

Full Length Research Paper

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

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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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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; Esmailzadeh 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 CO₂ 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 (Römkens et 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

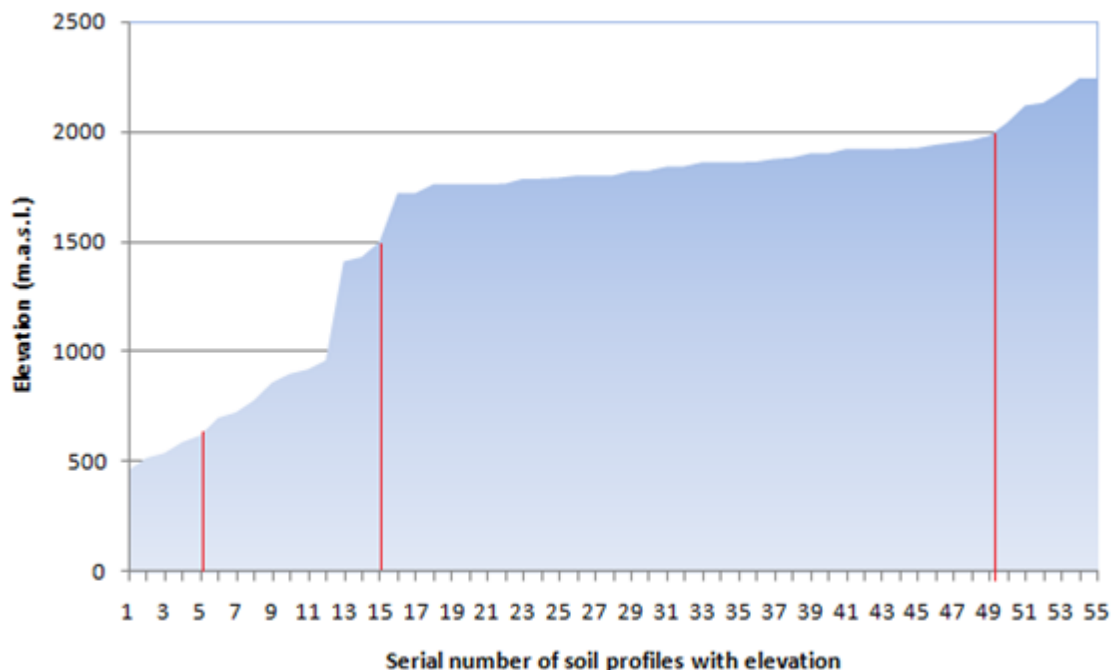


Figure 1. Topographic variation of soil organic carbon study sites in west Usambara Mountains, Tanzania.

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

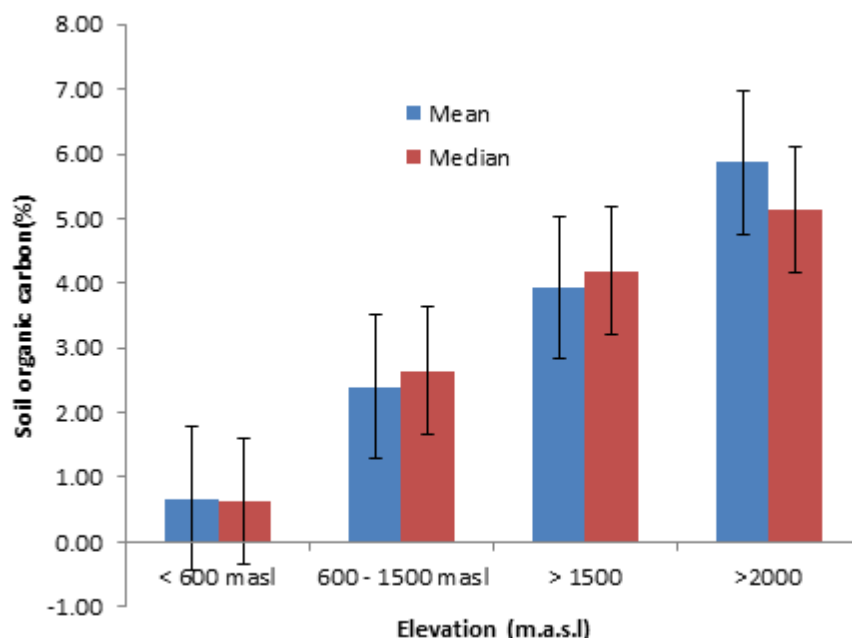
Influence of topography and landforms on soil organic carbon

The influence of elevation to SOC is depicted in Table 1 and in Figures 2 and 3. The carbon levels range between 0.55 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 et al., 2010; Atkins et al., 2015; Sheng-Xuan et al., 2015).

