fertilizers and increasing decline in the content of soil organic matter, the economic importance of S is increasing recognised.

The widespread recognition of the role of S in accelerating food production in most of the developing countries now increasingly calls for the addition of this macronutrient to soils. It is due to increased recognition of the contribution S makes towards increased crop production per unit area that S-containing granular fertilisers such as 23:21:0 + 4%S have been introduced in Malawi. Because of soil heterogeneity, blanket application of S-containing fertilisers recommended to smallholder farmers in Malawi is so uneconomical that farmers may fail to get value for money they invest in the purchase of fertilisers and consequently dissuade smallholder farmers from utilising fertilisers for their crop production. Economic fertiliser use is based on a number of factors one of which is fertiliser use efficiency, which in turn is dependent on several factors including root S influx rate, inherent capacity of soils to replenish S taken up by living biota, and sulphate adsorption/desorption processes.

The word "adsorption" refers removal of a solute from solution to a contiguous solid phase and is used specifically to refer to the two-dimensional accumulation of an adsorbate at a solid surface. "Surface precipitation" is used to refer to a three-dimensional accumulation of sorbate at the solid surface. When the specific removal mechanism is not known, the word "sorption" is used as a general term. Sulphate (SO_4^{2-}) is one of the important adsorptive, non-polymeric anions that are present in soil solution. When S-containing fertilisers are incorporated into the soil, some of the S in this ionic form is therefore sorbed. Hydrous oxides of Fe and Al are ubiquitous in the Ultisols, Alfisols, and Oxisols where they often exist as coatings on clay-size minerals causing these soils to have a high sorption capacity. The effective concentration of SO_4^{2-} ions in soil solution as predicted by adsorption/desorption curves provides valuable information on S bioavailability. Central among the sorption isotherms that have been used to obtain parameters useful for the description of a substrate sorption in soils are the Temkin, Freundlich and Langmuir isotherms (Hinz, 2001).

Langmuir and Freundlich adsorption equations have been used extensively by different workers to obtain parameters useful for the description of S and P sorption in soils (Sanyal et al., 1993; Sami et al., 2001; Ghosh and Dash, 2012; Uzoho et al., 2014). The parameters obtained from the isotherms include sorption maximum (*b*) which describes the maximum amount of sorbate that can be sorbed by a sorbent, the bonding energy (*k*) that explains the tenacity with which sorbates are sorbed to the sorbents, the equilibrium solution concentration (*C*) that shows the concentration of the sorbate in equilibrium solution concentration at which the amount sorbed is equal to that desorbed (Litaor et al., 2005; Brand-Klibanski et al., 2007).

One of the mechanisms of SO_4^{2-} sorption, which involves inner-sphere surface complexes, entails ligand exchange in which SO_4^{2-} ions enter into direct coordination with Fe or Al ions of the oxide surfaces as OH- groups are displaced, resulting in an alteration of the point of zero charge (PZC) of the oxide minerals (Marcono-Martinez and McBride, 1989; Zhang and Sparks, 1990), and a release of hydroxyl (OH^-) ions into soil solution that cause a decrease in soil acidity, an increase in the negative charge of the soil colloidal surface, and therefore an increase in CEC (Dolui and Mustaffi, 1997).

It has been suggested that these effects of SO_4^{2-} sorption can be of benefits to highly weathered, acidic soils that abound in the tropics (Ghosh and Dash, 2012). There is, however, a lack of information regarding the SO_4^{2-} sorption/desorption characteristics of Malawi acid soils. The present study was therefore conducted to determine the SO_4^{2-} sorption/desorption characteristics of selected acid soils of Malawi.

MATERIALS AND METHODS

Soil sample collection

Selected for the present study were ten soil samples randomly collected at a depth of 0 to 0.15 m. The representative soil samples were collected in bulk quantities from Mphelero in Mchinji district; Bunda in Lilongwe district; Bembeke in Dedza district; Manjawila in Ntcheu district; Lisasadzi in Kasungu district; Chipoka in Salima district; Champhira in Mzimba district; Malula in Balaka district; Nkhate in Chikhwawa district; and Masenjere in Nsanje district. Soils at each site have been classified by Brown and Young (1965) and Lancini, 1991). The samples were randomly collected from 20 spots from a square area of 1 km^2 at each site and mixed together to form a composite sample. The soil samples were air-dried at room temperature (25 ± 2°C) and sieved to pass through a 2 mm sieve mesh.

Physical and chemical properties

The sieved samples were analyzed for pH in a 1:2.5 soil to water slurry using a pH electrode as outlined by described by Blakemore et al. (1987) and particle size distribution using the Bouyoucos hydrometer method (Day, 1965) as described by Anderson and Ingram (1993). The organic carbon contents of the soils were determined by the potassium dichromate ($K_2Cr_2O_7$) oxidation method of Walkley and Black (1934) as described by Anderson and Ingram (1993). Organic matter was estimated by multiplying the total soil organic carbon with 1.724.

Phosphate sorption procedures

Three grams of soil were shaken for 24 h with 15 ml solution of K_2SO_4 varying in SO_4 concentrations from 20 to 120 mg S dm^{-3}. The sulphate sorption studies were carried out in triplicate. The suspension was filtered through Whatman No. 42 filter paper and the amount of S remaining in the solution was determined turbidimetrically (Chesnin and Yien, 1951). The amount of SO_4 sorbed was estimated as the difference between equilibrium SO_4 concentration and initial SO_4 added. The sorption data were fitted to the linear form of the Langmuir equations given as follows.
Langmuir equation:

$$C/x/m = 1/kb + C/b$$

Where, C = the concentration of SO_4^{2-} in the equilibrium solution (mg SO_4 dm^{-3}), x/m = the amount of SO_4 sorbed per unit weight of soil (mg SO_4 kg^{-1} soil); *b* = is the Langmuir sorption maximum (mg SO_4 kg^{-1} soil). *k* = is a constant related to bonding energy or the affinity of the soil by SO_4.

The Langmuir equation gave a good fit for all the soils when equilibrium S concentration (C) was plotted against *C/x/m.* This equation enabled the computation of Langmuir sorption maximum (*b*) and the constant relating to the bonding energy (*k*).

Sulphate desorption study

In the desorption experiment, soils were allowed to sorb sulphate as in the sorption studies and the sorbed sulphate was extracted by shaking for 24 h with 15 ml KH_2PO_4 solution containing 500 mg P dm^{-3}. Sulphate desorption studies were conducted in triplicate. The amount of sulphate desorbed was calculated with respect to the sorbed SO_4.

Statistical analysis

The relationship between sulphate sorption parameters with selected soil chemical properties was determined using simple regressions and correlations, and tested for significance at 0.01 and 0.05 probability levels using the 16th edition of GenStat statistical software. The contribution of soil properties to sorption parameters was examined using the stepwise model-building procedure.

RESULTS AND DISCUSSION

Soil properties

The soils used in the present study are representative of the major soil types in Malawi and exhibit a wide range of physical and chemical properties (Table 1). The clay fraction (<0.002 mm) ranged 170 g kg^{-1} in the soil collected from Masenjere in Nsanje district to 500 g kg^{-1} in the soil collected from Bunda, in Lilongwe district. The organic matter contents ranged from 6.7 g kg^{-1} in the soil collected from Masenjere to 39.3 g kg^{-1} in the soil collected from Mphelero in Mchinji district. Total S

Table 1. Physical and chemical properties.

Site	Soil taxonomy (USDA)*	pH	OM	Sand	Silt	Clay	Free Fe_2O_3	Free Al_2O_3	Available	Total
			(g kg^{-1})						S(mg kg^{-1})	
Mphelero	Ustalfs	4.9	39.3	530	170	300	44.7	45.6	24.7	350.7
Bunda	Ustults	5.0	36.3	270	230	500	39.7	44.5	26.1	398.3
Bembeke	Ustults	4.7	25.6	470	230	300	33.9	35.9	21.6	287.6
Manjawila	Ustalfs	5.7	14.1	530	200	270	32.7	27.7	25.7	356.9
Lisasadzi	Ustults	5.2	23.9	570	170	270	30.9	23.9	23.5	347.9
Chipoka	Fluvents	6.7	6.7	400	130	470	29.6	21.6	23.1	288.6
Champhila	Ustalfs	5.6	20.8	400	170	430	22.4	20.9	25.3	367.5
Malula	Ustults	5.3	12.1	530	200	270	20.2	18.7	26.7	299.4
Nkhate	Vertisols	6.3	29.6	430	170	400	19.3	17.8	27.9	345.3
Masenjere	Vertisols	6.2	9.4	600	230	170	18.9	18.8	28.9	378.1

*Soil Taxonomy (1999), USDA.

contents ranged from 287.6 to 398.3 mg kg^{-1} while extractable S ranged from 21.6 to 28.9 mg kg^{-1}. The soils had pH values that ranged from 4.7 to 6.7, free Fe_2O_3 that ranged from 18.9 to 44.7 g kg^{-1}, and free Al_2O_3 that ranged from 17.8 to 45.6 g kg^{-1} (Table1). The contents of Fe_2O_3 and Al_2O_3 observed in this study are of the order of magnitude similar to that of aluminium and ferric oxide contents observed previously (Ghosh and Dash, 2012). In general, most of the soils were acidic in their reaction and low in their fertility.

