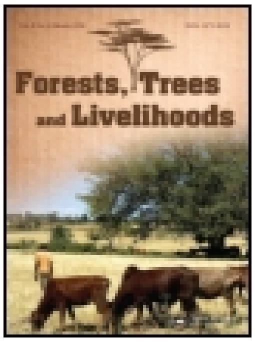

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Relationships between on-farm tree stocks and soil organic carbon along an altitudinal gradient, Mount Kilimanjaro, Tanzania

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ABSTRACT

Understanding above-ground tree biomass carbon (AGC) and relationships to soil organic carbon (SOC) stocks across a landscape provide opportunities for better management of the carbon pools. This study determined relationships between on-farm AGC and SOC stocks along an altitudinal gradient on the slopes of Mount Kilimanjaro. Fifty plots (100 × 100 m) were established, whereby all trees ≥5 cm dbh, were recorded. Soil samples from top (0–20 cm) and subsoils (21–50 cm) were collected at the centre of the plots using four subplots. Tree inventory and soil analyses were performed and statistical tests were conducted to understand relationships between AGC and SOC stocks. Results indicated that stem density increased with altitude, however the upland and the midland did not differ significantly while the lowland differs with both the midland and the upland. A similar pattern was observed for basal area and above-ground tree biomass (AGB), with no significant difference between the midland and upland whereas the lowland differed significantly from both the upland and the midland. SOC stocks varied significantly, being the largest in the upland, amounting to almost twice the size recorded in the midland or the lowland. SOC stocks indicated poor correlation (Pearson's: $r = 0.327$, df = 47, $p = 0.023$) and poor interaction (Wald = 0.0008, df = 1, $p = 0.977$) with AGC. This study concludes that the relationship between AGC and SOC stocks was masked by other factors including soil types, precipitation and land management. The protocol used to test the relationships might also have contributed further to current observation. Overall, the lowland area, having low AGC and SOC stocks, requires management interventions aimed at increasing SOC stocks.

KEYWORD

Ecosystem services; agroforestry; homegardens; carbon stocks; land use; productivity; sustainability; climate change adaptation

Introduction

The current trend of diminishing tropical forests and woodlands through deforestation and forest degradation (Gibbs et al. 2010; Green et al. 2013) is associated with declining stocks of soil organic carbon (SOC) (Lal 2006). SOC can be reduced by about 75% when tropical forests are converted to agriculture (Lal 2004); and as SOC stocks decrease, soil fertility

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declines and land degradation can be accelerated. Such losses of SOC undermine the wider provision of ecosystem services and can have negative livelihood impacts. Elevation also influences SOC especially via changing ground cover, tillage and other management practices (Martin et al. 2010).

While tree cover has been decreasing within natural forests, there have been some increases in agricultural lands (Zomer et al. 2014). This follows efforts to diversify tree cover on farmland through domestication of indigenous tree species and other high value tree crops that can bring broader co-benefits of increased ecosystem services (Dawson et al. 2013; Mpanda et al. 2014). Incorporating trees into agro-ecosystems can help mitigate the impacts of climate change, provide habitat for biodiversity (Nkem et al. 2007) and support crop production (Lal 2006) while increasing SOC. Changes in management practices can help reverse SOC losses, and interventions such as vegetation restoration can increase SOC by more than 20% within a decade (Wang et al. 2011). However, the link between tree biomass and SOC is currently uncertain and quantifying the value of this regulatory ecosystem service has been a challenge (Gluck 2000; SCBD 2001).

Previous studies on the slopes of Mount Kilimanjaro have assessed the structure of the Chagga home gardens and information on the biodiversity associated with forest, agroforests and the land use changes (Hemp 2005; Soini 2005). However, little is known about the distribution and relationships between on-farm tree biomass and SOC. Tree biomass itself is increasingly considered as an important ecosystem service under REDD+ (reducing emissions from deforestation and forest degradation with additional role of conservation, sustainable management of forests and enhancement of forest carbon stocks). REDD+ aims to enhance the terrestrial carbon stock to mitigate climate change by drawing down atmospheric CO_2. Whilst we do know that SOC represent a significant carbon store, further insights such as the study presented here contributes to a better understanding of SOC at local scale (Batjes 1996; Fonte et al. 2010).