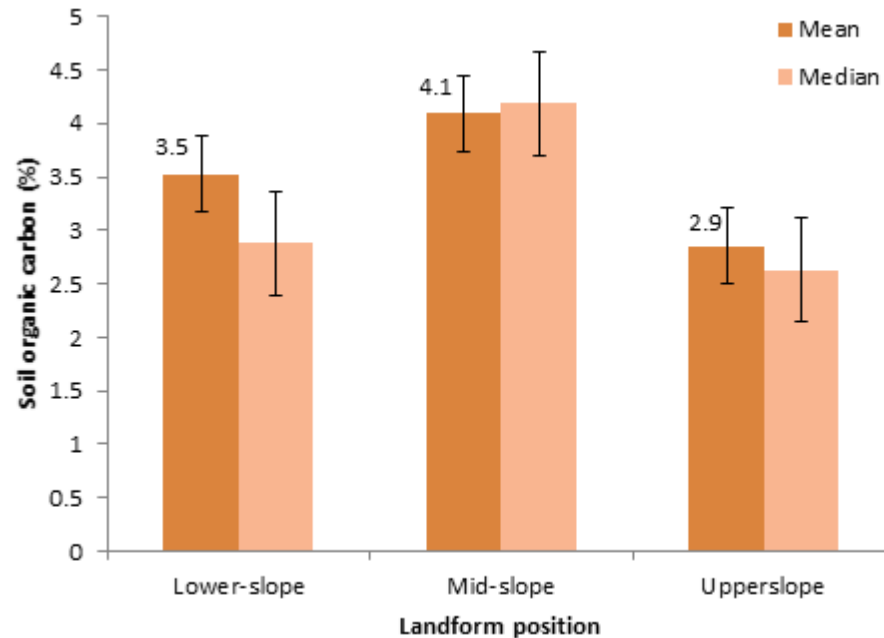


Figure 3. Influence landform position soil organic carbon in West Usambara Mountains, Tanzania.

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 Figure 3 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 characterised with shallow, sometimes gravelly soils which have

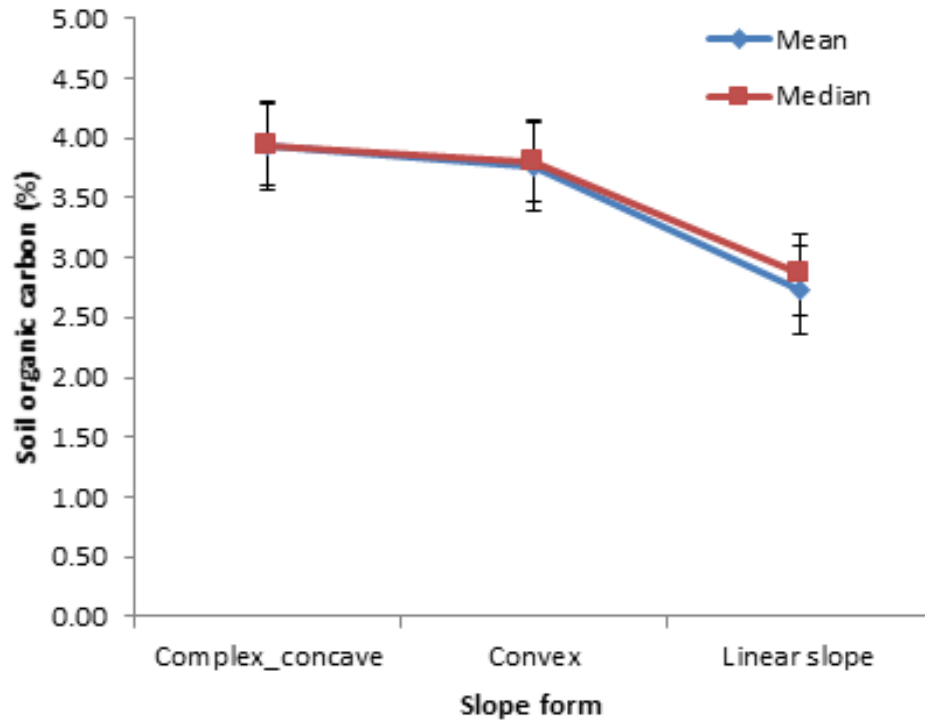


Figure 4. Influence of landform slope forms on soil organic carbon accumulation in West Usambara Mountains, Tanzania.