Sulphate adsorption and desorption behaviour

The SO_4 sorption and desorption pattern of the soils containing the various amounts of SO_4 is presented in Table 2. Within the solution SO_4 concentration range considered in this study, the pattern of SO_4 adsorption showed a linear relationship between SO_4 adsorption and the SO_4 concentration (Figures 1 and 2), which is consistent with previous observations (Dolui and Nandi, 1989; Ghosh and Dash, 2012). At higher SO_4 concentrations, however, the rate of adsorption has been observed to gradually decrease though not proportionally, thus giving hyperbolic shapes of curve (Ghosh and Dash, 2014). In this study the mean sorbed SO_4-S was highest (98%) in soils collected from Chipoka, Champhila, Malula, and Masenjere while the lowest (94%) amount of sorbed SO_4-S was in Nkhate (Table 2).

Desorption of adsorbed SO_4^{2-} from soil and clays has been observed to be irreversible leading to a large hysteresis effect (Reddy et al., 2001). During desorption, the amount of sorbed SO_4^{2-} at a given equilibrium concentration was always higher than that during desorption (Table 2). The adsorption isotherm was thus displaced to the left of the desorption isotherm. This was in accord with the findings of Reddy et al. (2001) and Ghosh and Dash (2014). The percentages of sorbed SO_4^{2-} that was desorbed were in the same order of magnitude as those observed in earlier studies, for example, by Dolui and Jana (1997) who obtained the desorption of 72 to 80% of the sorbed sulphate and Reddy et al. (2001) who reported the desorption of 73 to 80% of the sorbed sulphate, indicating an effect of hysteresis which may be defined as a deviation of a substrate desorption isotherm from adsorption isotherm.

After SO_4^{2-} ions have been sorbed on a solid phase, their desorption process is very often irreversible, leading to a large hysteric effect (Sammi et al., 2001). The extent of hysteresis effect involved in SO_4^{2-} sorption-desorption process, as observed in this study, is shown in Figures 1 and 2. Barrow (1985) has observed that hysteresis effect leads to an over estimation of the replacing ability of soil to an overestimation of the replacing ability of soil to supply sulphur to the solution, when sulphur solution isotherms are used for the purpose.

Affinity between the sulphate and soil colloidal surfaces

The data presented in Table 2 reinforce the notion that most of the removal of sulphate ions from solution to a contiguous solid phase is via an electrostatic (outer-sphere) adsorption mechanism (Peak et al., 1999, 2001; Bohn et al., 2001; Ghosh and Dash, 2012). Microscopic and spectroscopic investigations have, however, demonstrated sulphate inner-sphere surface complexation (Peak et al., 1999, 2001). It has been observed that (SO_4^{2-}) ions form outer-sphere surface complexes only at pH above 6.0 and a mixture of outer- and inner-sphere surface complexes is formed at pH less than 6.0 (Peak et al., 1999). Among the soils used for the

Table 2. Adsorbed and desorbed sulphate (**μg g^{-1}**) in soils treated with different levels of sulphur

Soil collected from	**Reaction observed**	**SO$_4$ conc. (μg g^{-1})**				
		40	**60**	**80**	**100**	**120**
Mphelero[1] (Mchinji)[2]	Adsorbed	36.0 (90)[3]	56.5(94)	76.7(96)	97.(97)	117.5(98)
	Desorbed	25.7(71)[3]	43.5(77)	63.7(83)	86.9(89)	98.0(83))
Bunda (Lilongwe)	Adsorbed	39.4(99)	59.4(99)	76.0(95)	96.4(96)	116.7(97)
	Desorbed	26.10(66)	48.6(82)	61.8(81)	87.0(90)	81.6(70)
Bembeke (Dedza)	Adsorbed	36.1(90)	56.5(94)	56.5(94)	97.3(97)	117.7(98)
	Desorbed	23.98(66)	49.6(88)	41.3(73)	88.3(91)	85.8(73)
Manjawila (Ntcheu)	Adsorbed	36.7(92)	57.2(95)	77.7(97)	98.2(98)	118.3(99)
	Desorbed	29.1(79)	49.2(86)	66.7(86)	80.1(82)	88.1(74)
Lisasadzi (Kasungu)	Adsorbed	37.6(94)	58.0(97)	78.4(98)	98.9(99)	119.3(99)
	Desorbed	25.3(67)	43.6(75)	66.6(85)	83.5(84)	89.6(75)
Chipoka (Salima)	Adsorbed	38.1(95)	58.2(97)	78.8(98)	99.2(99)	119.5(99)
	Desorbed	26.3(69)	47.5(82)	68.3(87)	83.9(85)	82.1(69)
Champhila (Mzimba)	Adsorbed	38.2(95)	58.6(98)	78.7(98)	98.8(99)	119.5(99)
	Desorbed	29.6(77)	44.4(76)	61.6(78)	85.9(87)	86.7(73)
Malula (Balaka)	Adsorbed	38.6(96)	58.8(98)	79.0(99)	99.0(99)	119.4(99)
	Desorbed	23.7(61)	47.6(81)	60.3(76)	84.8(86)	88.8(74)
Nkhate (Chikwawa)	Adsorbed	38.1(95)	58.6(79)	79.1(99)	99.5(99)	119.5(99)
	Desorbed	20.9(55)	46.8(80)	69.8(88)	89.6(90)	96.0(80)
Masenjere (Nsanje)	Adsorbed	37.8(94)	58.6(98)	79.0(99)	99.4(99)	119.6(99)
	Desorbed	29.9(79)	44.5(76)	61.3(78)	80.6(81)	88.1(74)

[1]Denotes the site and [2]district from which the soil sample was collected; [3]the figures in parenthesises denote adsorption or desorption percentage.

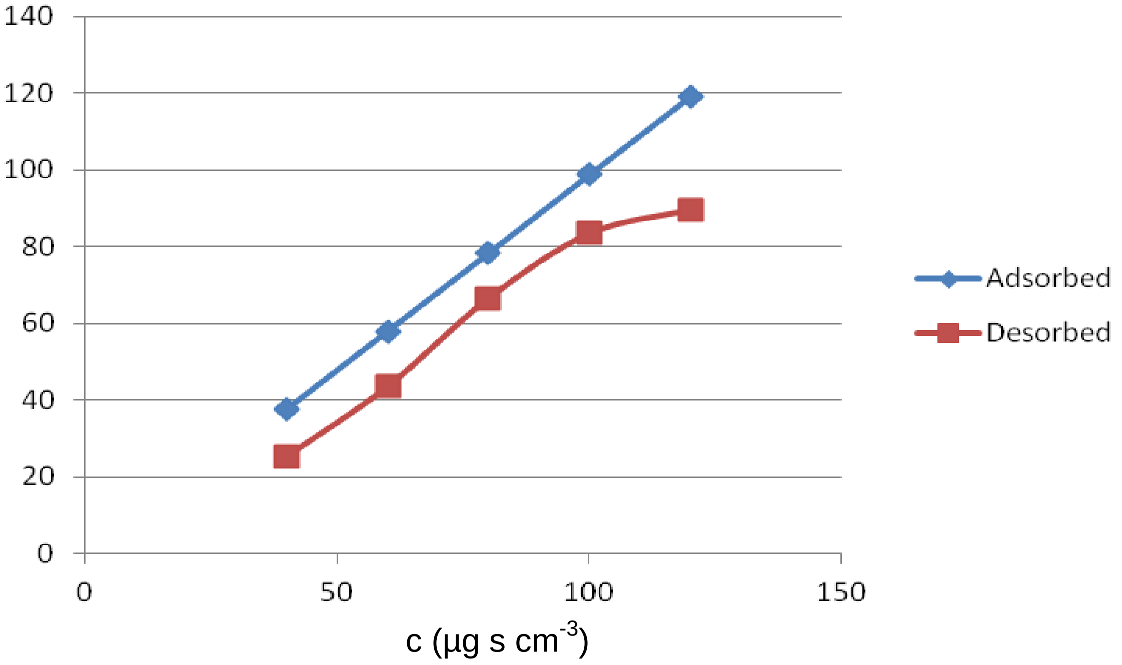

Figure 1. Relationship between sulphate sorbed or desorbed and equilibrium s concentrations in soil solution (lisasadzi, kasungu).

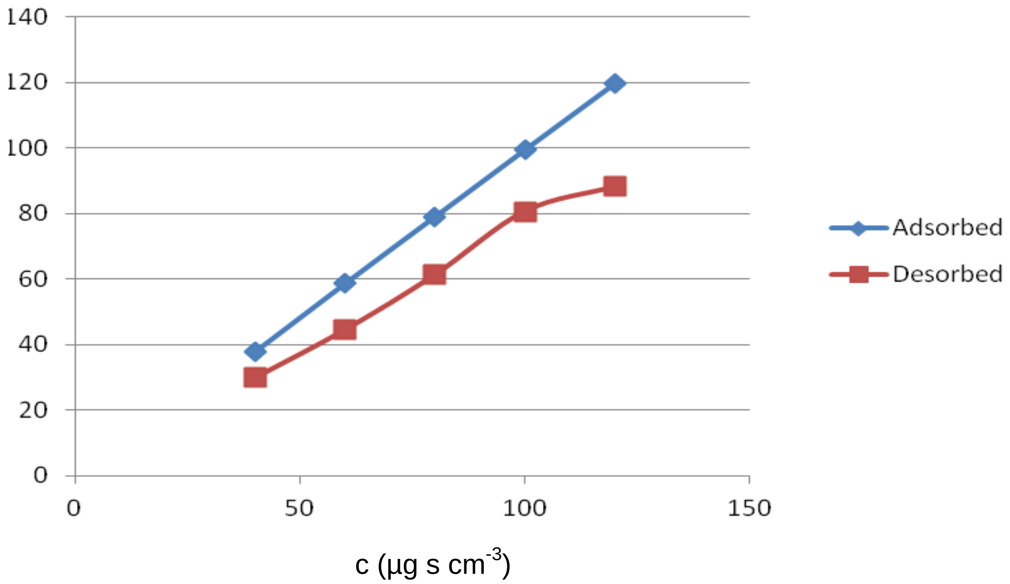

Figure 2. Relationship between sulphate sorbed or desorbed and equilibrium S concentrations in soil solution (Bunda, Lilongwe).