This study attempted to assess tree biomass carbon and SOC stocks on the slopes of Mount Kilimanjaro. Specifically, it aimed at, (i) identifying variation in the tree biomass carbon in the agricultural landscape, and, (ii) identifying variation in the SOC stocks in the agricultural landscape. We hypothesized that an increase in tree biomass carbon on farm corresponds to an increase in SOC stocks.

Material and methods

Study site and design

This study was conducted on the southern slopes of Mount Kilimanjaro, in Kilimanjaro administrative region in northeastern Tanzania (Figure 1). Mount Kilimanjaro is a stratovolcano, with the highest free-standing solitary mountain rising above the surrounding relief by 5000 m (Nonnotte et al. 2008). Rainfall is bimodal with longer rains from March to May and shorter rains in October to November. Kilimanjaro region's population stands at 1,640,087 and the average household size is 4.3 (URT 2013).

The landscape outside of the protected area on the slopes of Mount Kilimanjaro was divided into three broad land-use categories, namely the upland, midland and lowland (Table 1), that encompass differences in elevation (topography and slope), climate (precipitation and temperature), biophysical features (soils and vegetation) and land-use (URT 1998).

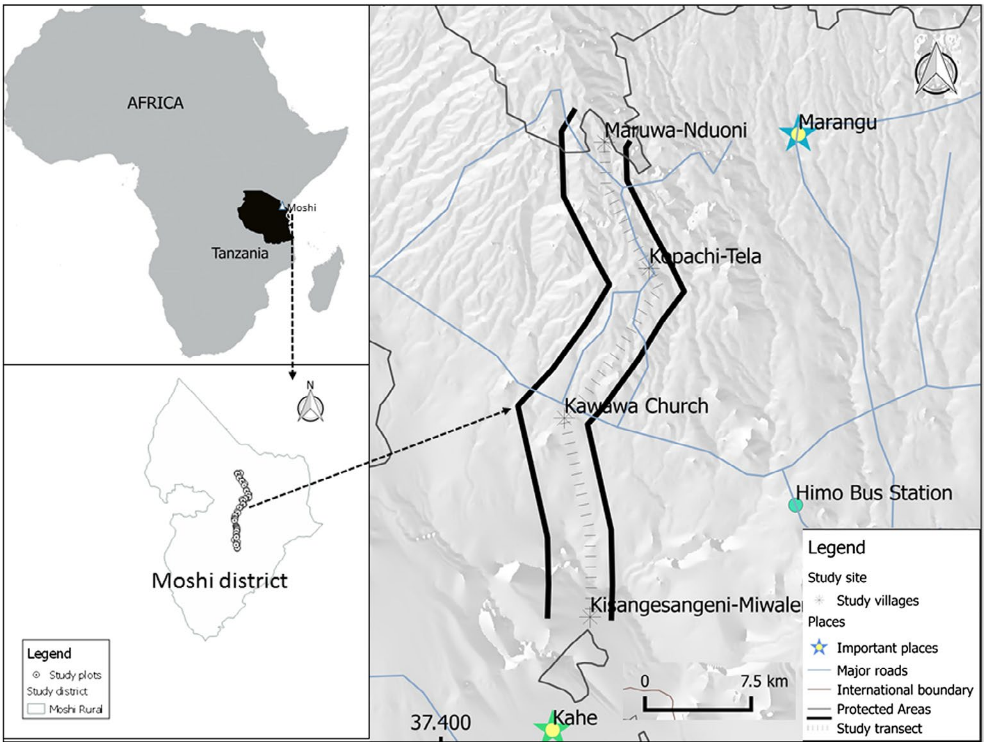

Figure 1. Location of the study transect that extends from the sub-montane to lowland agricultural fields on the southern slopes of Mount Kilimanjaro, Tanzania. Source: Mathew et al. 2016.