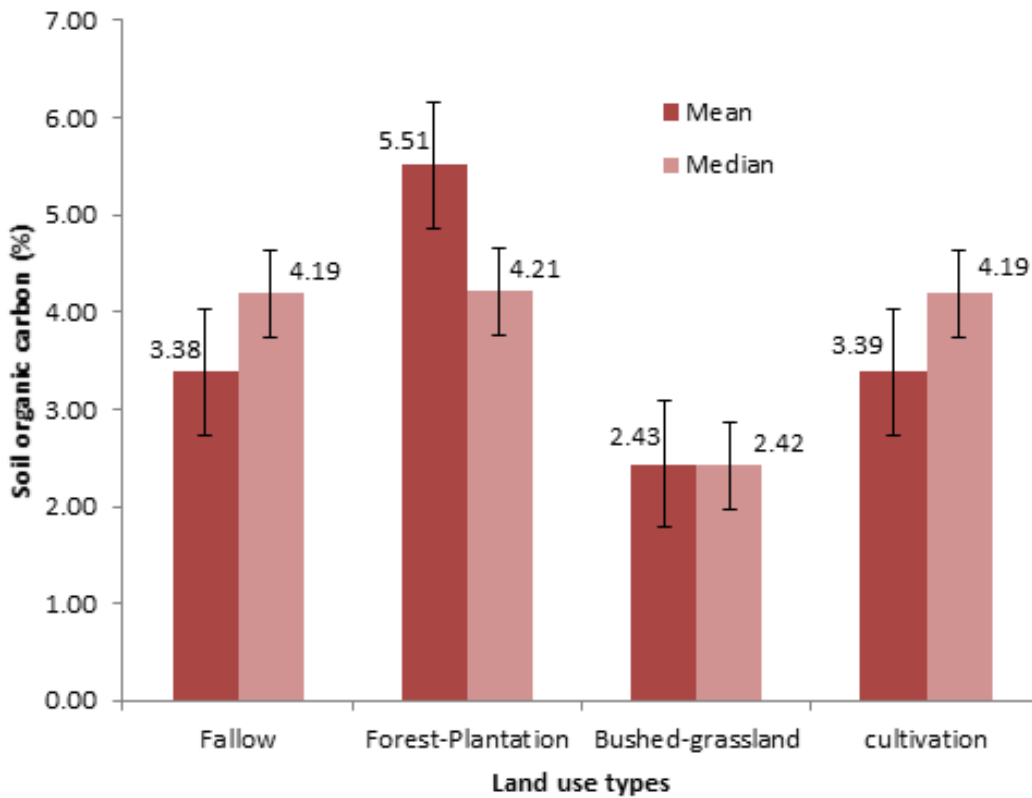


Figure 5. Influence of land use/cover on soil organic carbon in West Usambara Mountains, Tanzania.

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 (Römkenst et 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; Esmailzadeh 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 al., 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.

Parameter	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	***
Ca cmolc/kg soil	1	0.414	0.414	4.485	0.0525721	.
Mg cmolc/kg soil	1	0	0	0.0004	0.9837584	-
K cmolc/kg soil	1	1.539	1.539	16.6617	0.0011211	**
Na cmolc/kg soil	1	0.079	0.079	0.8585	0.3698602	-
TEB cmolc/kg soil	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.

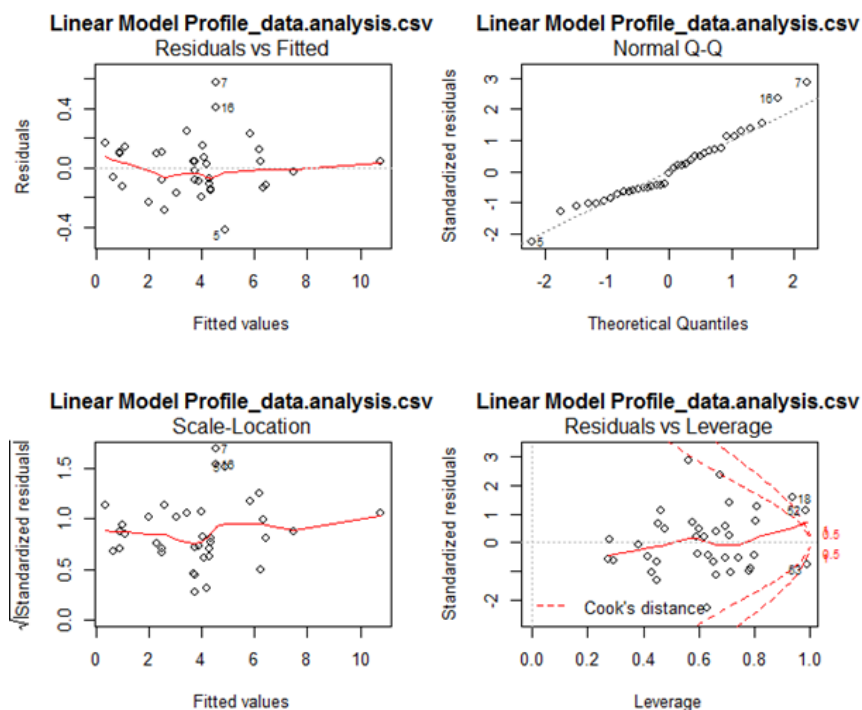


Figure 6. Model validation using residual analysis indicating that analysed data fitted well though there were outliers.

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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