present study, there were only three soils that had pH values above 6, thus suggesting that the SO_4^{2-} adsorbed by these soils was labile, and therefore, bioavailable. This may explain why, of the soils whose pH values were above 6, compared to all soils studies, have the highest extractable SO_4^{2-} (Table 2)

There is some evidence that suggests that interactions between SO_4^{2-} and the mineral surface are more complex and that SO_4^{2-} ions do participate in ligand exchange reactions with hydroxylated Fe and Al surfaces (Parfitt, 1980). The adsorption of SO_4^{2-} on the hydroxylated Al and Fe surfaces ($M_{oxide}]OH^0$) may be illustrated as follows:

$$M_{oxide}]OH^0 + SO_4^{2-} \rightleftharpoons M_{oxide}]SO_4^- + OH^- \qquad (1)$$

Reaction (1) shows that following the displacement of the OH ligand on the metal oxide surface results in the metal surface that is electrostatically neutral becoming negatively charged thus increasing the capacity of the surface to coulombically attract cations. When the adsorption of SO_4^{2-} results in the displacement of a water ligand, the surface of the metal oxide also becomes negatively charged as the following reaction illustrates:

$$M_{oxide}]OH_2^+ + SO_4^{2-} \rightleftharpoons M_{oxide}]SO_4^- + H_2O \qquad (2)$$

A simple ligand exchange has been shown at low pH where two adjacent -OH ligands are replaced by one SO_4^{2-} (Rajan, 1978). Because of the amphoteric properties of the sorption sites on the oxide surfaces, sulphate sorption increases with decreasing pH (Nodvin et al., 1986b; Fuller et al., 1987) due to the protonation of the adsorption sites on oxide surfaces which results in the surfaces becoming positively charged and able to electrostatically attract SO_4^{2-}.

The Langmuir sulphate sorption maxima (*b*) and the constant relating to bonding energy (*k*), computed from the Langmuir equation and shown in Table 3, further reinforce the extent to which the soils vary in their SO_4^{2-} sorption behaviour.

The soil collected from Mphelero in Mchinji district, which had the highest organic matter and free ferric and aluminium oxide contents, had the highest sulphate sorption capacity and a pH value of 4.9. The highest maximum buffering capacity (MBC) was observed in the soil of Mphelero in Mchinji district (37.6 $dm^3\ kg^{-1}$) followed by that of Bunda in Lilongwe district (23.8 $dm^3\ kg^{-1}$), Bembeke in Dedza district (17.8 $dm^3\ kg^{-1}$), Manjawila (16.3 $dm^3\ kg^{-1}$) in Ntcheu district and Lisasadzi in Kasungu district (13.1 $dm^3\ kg^{-1}$).

Since the higher the MBC, the greater the soil's resistance to changes in the concentration of SO_4^{2-} ions in soil solution is, the present observations appear to suggest that the effectiveness of S fertiliser applied at the same rate to these soils (blanket application) will vary with MBC, with the soil collected from Mphelero requiring much more additional S fertiliser than that required by the soil collected from Lisasadzi to obtain a similar crop yield with other growth factors being invariant.

Table 3. Langmuir constants of sulphate sorption.

Soil collected from		Langmuir constants		
		Bonding energy (k)	Sulphate sorption maximum (b)	Maximum buffering capacity (b x k)
Site	District	$dm^3\ mg^{-1}$	$mg\ kg^{-1}$	$dm^3\ kg^{-1}$
Mphelero	Mchinji	9.9	3.8	37.6
Bunda	Lilongwe	8.2	2.9	23.8
Bembeke	Dedza	7.4	2.3	17.0
Manjawila	Ntcheu	6.8	2.4	16.3
Lisasadzi	Kasungu	6.9	1.9	13.1
Chipoka	Salima	5.8	1.4	8.1
Champhila	Mzimba	5.9	1.5	8.9
Malula	Balaka	6.9	1.2	8.3
Nkhate	Chikwawa	5.8	1.0	5.8
Masenjere	Nsanje	6.7	1.2	8.0

Table 4. Relationship between sulphate sorption and soil properties

Parameter	k	b	MBC	Fe_2O_3	Al_2O_3	pH
b	0.9048***					
MBC	0.9554***	0.9814***				
Fe_2O_3	0.8045*	0.9530***	0.9101***			
Al_2O_3	0.8773***	0.9482***	0.9293***	0.9319***		
pH	-0.7171*	-0.6757*	-0.6569*	-0.5931^{ns}	-0.7028*	
OM	0.6737*	0.6856*	0.7164*	0.6167^{ns}	0.7417*	-0.6219^{ns}
Clay	-0.1563^{ns}	0.0554^{ns}	0.0130^{ns}	0.2037^{ns}	0.2015^{ns}	0.1457^{ns}
P_{ex}	-0.1538^{ns}	-0.3570^{ns}	-0.2714^{ns}	-0.5376^{ns}	-0.3632^{ns}	0.3904^{ns}
Silt	0.2912^{ns}	0.1625^{ns}	0.1364^{ns}	0.0395^{ns}	0.3005^{ns}	-0.4774^{ns}
	OM	Clay	P_{et}			
Clay	0.2863^{ns}					
P_{et}	-0.1092^{ns}	-0.2079^{ns}				
Silt	0.1295^{ns}	-0.3739^{ns}	0.2580^{ns}			

*, ** and *** denote significant at P = 0.05, 0.01 and 0.001 respectively, while ns denotes not significant, k denotes bonding energy (affinity coefficient), MBC denotes maximum buffering capacity; number of observations = 10.

of the total variation in the sulphate sorption maximum was accounted for by free aluminium oxide while free ferric oxide accounted for about 91% of the total variation in the sulphate sorption maxima (Figure 4).

Soil pH was observed in this study to be negatively and significantly correlated ($P<0.05$) with the bonding energy or the affinity (k) of sulphate by the soil, Langmuir sulphate sorption maximum (b) and maximum buffering.

Relationship between sulphate adsorption parameters and soil properties

The use of soil physical and chemical properties to explain the Langmuir sorption parameters showed the best relationships between free aluminium and ferric oxides and b and MBC each of which was positive and significant at the same level of significance ($P<0.001$). While free Fe_2O_3 was positively and significantly correlated with the bonding energy (k) at $P<0.01$, the free Al_2O_3 showed a better affinity for k at $P<0.001$ (Table 4).

Barreal et al. (2003) have also demonstrated a positive correlation between Al and SO_4^{2-} sorption, and have related the relationship to an increase in surface area associated with the substitution of Al into otherwise crystalline Fe minerals (García-Rodeja et al., 1986; Curi and Franzmeier, 1984). Potter and Yong (1999) have shown such substitutions to raise the point of zero net

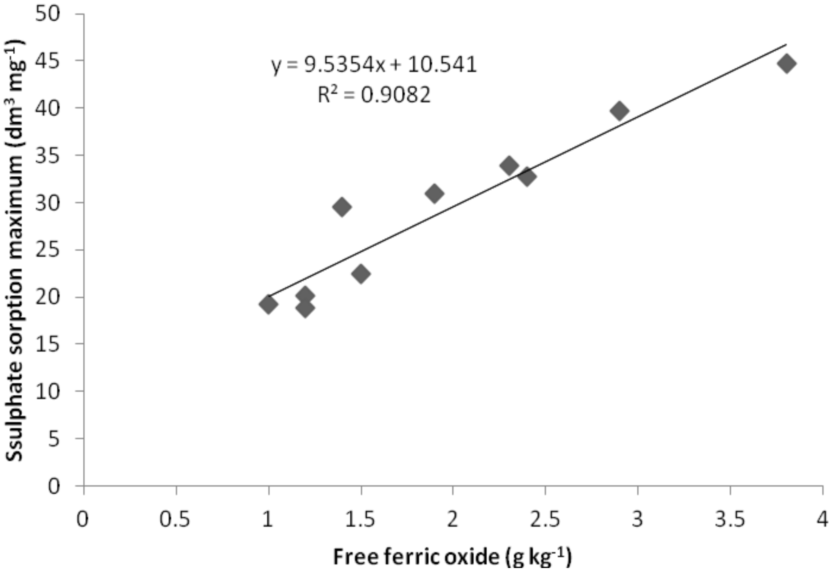

Figure 3. Relationship between the Langmuir sulphate adsorption maximum and free aluminium oxide