Table 1. Characteristics of the three land-use zones on the slopes of Mount Kilimanjaro, Tanzania.

Land-use zone	Description
Upland	Elevation: 1438–1696 m a.s.l. Precipitation: 1250–2000 mm per annum Temperature: 24 °C Topography: gentle slope (20–30°) Major soils: weathered volcanic ash, Humic Nitisol Characteristics: cultivated farms, Chagga homegardens, zero grazing, high density of coffee and banana
Midland	Elevation: 901–1337 m a.s.l. Precipitation: 1000–1200 mm per annum Temperature: 26 °C Topography: gentle slope (20–30°) Major soils: Sodic volcanic ash, mainly in slopes, Haplic Phaeozom Characteristics: cultivated farms, transition of homegardens and maize belt, zero grazing
Lowland	Elevation: 680–834 m a.s.l. Precipitation: 400–900 mm per annum Temperature: 33 °C Topography: Flat terrain (5–10°) Major soils: sediments influenced by volcanic ash, Eutric Fluvisol (alluvial with little profile development) Characteristics: cultivated farms, savannah plain, free grazing

Three major patterns of tree distribution on farm were observed during the tree inventory; (i) boundary planting with a high number of trees of relatively low dbh (diameter at breast height), (ii) scattered trees of medium to large size, at variable densities and (iii) a combination of (i) and (ii), i.e. boundary planting and scattered trees on farm. In the upland and midland zones, the Chagga homegarden was the common farming system, featured with multi-storey agroforests, where layers of closed tree canopy overlaps with understory layers of coffee and banana (Fernandes et al. 1984).

Methods

Assessing carbon stock from trees on farmland

A total of 50 (100 × 100 m) farm plots were sampled along a predetermined zigzag 25 km length study transect (Figure 1). Within each plot all trees (except for coffee shrubs and climbers) ≥5 cm diameter at breast height (dbh) were identified by a botanist and their dbh measured. One hundred trees ranging from 5 to 90.7 cm dbh were randomly sampled for height-dbh measurement for establishing the equation (*expression* (I)) used in estimating height of the rest of trees. For trees outside this range, it was assumed that their height could not be higher than 45 m which was the height of maximum range of 90.7 cm dbh. Only 2.16% of all trees were later found to be larger than dbh of 90.7 cm.

$$\mathrm{LnHt} = 0.553 + 0.6817 \times \mathrm{Ln}(D);\ \left(R^2 = 0.7741,\ \mathrm{SE} = 0.037,\ n = 100\right) \quad \text{(I)}$$

where Ln = natural logarithm, Ht = height (m), D = diameter at breast height (cm), R^2 = coefficient of determination and SE = standard error.

Above-ground tree biomass (AGB) was computed using allometric equation (*expression* (II)) developed by Chave et al. (2014), carbon content was computed as 50% of the dry tree biomass.

$$\mathrm{AGB} = 0.0673 \times \left(\rho D^2 H\right)^{0.976} \quad \text{(II)}$$

where AGB = above-ground biomass, ρ = wood specific gravity (g cm^{-3}), D = diameter at breast height cm) and H = height (m).

Wood specific gravity of each species was determined from Global Wood Density Database (Chave et al. 2009; Zanne et al. 2009). Tree stocking parameters on per hectare basis for number of stems (N), basal area (G), AGB and above-ground tree biomass carbon (AGC) were computed.

Assessing SOC on farmland

Within each sample plot, four subplots (Figure 2) were established for soil sampling using inverted Y-shaped design adapted from the African Soil Information System protocol (UNEP 2012). The layout of the four subplots ensured good representation of the soils in the centre of the sample plot and thus dissociate from external influence from boundaries.

In the plots where slope was >10%, a correction factor was applied using the following formula (*expression* (III)).

$$L_s = L / \cos(S) \quad \text{(III)}$$

where L_s = slope distance, L = horizontal distance, S = slope angle in degrees.

Composite soil samples (litter was removed) from topsoil (0–20 cm) and subsoils (21–50 cm) were collected from each of the four subplots, and separately mixed thoroughly.

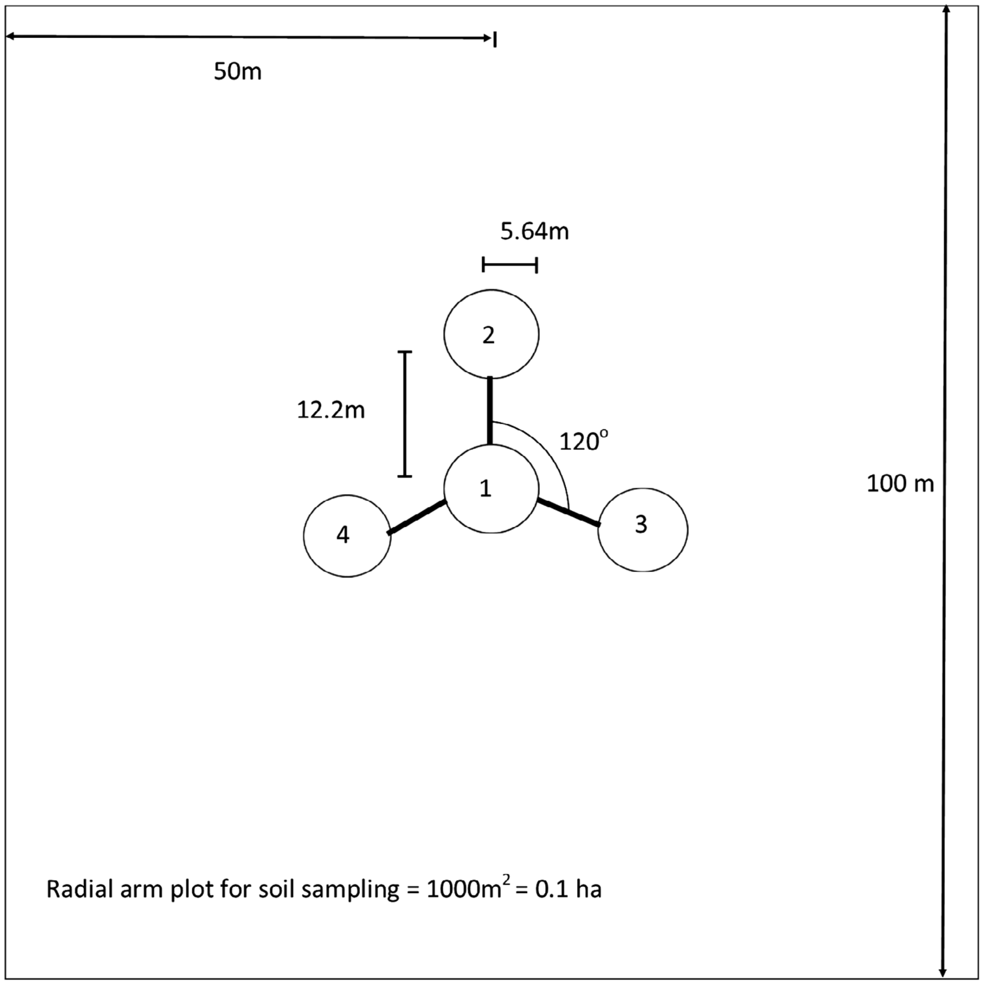

Figure 2. Layout of the tree sampling plot and nested soil sampling sub-plots.

About 500 g of the composite sample for each top and subsoils were packed in zip-lock bags and labelled.

Cumulative soil mass samples were collected at the centre of each plot (subplot 1) using an Edelman combination auger, at depths of 0–20 cm and 21–50 cm. A sampling plate was used as an auger guide to enable full recovery of the sample. Cumulative soil mass collected from top and subsoils were separately packed and labelled in zip-lock bags.