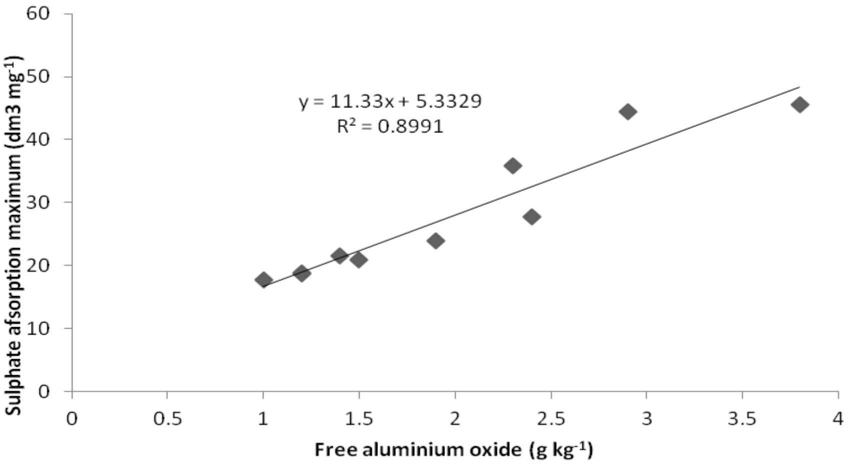

Figure 4. Relationship between the Langmuir sulphate adsorption maximum and free ferric oxide.

charge (PZNC) of the mineral surface and increase ion exchange capacities. Other workers have observed relationships between anion sorption and the development of Al-humus complexes that inhibit crystalline formation and result in an increase in mineral surface area (Alves and Lavorenti, 2004; Camps et al., 1999a, 2001; Barreal et al., 2001) and the formation of short-range-order Al oxides with a potential positive surface charge under acidic conditions (Inoue and Huang, 1986). The present study showed that about 90 per cent of the total variation in the sulphate sorption maximum was accounted for by free aluminium oxide (Figure 3) while free ferric oxide accounted for about 90% of the total variation in the sulphate sorption maxima (Figure 4). The present study showed that about 90% capacity (MBC). In the sorption of the sorptive, non-polymeric anions such as SO_4^{2-}, the effect of soil pH is, as has been noted earlier, associated with the amphoteric properties of reactive soil colloidal particles which predominate in soils with variable charge. The fact that surfaces of the amphoteric properties of the oxide surfaces increasingly become positive with increasing effective hydrogen concentration explains the inverse relationship between soil pH and each of the Langmuir sulphate sorption parameters at $P<0.05$ (Table 4). Previous workers such as Dolui and Nandi (1989) also observed statistically significant relationship between sulphate sorption maximum.

Whereas Sposito (1984) has suggested that sulphate sorption might be of an intermediate nature, sorbing under different conditions as an outer-sphere complex versus an inner-sphere complex, other authors (Turner and Kramer, 1991; Eggleston et al., 1998; Rietra et al., 1999; Sparks, 1999) have observed that as pH is lowered and the concentration of SO_4^{2-} increased, a higher percentage of inner-sphere complexes are formed by SO_4. Peak et al. (2001) have also observed that sulphate forms inner-sphere monodentate surface complexes on hematite from pH 8.0 to 3.5 and across a wide range of surface loadings, whereas on goethite, SO_4^{2-} forms only outer-sphere surface complexes at pH 6.0 and forms a mixture of outer-sphere and inner-sphere complexes at pH < 6.0. It has also been shown that SO_4^{2-} forms predominantly outer-sphere surface complexes on ferrihydrite and on the basis of these observations it has been concluded that it is important to consider not only the effects of pH, ionic strength, and reaction concentration on SO_4^{2-} sorption, but also the nature of the sorbent under study (Peak et al., 2001).

The results given in Table 4 showed that soil organic matter was positively and significantly related with each of the Langmuir sulphate adsorption parameters at the same level of significance ($P<0.05$). The effect of organic matter on the sorption of non-polymeric anions including SO_4^{2-} can either promote or reduce the adsorption of these anions. In aqueous solution, organic ligands reduce the effective concentration of Al and Fe by complexing these cations thus hindering the crystallization of Al and Fe oxides. It has been demonstrated that organic acids such as malic, citric, aspartic, oxalic, and tannic acid, promote formation of active sites for the sorption of phosphate by distorting the structure of precipitation products of aluminium and enhancing their specific surface Huang and Violante, 1986; Violante et al., 1996). Maintenance of the short-range structure of the precipitates with a large specific surface area by the presence of critical concentrations of some bio-molecules helps to promote a high sulphate retention capacity of organomineral complexes. The competition of organic ligands with sulphate for sorption sites of variable charge mineral such as aluminium and ferric oxides can result in the reduction of sulphate adsorption.

It has been observed that the amount of sulphate (SO_4^{2-}) adsorbed is dependent on the surface area of the clay and the surface charge, and that the higher the Al content the soil has, the greater the anion adsorption (Bohn et al., 1986). This clearly suggests that soil reaction and type of clay minerals are the main factors that influence the adsorption of SO_4^{2-} ions on the surfaces of aluminium and iron oxides. The soils used in the present study had been subjected to varying degree of intensive weathering and, as a consequence, kaolinitic clay minerals, which usually adsorb higher amounts of SO_4^{2-} ions than the 2:1 clay minerals, predominate in these soils.

Conclusion

The soils varied in their physical and chemical properties, and their SO_4 sorption behaviour also varied widely. Since the higher the MBC, the greater the soil's resistance to changes in the concentration of SO_4^{2-} ions in soil solution is, the present observations show that the effectiveness of fertiliser S applied at the same rate (blanket application) to these soils will vary with MBC. The soil collected from Mphelero in Mchinji district, for example, requiring much more additional S fertiliser than that required by the soil collected from Lisasadzi in Kasungu district to obtain a similar level of crop yield under similar pedo-climatic conditions. This observation is reinforced by the SO_4^{2-} desorption percentages that ranged from 55 to 91%, suggesting differences in the lability of sulphate sorbed by these soils. These observations emphasise the need for fertiliser S application, like the application of any of the other essential nutrients, to be based on indices of soil fertility obtained using well-calibrated soil test methods in order to maximise economic fertilise use and to avoid environmental pollution.

Conflict of interests

The authors hereby declare that no conflict of interest exists among them.

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Full Length Research Paper

Farmers perception on soil fertility status of small-scale farming system in southwestern Ethiopia

Bahilu Bezabih[1]*, Mulugeta Iemenih[2] and Alemayehu Regassa[1]

[1]Department of Natural Resources Management, Jimma University College of Agriculture and Veterinary Medicine, P. O. Box 307, Jimma, Ethiopia.
[2]Forestry and Natural Resources Management section, Farm Africa, P. O. Box: 1750, Addis Ababa, Ethiopia.

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Soil is one of the most essential natural resources. That is why soil fertility management is a major global concern. The current study in Delta sub-watershed was conducted to assess farmer's perception on soil fertility status of small holder farming system under different land uses, Enset (*Ensete ventricosum*) farm, grazing and agricultural land. Both secondary and primary data were collected through direct field observation, focus group discussion, key informants and household interviewing. The results revealed that farmers of the study area employed different traditional indicators to assess soil fertility status. Among the indicators used, about 44.4% of the interviewed farmers perceive reduction of crop yield, 25.4% perceives change in soil color and 28.57% of the farmers perceive weed dominance and indicator plant species as a main indicator of soil fertility decline. Using the indicators, they ranked soil fertility status of grazing and Enset farm lands as more fertile than agricultural land. In order to tackle the problem of decline in soil fertility, the interventions should focus on supporting farmers to implement diversified nutrient management strategies that can maintain and conserve soil in order to ensure sustainably high crop yield as well as long term productivity of the soil.

Key words: Crop yield, land use, farming system, soil fertility indicator.

INTRODUCTION

Soil fertility depletion is the fundamental cause of declining per capital food biomass, especially in developing countries (Joshi et al., 1997, Omotayo and Chukwuka, 2009). In intensive agricultural systems, soil fertility can be maintained through applications of manure and other organic materials, inorganic fertilizers, lime, and the inclusion of legumes in the cropping system, and combination of some of these (Pandey et al., 2006, Singh et al., 2007). Although, the reliance on biological nutrient sources for soil fertility regeneration is adequate with low cropping intensity, it becomes unsustainable with more intensive cropping unless artificial fertilizers are applied (Mulongey and Merck, 1993). However, in many parts of the developing countries, the availability, use and profitability of inorganic fertilizers have been low whereas, there has been intensification of land-use and expansion of crop cultivation to marginal soil. As a result, soil fertility has been declined and it is perceived to be

*Corresponding author: E-mail: bahilubezabih@ju.edu.et; behailubeza@gmail.com.

widespread, particularly in sub-Saharan Africa including Ethiopia (Belachew and Abera*, 2010). So, soil fertility maintenance is a major concern in the region to improve agricultural production in order to feed the growing population.

The fertility continued to decline due to continuous cropping (abandoning of fallowing), reduced manure application, removal of crop residues and animal dung for fuel wood and erosion coupled with low inherent fertility of the soils (Yohannes, 1994; Tilahun et al*., 2007). According to Abebe (1998),other challenges of soil fertility decline in Ethiopia are related to cultural cropping practices like traditional cultivation, removal of vegetative cover (such as straw or stubble), burning plant residues as practiced under the traditional system of crop production or the annual burning of vegetation on grazing lands. These are the major contributors to the loss of nutrients. According to Barry and Ejigu (2005), the main causes of fertility decline in southwestern Ethiopia are deforestation, land fragmentation, overgrazing, low fertilizer inputs, inadequate soil and water conservation practices and cropping of marginal lands. All of these have resulted in lowering of agricultural production which is leading to food insecurity and increased poverty. Inappropriate land use, overgrazing, deforestation and continuous cultivation of the same land without appropriate and sufficient management lead to soil degradation and its consequences like depletion of nutrients and reduction of output (Conant, et al., 2003, Kebede et al., 2013, Bernoux et al., 1998,). Likewise, the study area is characterized with densely population and rolling topography, making it vulnerable for soil fertility decline, deforestation is also causing soil erosion. On the other hand, shortage of grasslands (grazing areas) in the study area forced the farmers to remove crop residues from cultivated land for animal feed.