Soil samples (composite and cumulative separately) were later air dried at 40 °C, then weighed to the nearest 0.1 g using a calibrated top-pan balance. Samples were then sieved with 2 mm mesh size sieve and the course fragments (>2 mm) weighed. Cumulative sub-samples were used for estimation of gravimetric water content and bulk density. Sub-samples were oven-dried at 105 °C for 48 h until a constant weight was obtained, and thereafter computation for the *expressions* (III) and (IV) was effected.

$$\text{Gravimetric water content } (\%) = ((\text{Air dried soil} - \text{Oven dried})/\text{Oven dried}) \times 100 \qquad \text{(IV)}$$

$$\text{Bulk density}\left(g/cm^3\right) = M_d/V \tag{V}$$

where M_d = mass of dry soil sample, V = soil volume.

Composite subsamples were analysed in the soil laboratory to determine organic carbon stocks by the Walkley–Black method (Nelson & Sommers 1982).

SOC was calculated as shown in *expression* (VI);

$$\text{SOC} = (C/100) \times \rho \times D \times (1 - \text{frag}/100) \times 100 \tag{VI}$$

where SOC = soil organic carbon stock (t Cha^{-1}), C = soil organic carbon concentration determined in the laboratory (g kg^{-1}), ρ = soil bulky density (g cm^{-3}), D = soil depth of sampled soil layer (cm), frag = % volume of coarse fragments/100, 100 = is a conversion factor to t Cha^{-1}.

Assessing the relationships between tree biomass carbon and SOC in the three land-use zones

A normality test was conducted and indicated that tree stocking parameters and SOC distribution did not conform to normal tendency, hence a non-parametric Kruskal–Wallis (K–W) and Mann–Whitney–Wilcoxon (MWW) were used for significance tests. The null hypothesis tested if the distribution of the tree stocking parameters and SOC were the same with altitude and land use zones (e.g. Hassani & Silva 2015). Pearson's correlation was conducted to determine relationships between AGC and SOC in each land-use zone (two plots were treeless, hence were omitted in the comparison). The interaction between AGC tree carbon and SOC was conducted using Generalized Linear Model presented by Wald's test using GenStat 14th Edition (Payne et al. 2009).

Results

A total of 1660 individual trees were recorded belonging to 69 species and 28 families. Out of recorded individual trees, 846 were exotics and 814 were belonging to indigenous species. The number of stems per hectare increased with altitude (Figure 3), however the upland and the midland did not differ significantly (MWW test: df = 1, $p = 0.354$), while the lowland differs with both the midland ($p < 0.001$) and the upland ($p < 0.001$). The same pattern was observed for basal area (Figure 3), and for above-ground tree biomass (AGB, Table 2), with no significant difference between midland and upland (MWW test: df = 1, $p > 0.05$ for basal area and $p = 0.939$ for AGB) whereas the lowland differed significantly from both the upland and the midland ($p < 0.001$ for both basal area and AGB).

Results show that SOC ($Mgha^{-1}$) was highest in the upland, accounting to almost twice the levels of the midland or of the lowland areas (Table 2). Soil moisture (%) recorded a similar trend as SOC, while soil bulk density (g cm^{-3}) tends to decrease from lowland to upland areas.

Subsoil has relatively higher values than topsoil for SOC stocks and gravimetric water content in the three land-use zones (Table 2). SOC stocks differences between the three land-use zones were statistically significant at $p = 0.001$ (the upland vs. midland), $p < 0.001$ (the upland vs. lowland) and $p = 0.007$ (the midland vs. lowland).

The relationship between AGC and SOC had poor correlation (Pearson's: $r = 0.327$, df = 47, $p = 0.023$) and low interaction (Wald = 0.0008, df = 1, $p = 0.977$) with elevation. At land-use