Manure and other home refuses are used mainly for specific land use type especially for homestead gardens to maintain soil fertility status of Enset farm. And also, many farmers subjected to continuous cultivation of steeply slope lands without any adequate soil fertility amendments and soil and water conservation measures. Even though the consequence of soil fertility decline is very serious, it has not received more research attention in the region, only few studies (that is Wakene and Heluf, 2004; Ashagrie et al., 2005; Kebede et al., 2013) have considered the influence of farmers perception and associated soil management practices on soil physical-chemical properties and soil fertility status. Until recently, farmers' knowledge of soil fertility has been largely ignored by soil researchers, but with increasing use of participatory research approaches, it is becoming clear that farmers have a well-developed ability to perceive differences in the level of fertility between and within fields on their farms (Arnaud et al., 2003).

Farmers Use different criteria to evaluate and identify their soils. Usually, they characterize their field as fertile(good /high) or infertile (bad/low) by using soil color, soil texture, soil depth, soil drainage, topography and distance from home as criteria to classify into different groups as fertile and non fertile (Gebeyaw, 2015). Farmers' decisions to conserve natural resources in general, and soil and water in particular are largely determined by their knowledge of the problems and perceived benefits of conservation (Amsalu and Graff, 2007). However, farmer perceptions of soil erosion and soil fertility management problems in Ethiopia have received little emphasis either in status analysis or use in conservation planning. In order to give a sustainable solution to all above mentioned challenges, researcher and farmers response is very crucial. Therefore, this study was initiated to investigate farmer's perception on soil fertility status of small holder farming system through identifying different local soil fertility indicators and different land management practices used by the local households to enhance soil fertility.

MATERIALS AND METHODS

Description of the study area

The study watershed is situated in the Essera district of Dawuro zone, Southern Nations, Nationalities and Peoples Regional State (SNNPRS) of Ethiopia It is situated in the Omo basin at about 507 km Southwest of Addis Ababa, the capital of Ethiopia (Figure 1). The area is topographically undulating and rugged. The Dawuro Zone covers total area of 4436.7 km² and lies between 6.59 to 7.34°N latitude and 36.68 to 37.52°E longitudes, with an elevation ranging 501 to 3000 m (Mathewos, 2008). The zone has 5 districts with a total population of 398,796. The zone has three agro-Ecological zones identified as: kola, *Weynadega and Dega* occupying 55.6, 41.4 and 3%, respectively. The annual mean temperature ranges between 15.1 and 27.5°C. The rainfall is a bimodal type: the short rainy season is between (February and March) and the long season between (May and September). The average annual rainfall ranges from 1201 to 1800 mm. The regional data on land utilization, shows that 38.4% is a cultivated land, 13.39% is a grazing land, 16.81% forest bushes and shrub land, 17.09% cultivable and 14.31% is covered by others. The livestock resource of the zone was estimated to be 313,094 cattle, 113,554 sheep, 45,703 goats, 7,081 horses, 1,934 mules, 5,064 donkey, 157,996 chicken, and 28,557 traditional hives (CSA 2006). According to FAO (2006) soil classification, the dominant soil of the region is Humic Nitisols with a clay and clay loam texture with dark reddish brown color (Figure 4).

Farming system

Agriculture in the area is characterized by small-scale subsistence mixed farming-system (crop-livestock complex) which includes a combination of livestock integrated with a wide range of cereals, pulses, enset root, tubers and cash crops grown for household consumption and marketing. It can be broadly classified into cereal-livestock based farming system and enset-Root crops complex in combination with different agro-forestry systems**.** The major annual food crops grown in the area, includes cereals (maize, sorghum, barley, wheat, and teff), pulses (beans, peas). Maize and wheat followed by beans and peas were grown in the highest proportion. The most common agro-forestry tree species, in the grazing and enset farm in the study area includes, *Cordiaafricana,*

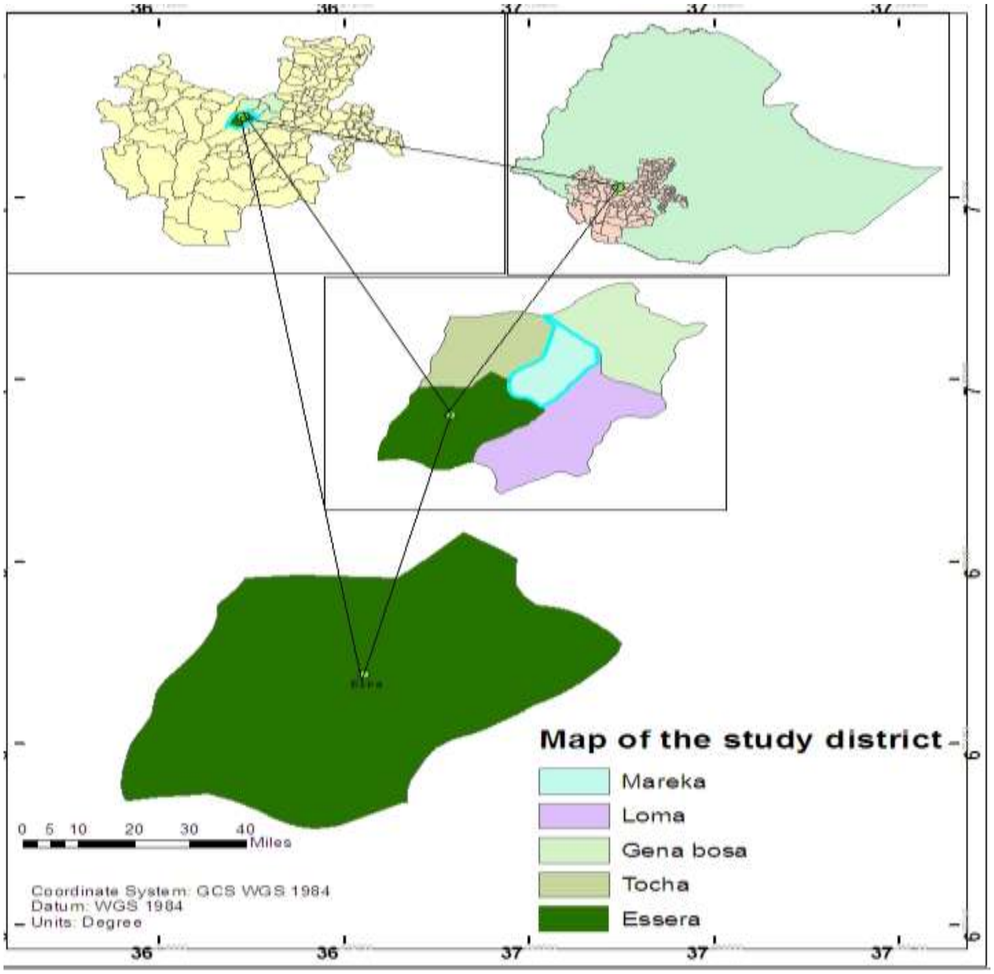

Figure 1. Map of the study area.

Millettiaferruginea, Ficus spp., *Grevillarobusta, Acacia* spp, *Coffee (C.arabica)* and some fruit trees like *Mangiferaindica L.,* and *Persea Americana*. *Musa acuminate* and root crop (potatoes and taro) are also grown considerably especially in enset farm land. Enset is a plant native to Ethiopia that is often referred to as the false banana because, not surprisingly, of its resemblance to the banana plant. It is grown in the less arid highlands of the southwestern region of Ethiopia.

Methods of data collection and analysis

Both quantitative and qualitative biophysical and socio economic data were collected from primary and secondary data sources. The primary data were collected by using key informants, household survey and focus group discussion (FGD). Secondary data were collected from published and unpublished materials such as office records and reports, journals, books and files from internet /web pages.

Focus group discussion

Focus group discussion after detail survey was held using semi-structured questionnaires interviews. The questions focused on identifying the local indicators of soil fertility and management practices to enhance soil fertility under different land uses. The discussion was conducted with purposely selected farmers (age ranges from below 30, 30 to 50 and 50years). Based on these, ten farmers from upper, middle and lower slope position of the watershed were selected to form a discussion group. During the discussion, topics covered included soil fertility, management practices, and local indicators used to assess the fertility status of a field and perceived trends in soil fertility. In order to evaluate soil fertility status, they broadly categorized the soils of the sub-watersheds into three groups: fertile (good), infertile (bad), and intermediately fertile (medium), with respect to crop yields and some local indicators.

Key informant’s interview

Primary data were also generated by informal interview with local extension agents in addition to direct field observations and a number of informal discussions with village elders and farmers groups.

Household interviews

Information on farmers perceptions of soil fertility under different

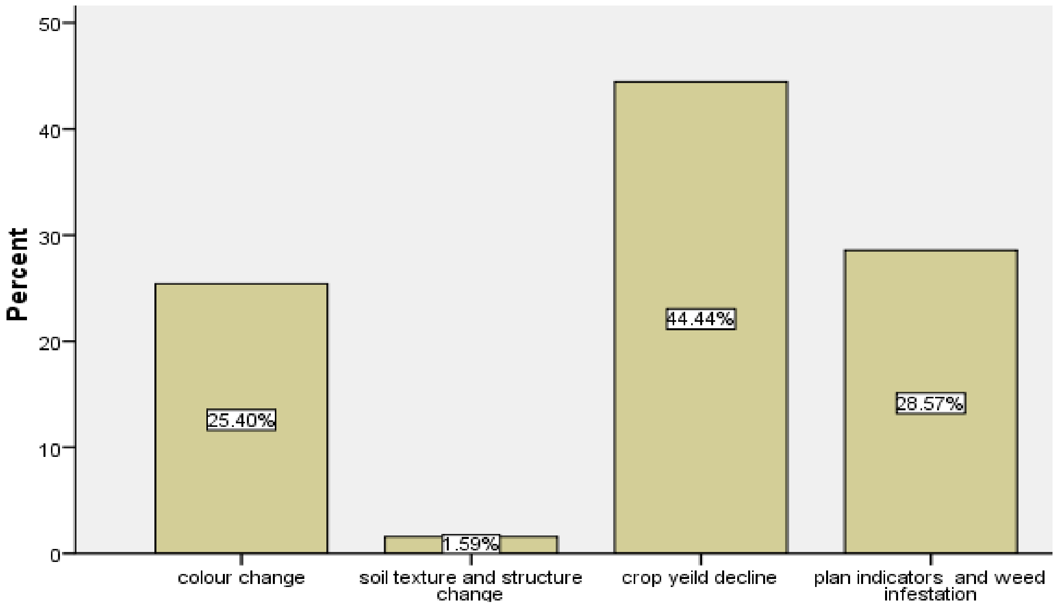

Figure 2. Farmer’s perception on indicators of soil fertility decline.

land uses and management practices were gathered by using structured questionnaire through individual interviews which took place in the interviewee’s house. Only field owned farmers were selected as household interviewee. Fields that were rented out to other farmers were excluded to minimize errors due to a possible lack of knowledge regarding the management of their fields. Farmers in each village (transect of the sub-watershed) were stratified according to wealth status and their sex according to up-to-date farmers list which was obtained from the respective district office was used as a sample frame. The set-up of transect was made through classifying the sub watershed into three parts based on the elevation difference and slope category. Accordingly, three transect walks were conducted across the slope that is, transect walk in the highest elevation area, transect walk in the medium elevation area and transect walk in the lowest elevation area. In each transect walk, systematic random sampling procedure was used to select total sample households from the identified wealth status and sex group. The wealth status was identified based on resource endowments especially the size of arable land and the number of livestock that they owned. The total number of sample size for the questionnaire was determined using Cochran (1977). Accordingly, a total of 63 sample households’ head were selected using systematic random sampling techniques for the study. Allocations of the number of sample in each transect, wealth status and sex depends on variability of a population to be sampled.

Data analysis

The qualitative responses were summarized, categorized and coded into numeric values. Both quantitative as well as qualitative generated data by structured questionnaires were entered in the SPSS software version 16 for analysis of various parameters. After analysis, the data were presented using descriptive statistics (that is frequencies and x^2-square). Information obtained from field observation, semi-structured interviews and informal interviews from key informants and focus groups were written in the form of verbal/narrative information. This information is more qualitative in nature and used to support the coded qualitative and quantitative data analysis.

RESULTS AND DISCUSSION

Socio-economic characteristics and soil fertility status in the Delta sub-watershed

Chi-square result revealed that there was no significant variation in soil fertility *(*$P \le 0.05$*)* due to difference in age, sex, marital status, education level, land holding and off farm activities of the respondent’s. That means there was no association between the soil fertility status of the respondent’s farmland with the aforementioned variables. However, family size, home to farm average distance, wealth category, agricultural input and management practice significantly affected soil fertility status at ($P < 0.01$ and $P \le 0.05$*)* (Table 1). This can be explained by the application of manure and crop residues and response to different agricultural inputs. That means a house hold with large family size had excess labor force to transport their farm yard manure and crop residue for their farms and distance from homestead also positively influenced soil fertility. Most of the interviewed farmers only apply their compost and crop residue in nearby farms to their home. Similarly, agricultural input, management practice and wealth category positively influenced soil fertility, as rich farmers have more livestock that contribute to soil fertility through generating more manure and also they have a capacity to purchase expensive fertilizer to maintain soil fertility and productivity (Table 2).

Household energy consumption impact on soil fertility

Eighty nine percent of the respondents reported that

Table 1. Chi-square value of soil fertility status in association with different variables.

Parameter	X^2-value	Df	p-value
Age	46.717	2	0.681
Sex	6.859	1	0.144
Marital status	1.645	2	0.801
Family size	6.239	4	0.044
Education level	5.967	4	0.651
Land holding	38.353	3	0.545
Distance from homestead to farm	6.239	1	0.044
Off farm activity	1.552	1	0.460
Agricultural input	34.613	5	0.000
Management practice	21.153	6	0.007
Wealth category	18.215	2	0.001

Table 2. Influence of household wealth on land management practices.

Land management practices	Wealth categories		
	Poor (%)	Medium (%)	Rich (%)
Inorganic fertilizer	75	88	99
Compost /manure	15	27	45
Manure and artificial fertilizer	18	45	80
Fallow	14	50	60
Crop rotation	14	30	60
Intercropping	35	25	30
Agro forestry	66	92	97

firewood was the single most frequently used source of household energy and the remaining 11% use kerosene and crop residues in addition to firewood. The source of fire wood was from homestead plantation and nearby natural forest which caused deforestation. Thus, deforestation might have aggravated soil erosion problems, loss of organic matter and resulted in soil fertility decline. The reconnaissance survey and the household questionnaire revealed that small scale farmers perceived deforestation mainly through an increasing scarcity of tangible forest products such as fire wood, timber and building poles. These farmers explained that the time and distance travel showed progressive increment due to deforestation. In addition, 85% of the respondents grew eucalyptus tree species on their farm boarder area and extremely degraded lands for firewood and construction purposes. However, planting of eucalyptus particularly on farm border may be cause of high moisture stress and further aggravates soil degradation.

Soil fertility indicators to evaluate soil fertility

The farmers in the sub-watershed used various criteria to judge soil fertility. Among the different criteria used, crop yield decline as predominate in terms of frequency followed by soil color change, farmer's response to artificial fertilizer, weed infestation and indicator plants. About 44.4% of the respondents perceived decline in crop yield as the main indicator of soil fertility decline (Figure 1). The quantitative data of the yield of the major crops grown in the study watershed also shown 12 to20% crop yield reduction from 1998 to 2007 (Table 3). Plants indicators for fertile, infertile and intermediately fertile soils as used by farmers are also shown in Table 4. They identified over 11 plant species used to indicate fertile, intermediately fertile and infertile soils. Softness of the soil and colour change is also used as indicators to judge soil fertility. Farmers used the word"*shafebitta*" an expression in "Dawuregna" that means "getting red" while the word "*Aradabitta*" means getting black soil. Accordingly, farmers of the Delta sub-watershed identified three major soil types for the sub-watershed namely *zo'o*(red), *bokintha*(whitish) and *karetha*(dark) soil (Figure 3).

In terms of fertility, the red and whitish soils are classed as less fertile while dark (black) soil is very fertile. This could be more or less similar with soil classification based on FAO (2006). Accordingly, the dominant soil type of the sub- watershed may be Humic Nitisols with dark and reddish soil color based on this observation, it is worth

Table 3. Comparison of crop yield of 1998 and 2007.

S/N	Crop type	Average yield ton/ha in 1998			Average yield ton/ha in 2007				
		Min.	**Max.**	**Average**	**Min.**	**Max.**	**Average**	**Yield Difference**	**Reduction in yield (%)**
1	Teff	0.66	0.99	0.83	0.55	0.77	0.66	0.17	2.20
2	Barley	2.09	2.42	2.26	1.43	2.53	1.98	0.28	1.32
3	Maize	3.74	5.06	4.40	3.08	3.96	3.52	0.88	2.20
4	Beans	0.99	2.75	1.87	1.21	1.76	1.48	0.38	2.31
5	Wheat	1.65	2.42	2.04	1.43	2.09	1.76	0.27	1.54
6	Peas	1.98	3.52	2.75	1.54	3.08	2.31	0.44	1.76
7	Sorghum	0.88	1.65	1.26	0.77	1.43	1.10	0.16	1.43

Min. = Minimum, Max. = maximum; Source: Essera *Woreda* office of agriculture and rural development.

Table 4. Plant species used by farmers to indicate soil fertility in the sub-watershed.