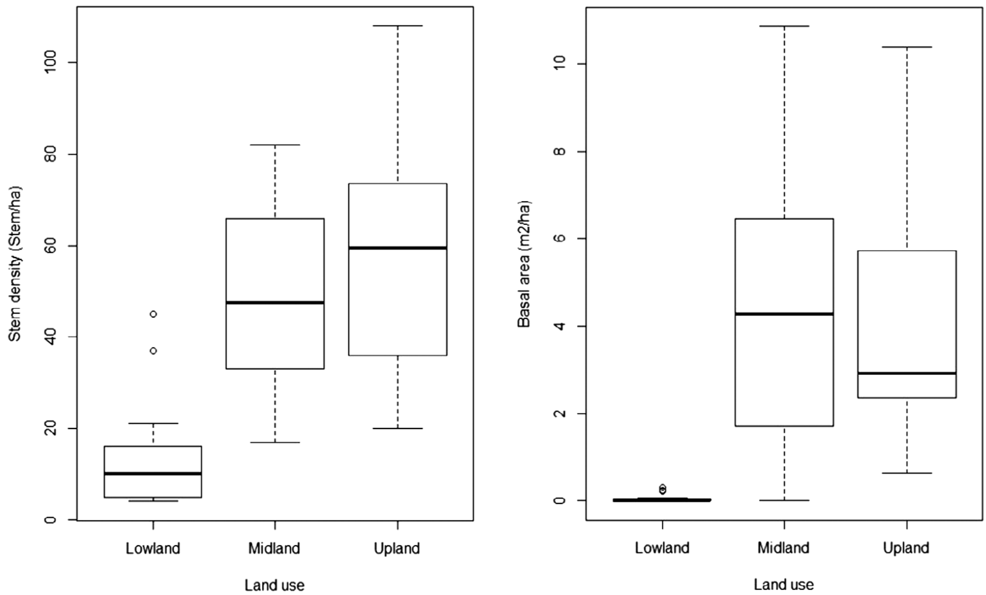

Figure 3. Box and whisker's plots representing the median values per plot of the number of stems and basal per hectare across the three land-uses.

Table 2. Above-ground tree biomass carbon (AGC), soil organic carbon (SOC), bulk density and gravimetric water content (gravimetric WC) in the three land-use zones on the southern slopes of Mount Kilimanjaro, Tanzania (Mean ± SE).

Parameters	Upland (1438–1696 m a.s.l) *n* = 12	Midland (901–1337 m a.s.l) *n* = 14	Lowland (680–834 m a.s.l.) *n* = 24
AGC (Mgha^{-1})	20.11 ± 5.23	22.17 ± 4.9	7.11 ± 2.59
SOC (Mgha^{-1})			
0–20 cm depth	439.2 ± 62.83	257.57 ± 54.17	207.09 ± 34.47
20–50 cm depth	474.96 ± 69.45	294.15 ± 63.48	233.8 ± 29.08
Bulk density (gcm^{-3})			
0–20 cm depth	0.6 ± 0.01	0.6 ± 0.06	0.7 ± 0.03
20–50 cm depth	0.5 ± 0.03	0.6 ± 0.03	0.7 ± 0.03
Gravimetric WC (%)			
0–20 cm depth	15.06 ± 1.44	11.71 ± 0.98	10.28 ± 0.56
20–50 cm depth	19.43 ± 2.08	13.7 ± 1.55	11.78 ± 0.7

zone level, the relation between AGC and SOC was negative for the lowland and for the upland, but was positive for the midland (Figure 4). In each case however, the coefficient of determination was very low, confirming the low correlation between our two variables.

Discussion

This study observed distinct tree stocking levels associated with the three main land-use zones. Levels of SOC exhibited a strong pattern within land-use types although SOC and AGC stocks were poorly correlated. The lowland zone supported considerably lower tree stock densities than both the midland and the upland zones, while SOC was much higher in the upland zone than in both the midland and the lowland zones. Overall observed AGC