Scientific name	Local name (Dawuregna)	Family name	Abundant in
Bidensprestinaria(sch.Bip) cufod.	*Addiliya*	*Asteraceae*	Infertile soil
*Dichondrarepens*J.R&G.Forst	*Ecerehayitha*	*Convolvulaceae*	Infertile soil
Guizotiascabra(vis.) chiov.subsp. *Schimperi*(sch. Bip. Ex A. Rich.) Baagoe	*Qodhuwa*	*Asteraceae*	Infertile soil
Cyanodondactylon(L.) Pers	*Sura*	*Poaceae*	Intermediately fertile soil
*Cyprusrigidifolius*steud.	*Xatha*	*Cyperaceae*	Intermediately fertile soil
*Euphorbia hirta*L.	*Shatomata*	*Euphorbiaceae*	Intermediately fertile soil
*Galinsogaparviflora*cav.	*Emathiya*	*Asteraceae*	Intermediately fertile soil
*Pennisetumclandestinum*chiov.	*Gorxa*	*Poceae*	Fertile soil
Snowdoniapolystachya(Fresen.) pilg.	*Maga*	*Poceae*	Fertile soil
Spilanthusmauritianaauct.,non (Rich.ex pres.) Dc	*Ayidamiya*	*Asterceae*	Fertile soil
Trifolium decorum chiov.	*Azimiiya*	*Fabaceae*	Fertile soil

noting that using of organic manure in enset cultivation contributed towards maintenance of the diversity of soil fauna that helps build up the decomposers population in the agro-ecology. Farm activities within the enset garden encouraged the presence of the decomposer groups such as the earth worms, millipedes, centipedes, termites, etc. that were essential for organic matter dynamics and nutrient cycling (litter transformation) and soil aeration (Figure 3b). This might be attributed to the presence of different agroforestry tree species that are commonly practiced with grazing and enset farm includes, *Cordia africana*, M*illettiaferruginea, Ficus spp*., *Grevillea robusta, Acacia spp, Coffee arabica,* and some fruit trees like, *Persea Americana*, *Mangiferaindica* L., *Musa acuminate* with undergrowth of annuals (cereals, root crops and spices). This created a multi-strayed agroforestry system within their farms with mosaic of species and serving various environmental functions (soil conservation through canopy and surface cover, provision of habitat for useful micro fauna and flora, etc.). Field observation also revealed that there were large populations of decomposers in the enset garden due to the accumulation of leaf mulch, litter, animal manure and other organic matter. Through their activities of feeding, burrowing and casting might modified physical, chemical and biological properties of the soil and thus, its ability to support above ground vegetation. Farmers' response to inorganic fertilizer is also another indicator of soil fertility decline in the study area. The survey result from respondent farmers revealed that the trend of using inorganic fertilizer increased from 1998 to 2010; about 84.1% of the respondent increased the amount of using artificial fertilizer from year to year and 11.1% decreased while 4.8% using the same amount of fertilizer year after year. Thus, highest proportion of farmers using artificialfertilizer in increasing trend indicates the declining trend of the soil fertility of the sub-watershed (Figure 2).

Regarding the causes of crop yield decline, most farmers described soil fertility decline as a consequence of soil erosion, continuous cultivation and lack of manure application (Figure 4). According to farmers response, the presence of *Pennisetumclandestinum*chio, *Snowedeniapolystachya* (Fresen.) pilg., *Spilanthusmauritianaauct*.,non (Rich.ex pres.) Dc,

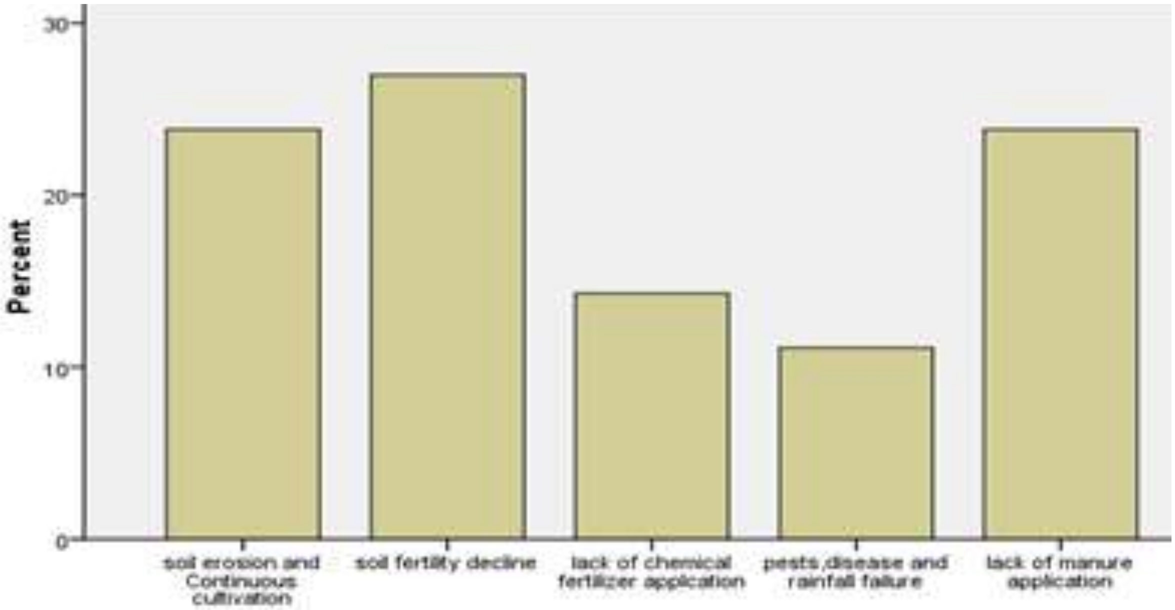

Figure 3. Farmers" perception on major cause of crop yield decline.

Trifolium decorum chiov indicates that soil is fertile. This could be due to the fact that grass spreads vigorously and grows quickly, and spreads readily, thanks to its stolons and rhizomes that are forming a dense sod that requires minimal management. It is therefore, used to control erosion, especially near regulators and water wheels, on river banks, degraded catchments and steep cultivated lands. Apparently, they also confirmed that these grasses had drought resistant physiological behavior which helps to maintain soil fertility for a long period of time. In addition to that, they are very resistant to constant heavy grazing and trampling provided fertilizer levels which are maintained. It should be grazed to a height of 5 cm and allowed to regrow to 15 cm to preserve forage quality and palatability, which mostly found in mono-specific pastures since it competes aggressively with other grass species. However, it can be sown with legumes such as *Vigna parkeri*, *Arachis pintoi*, *Trifolium repens*, *Trifolium burchellianum*, *Trifolium semipilosum, Desmodium intortum* and *Neonotonia wightii* provided that is grazed sufficiently to let the legumes grow. However, the presence of rest grass species could be adapted to particular habitats, their presence may indicate problems with the soil's nutrient status or soil structure.

Farmers perception on soil fertility and amendment practices under different land use types

Farmers in the study areas have a wealth of knowledge about their land resources, its characteristics, limitations, potentials and management options. About 88.9% have perceived the existence of soil fertility problem while only11.1% of surveyed households were not aware of the existence of soil fertility problems on their different land use types which resulted in productivity decline. According to their perception, the highest proportion of the respondent farmers perceive that enset farm land and grazing land is classified as highly fertile soil while cultivated land is classified as low soil fertility class.

Application of manure

Most farmers take various measures for different land use types to improve soil fertility in the studied sub-watershed. Hundred percent of the interviewed farmers uses farm yard manure to maintain soil fertility of homestead gardens especially for enset farm land. The major land use systems in the community included homestead farms, where the most important crops such as enset, some coffee and vegetables are grown. Enset is a long-lived banana-like perennial plant used for food, feed and fiber throughout the Southern Highlands of Ethiopia. The traditional enset system of the highland regions of Southern Ethiopia is an indigenous, famine-avoiding agricultural system unique to Ethiopia. The primary strategic importance of enset in food security is the prevention of famine by surviving during droughts when other food crops fail. This makes enset an important food security crop and that is why, totally, farmers use animal manure for enset fields continuously, than applying it on the other crops. However, enset-based livelihood systems do face some fundamental structural weaknesses particularly the need for manure to

Figure 4 (a). Red soil from cultivated land. (b). Black soil from enset farmland.

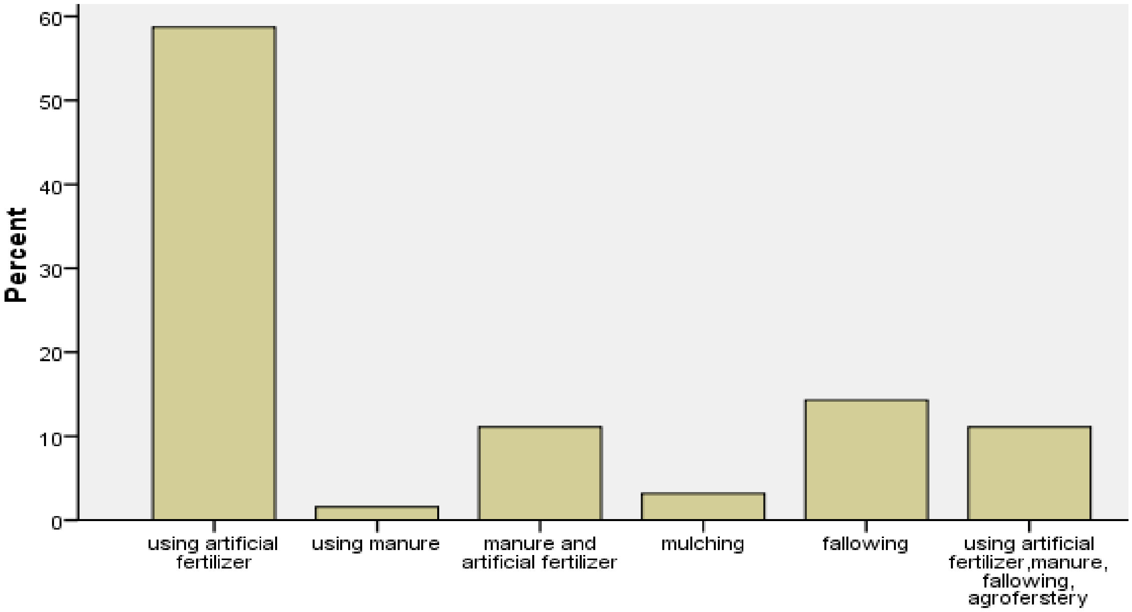

Figure 5. Agricultural inputs used to manage soil fertility of cultivated field.

maintain vigorous growth.

Inorganic fertilizer use

Highest proportion of the interviewed farmers used inorganic fertilizers as the sole source of improving soil fertility and productivity for cultivated land where cereal crops grow (Figure 5). Relatively, very few farmers tended to use a combination of organic and inorganic fertilizers instead of purely relying on inorganic fertilizers. Discussions with local extension agents and focus group proved that the progressive increment of fertilizer usage is related to the decline in soil fertility status of the sub-watershed. However, there was also a major bottleneck for small scale farming system to use equal amount of fertilizer or to increase the amount of fertilizer from year to year as, they had used before. They are always reluctant to use inorganic fertilizers because they perceive that the cost of inorganic fertilizers is unaffordable, and the productivity is unpredictable due to the erratic nature of rainfall.

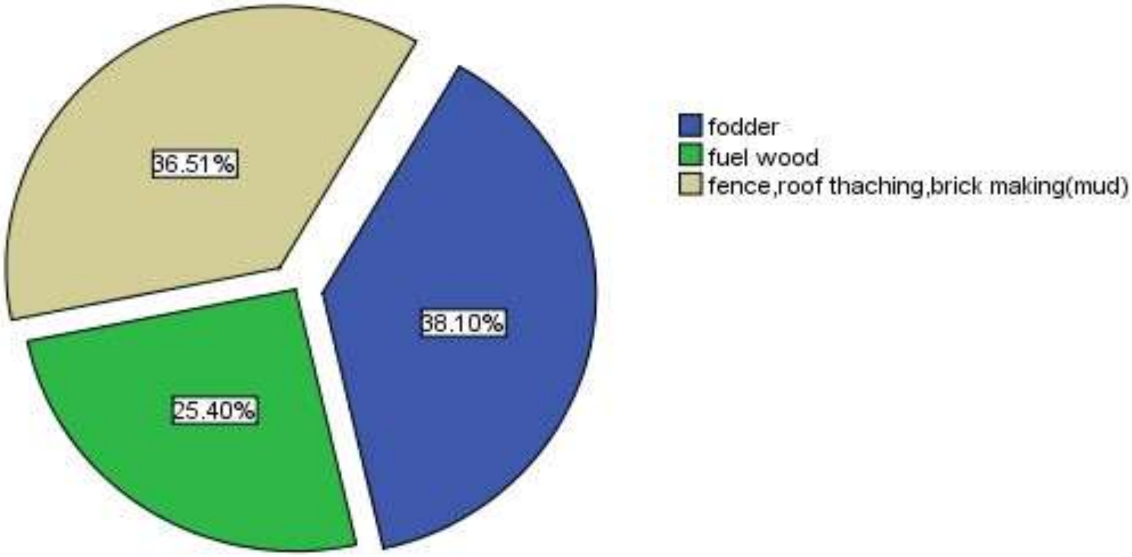

Figure 6. Use of crop residue in farm soil management.

Figure 7 (a). Teff residue collected for fodder, **(b).** Sorghum residue collected for fence.

Use of crop residue

The results indicated, that the uses of crop residues for livestock feeding were common practices in the study area (Figure 6). Discussion with farmers and extension agents revealed that crop residue from cereals crops (wheat, barley and teff) and legumes (beans and peas) are transported from field to the home compound and stored for animal feed due to chronic feed shortage. In addition, teff residue and sorghum stalk are used mainly for fodder, fuel wood and fencing (Figure 7). However, the leaf and leaf sheath are grazed by animals in the field. It implies that soil fertility is declining more rapidly in the main fields, as crop residues were removed from these areas and used for livestock feed, while animal manure is used only to maintain soil fertility of homestead gardens where enset and coffee are grown.

Field observation confirmed that homestead soils were dark brown to black, mainly due to high organic matter content. Soils of the neighboring field except the homestead were red in color. A study conducted by (Eyasu, 1998) showed that the main field is the most depleted, and there is a clear nutrient gradient from the homestead to the main fields. This implies that soil fertility decreases with distance from the homestead, which is attributed mainly to crop residue and farmyard manure management. Mulching, covering soil surface with crop residues, is another potential measure to reduce soil/nutrient loss because mulching was only practiced by 4.8% of the interviewees where as 95.2% of respondent revealed that mulching is not applicable in their cultivated and grazing field of the study area due to unavailability of crop residue and other mulching materials. However, enset farm land recieves manure, household refuses and extra mulching residue of other crops.

Farmers mainly export to the enset field because enset is considered as a security crop for the household. Earlier investigations in neighboring district showed that the enset field is the most fertile corner of the farm, especially in terms of organic matter and nitrogen (Eyasu et al., 1998). According to Bekunda (1999) and Elias (2000), there was also significant variation of nutrient contents in the homestead soils which is dominantly covered with enset farming system than in the outfield; regardless of farmers' resource endowment. Because enset farmland receives a large amount of household wastes, livestock manure, wood and/or dung ash and other decomposable materials are often thrown to the enset, which in aggregate changes nutrient and carbon storage over a long time. Proximity of enset for homestead also makes easy the manual transportation of household refusal, stall manure and application of manure. Due to that, soil status of organic matter rich land has appropriate performance of subsurface drainage systems which caused adequate inflow to the drain for improvement of soil environmental conditions (Valipour M, 2013). Thus, poor management and unwise use of crop residues may have reduced the quality and availability of residues to be used for soil fertility restoration, especially in cereal-based farming systems in the area.

Cropping systems

Traditionally, the major cereals are grown in rotation with sorghum or maize. More than 55.6% of the respondents reported that they practice crop rotation. But, a relatively high proportion of farmers reported that they grow sorghum or maize in rotation with teff, wheat, beans and peas. They preferred this sequence of crop rotation; as they believe that soil fertility would be improved when cereals are grown in rotation with sorghum or maize. Intercropping is another type of cropping system in the study area but not widely practiced. Out of interviewed farmers, only 32.7% of the respondents practiced intercropping. Intercropping, particularly with legumes is a deliberate measure to maintain soil fertility. For example, intercropping cereals with legumes, such as faba bean with other crops is a common practice in the sub-watershed. The emphasis on legumes is to enhance soil fertility, since the use of inorganic fertilizer has fallen drastically because of the high prices. Under this system, different crops are intercropped in the study area, which includes maize with faba bean, maize with potato, maize with cabbage and faba bean with potato.

There are essentially two practical advantages of the intercropping system, for example, mixing legumes with a grain crop especially maize. Firstly, legumes are nitrogen fixing plants, therefore, by intercropping the two farmers don't even have to apply so much inorganic fertilizer since most of them cannot even afford to buy fertilizers. Besides, legumes are also used as cover crops so they suppress the growth of weeds and minimize the difficult task of weeding and soil loss due to erosion. The practice of fallowing is also virtually absent in the watershed. This further reflects the ever increasing trend of pressure and shortage of arable land, which forces farmers to discontinue fallowing. The field operations in the study area are characterized by continuous cultivation which makes the soil susceptible to erosion and finally resulted in nutrient depletion. Thus, continual farming, without considering conservation measures and using adequate external inputs to compensate soil fertility decline is expected. A study conducted at the Gununo site, Bolosso Sore district (Areka) in Wollaita zone has also shown that most plots that are cultivated every year without fallow are subject to a significant loss in soil fertility (Eyasu 1998; Amede, 2001).

Perceived effects of soil and water conservation (SWC) measures on productivity and soil fertility

About 92% of the interviewees in the catchment were aware of the problem of soil erosion and they believe that, the severity of the problem had increased in recent years. However, very minimum proportion (36.5%) of the interviewed farmers implemented soil and water conservation practices, especially soil bunds, fanayajuu and stone bunds, while the rest 63.5% of the respondents had no soil water conservation structure on their farms. Complaint of farmers to adopt SWC was as a result of its inconvenience during farm operations, especially for free movement of oxen plough followed by labour shortage and lack of construction know-how. As far as the magnitude of soil erosion is concerned, the respondents rated the level of the problem as very severe, moderate and slight. About 85% of the respondents for the upper catchment zone rated the level of erosion as very severe. In addition, about 75% of the respondents acknowledged that the rate of erosion is increasing from time to time on their plots. This, is in line with (Morgan, 2005) observation who reported that high rainfall rates in steeply sloped areas with absence of protective measures were caused by high rates of soil erosion.

The majority of farmers those who implemented soil and water conservation structure on their farms, perceived that SWC structure increased crop yield, prevented soil erosion, improved water retention capacity of the soils and enhanced soil fertility. But, very few farmers believed that SWC structure could indeed assure long-term productivity of the land. This implies that farmers were likely to invest in simple and cheap short-term benefit measures rather than to go for the recommended mechanical structures, such as bench terraces and soil bunds. Because of the top down enforcement to adopt mechanical SWC structure that was not properly implemented, farmers have convinced opinion that these structure are less successful in soil erosion control. As such, 81.5% of farmers perceived that conservation measures are incapable of preventing (or stopping) soil erosion phenomenon, based on the performance of the SWC on their fields, despite the positive perceptions they had for the SWC structure. This finding is consistent with the result of (Woldeamlak B., 2003), who reported that the major cause of dis-interest shown by most of the farmers towards the SWC activities is the perceived ineffectiveness of these technologies.

Conclusion

In conclusion, farmers perceived reduction of crop yield, change in soil color, and indicator grass species as important tools to evaluate soil fertility status of their field. Apparently, SWC structures were also perceived by farmers to improve soil fertility and soil retention to increase of crop yield.

Conflict of Interests

The authors have not declared any conflict of interests.

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