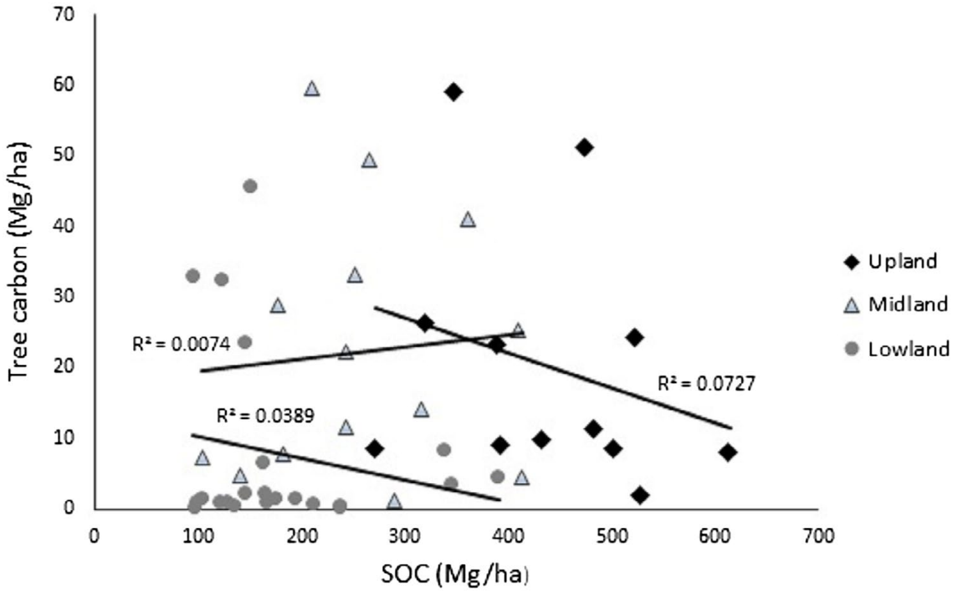

Figure 4. Scatter matrix of SOC and tree carbon showing their relation across the land use zones.
Notes: Middle regression line (midland zone plots) shows a positive trend; the upper regression line (upland zone plots) and the lower regression line (lowland zone plots) show negative trends.

stocks were in the same range as noted by other studies conducted in the nearby areas (Ensslin et al. 2015). Reasons for the decline of basal area and tree biomass carbon in the upland remained unclear but is likely to result from a cooler climate that prompt farmers to destock trees to allow more space for crops.

Distribution of SOC

SOC stocks were found to strongly decline from the upland to midland, and to lightly decline from midland to lowland. These variations might be linked to the differences in soil types, environmental variables and management regimes (Table 1). SOC stocks trend relates to precipitation and soil moisture content, which increased upslope, and thus may have contributed to the acceleration of decomposition of organic matter. Other studies have noted similar trends, where increased soil moisture corresponded to increase in SOC (e.g. Manns & Berg 2014; Klopfenstein et al. 2015). Furthermore, SOC stocks recorded in this study were within the range of other studies conducted close to the study area (e.g. Munishi & Shear 2004; Mwakisunga 2012; Winowiecki et al. 2015).

Land management practices are different in each land-use zone, and probably contributed in influencing the distribution of SOC stocks. The build-up of SOC stocks in the upland and the midland may be reflective of the indigenous practices associated with the Chagga home-garden systems. Fernandes et al. (1984) noted that the intensification in the Chagga home-gardens, where tree intercropped with banana, coffee and zero grazing of livestock sustained the integrity of the system. The amount of litter-fall and other vegetation biomass from this system have higher contribution to SOC stocks accumulation especially in the upland, where there is higher concentration of coffee and banana than in the midland. Additionally, due to shortage of fodder for livestock in the upland and midland, biomass transfer of crop residuals from the lowland upslope are a common practice (Mambo 2005). In the lowland, the change of savannah vegetation to cropland and free livestock grazing may have contributed to low levels of SOC stocks (e.g. Oberholzer et al. 2014).

The low levels of SOC in the midland and lowland areas imply reduced crop productivity compared to the upland. Lal (2006) estimated that between 15 and 150 kgha^{-1}yr^{-1} increased maize yield can be projected for every 0.5 Mgha^{-1}yr^{-1} increase in SOC pool. Therefore, any efforts to increase SOC stocks in the lowland area could amount to improvement in crop production. Cropland management such as crop residual retention and crop rotation contribute to improving SOC stocks (Raffa et al. 2015) so these strategies could be utilized in the lowlands to help enhance crop productivity.

Relationship between AGC and SOC stocks

Vegetation is one among many factors influencing SOC stocks (Oueslati et al. 2015; Sun et al. 2015). Trends of tree vegetation and SOC stocks along land-uses in the study area indicated some commonalities and contrasting features. While the lowland had lower AGC and SOC stocks, the AGC stocks peaked in the midland and SOC stocks peaked in the upland. Our results seem to indicate that at farm level contribution of tree stocks in the build-up of SOC stocks might have been masked by other factors, both long and short term. Therefore, the observed poor correlation and interaction between AGC and SOC stocks can be a result of various contributing factors. Tree cover alone might not be the main contributor especially at larger scale such as farm and landscape. For instance, SOC stocks were found to be similar in adjacent sites containing primary and secondary forests (forest degraded by timber harvesting from late 1960s to early 1980s) in the nearby East Usambara Mountains in Tanzania. This was the case despite clear differences in tree biomass and vegetation cover. The observation means that differences in tree cover may not necessarily affect SOC stocks, if the cause of the differences did not involve soil disturbances (Kirsten et al. 2016). Similarly, Kinoshita et al. (2016) noted that SOC was influenced mainly by soil properties. The study further noted that topography and vegetation had very little impact. These observations may align with results of our study in which soil types (Table 1) probably contributed to the variability of SOC stocks, irrespective of the tree vegetation within the land-use zones.

Alternative explanation pertaining to poor correlation of carbon pools can be due to effect of long term and current land management practices on build-up of SOC stocks especially in the upland and midland. Zech et al. (2014) noted paleosols sequences with high SOC content of up to 3 m depth on the slopes of Mt. Kilimanjaro, which is irrespective of the tree cover. The accumulation of the SOC might be due to long-term processes. Therefore, observed SOC stocks in our study (Table 2) may also be a result of similar long-term land management practices.

Biomass transfer such as crop residuals, application of manure and other land management practices used on farm at different levels and intensities may have contributed to either built-up or depletion of SOC stocks on farm. As there was no uniformity and clear patterns on land management due to fragmentation of smallholder farms in the study area, differences of SOC stocks was inevitable. Therefore, miscellaneous inputs of organic matter may have caused disruptions and mismatch in the correlation trends between tree carbon and SOC stocks.

It is also apparent that the protocol used in collecting field data for trees and soils in the current study might have contributed to the observed low correlation and interaction between AGC and SOC stocks. For instance, Cardinael et al. (2015) noted that an alley cropping agroforestry system involving hybrid walnuts accumulated more SOC than only agricultural crops. This study took into consideration distance to trees and tree rows, and showed that carbon accumulation takes place under and at very short distance from the trees. In contrast, our study employed fixed subplots position for soil sampling while trees were in irregular patterns, meaning that our protocol may have been poorly suited to the estimation of SOC in such a mixture of trees and crops. Therefore, attempts by the present study to look at the bigger picture on the relation between AGC and SOC stocks accumulation at farm and landscape level revealed that, (i) contribution of tree biomass in SOC stocks was masked by other factors including soil types, precipitation and land management, and, (ii) the protocol used might have contributed to the observed lack of trend as it was ill adapted to capture the irregular patterns of trees on farm.

Conclusion

Understanding AGC and SOC stocks and their spatial relationship in a landscape is important as it provide opportunities for better management of the carbon pools. Tree stocking (basal area and carbon) varied along the altitudinal gradient, with peak in the midland. There was high variability for SOC stocks along the land-use zones with a decreasing trend, where Upland > Midland > Lowland. A poor relationship was observed between AGC and SOC stocks. This study suggested that the role of tree biomass in enhancing accumulation of SOC stocks was masked by other contributing factors such as soil types, climate (precipitation) and land management factors, and possibly by a SOC stocks estimation protocol not suited to the land-uses encountered in this study. Results from this study can be used to inform interventions aimed at improving tree stockings and building up of SOC stocks in areas with low levels. Overall, the lowland was destocked of the tree resources and had low SOC stocks and thus requires intervention.

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Disclosure statement

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