Scientific Research Publishing

Comparison and Prediction of the above Ground Carbon Storage in Croplands on the Inhabited Slopes on Mount Kilimanjaro (Tanzania) and the Taita Hills (Kenya)

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Abstract

Mount Kilimanjaro and the Taita Hills are adjacent montane areas that experience similar climate and agricultural activity, but which differ in their geologic history, nature of elevation gradients and cultures. We assessed differences in cropland above ground carbon (AGC) between the two sites and against environmental variables. One hectare sampling plots were randomly distributed along elevational gradients stratified by cropland type; AGC was derived from all trees with diameter ≥ 10 cm at breast height in each plot. Predictor variables were physical and edaphic variables and human population. A generalized linear model was used for predicting AGC with AIC used for ranking models. AGC was spatially upscaled in 2 km buffer and visually compared. Kilimanjaro has higher AGC in cropped and agroforestry areas than the Taita Hills, but only significant difference in AGC variation in agroforestry areas ($F = 9.36$, $p = 0.03$). AGC in cropped land and agroforestry in Kilimanjaro has significant difference on mean ($t = 4.62$, $p = 0.001$) and variation ($F = 17.41$, $p = 0.007$). In the Taita Hills, significant difference is observed only on the mean AGC ($t = 4.86$, $p = 0.001$). Common tree species that contribute the most to AGC in Kilimanjaro are *Albizia gummifera* and *Persea americana*, and in the Taita Hills *Grevillea robusta* and *Mangifera indica*. Significant and univariate predictors of AGC in Mount Kilimanjaro are pH ($R^2 = 0.80$, $p = 0.00$) and EVI ($R^2 = 0.68$, $p = 0.00$). On Mount Kilimanjaro, the top multivariate model contained SOC, CEC, pH and BLD ($R^2 = 0.90$, $p = 0.00$),

whereas in the Taita Hills, the top multivariate model contained elevation, slope and population (R^2 = 0.89, p = 0.00). Despite of the difference in land management history of Mount Kilimanjaro and the Taita Hills, mean of AGC in croplands does not differ significantly. Difference occurs on variation of AGC, type of trees contributing AGC, and environmental variables that explain AGC distribution. The research results provide reference for management of carbon sequestration on inhabited montane areas.

Keywords

Aboveground Carbon, Cropland, Agroforestry, Cropped Land, Elevation Gradient

1. Introduction

Cropland is a broad land-use category and can be divided into three types based on the land management: rice paddies, cropped land and agroforestry systems [1]. The latter is characterised by crops and/or livestock combined with shrubs and trees, but with the density of trees falling below the threshold used for the Intergovernmental Panel on Climate Change (IPCC) Forest Land category [2]. The amount of carbon lost when forest or woodland is converted to cropped land varies considerably between the agroforestry and cropped land systems. About 40 - 180 Mg C ha^{-1} aboveground carbon and 10 Mg C ha^{-1} topsoil are lost when forest is converted agroforestry, in comparison to an estimated 80 - 400 Mg C ha^{-1} and 25 Mg C ha^{-1} respectively under conversion to continuous cropping [2]. Areas converted into agroforestry can be more productive than treeless alternatives and continue to provide environmental benefits for land users at all levels [3] [4].

Croplands in montane areas are part of forest or woodland that was converted by expanding agricultural communities. The conversion of forest, woodland or shrubland into cropland adversely affects the productivity of vegetation [5] and this is associated with the tree species and amount of carbon loss on the landscape. Some indigenous trees are often left and exotic trees are planted for food production and timber on cropland [6] [7] [8]. These areas, however, form important part of an agro-ecosystem that supports biodiversity and carbon sequestration [9].

The rate of cropland expansion in the horn of Africa has in the recent years decreased from 2.3% between the period of 1975 and 2000 [10] to 1.4% between 1990 and 2010 [11] [7]. Cropland cover area in East Africa has shown variation in estimation ranging from 1.8% [12] in some areas, 12.5% [13] and 22.7% in other areas according to Global Land Cover 2000 [14] in the late 1990s/early 2000s [15]. Around Mount Kilimanjaro croplands constitute over 50% of the land [16] and this is projected to cover 60% of the area by 2030 [17]. The lowlands and foothills of mountains experience expansion of croplands at the expense of thickets and shrublands [18]. The expansion of croplands is associated

with high human population growth [19] that exerts pressure on land due to increased demand for food.

Croplands in tropical Africa store about 5.3 Mg C ha^{-1} and the mosaic forest/cropland has 91.5 Mg C ha^{-1} [20]. In East Africa, the median range for carbon storage in cropland is estimated between 1.6 - 4.8 Mg C ha^{-1} [21]. Existing literature that covers carbon standing stock and carbon soil in croplands [22] depends on large spatial scale studies that do not provide comprehensive and reliable information on local carbon storage in the sub-montane and montane areas in East Africa. Moreover, carbon storage in montane forests has been given more attention than the adjacent cropland. Carbon storage in the croplands of the Taita Hills occurs between 2.3 to 9.1 Mg C ha^{-1} [7]. In Kilimanjaro (Mwanga area) areas with high aboveground carbon storage occur in agroforestry areas which has an estimated average amount of 19.4 Mg C ha^{-1} (between 10.7 to 57.1 Mg C ha^{-1}) [23].

Most studies on carbon storage are based on a particular biome (woodland and forests) and rarely look at cropland along an elevation gradient in mountainous areas. Elevation gradients play an important role in influencing climate; for instance, the highlands influences rainfall and temperature regime [24] that ultimately influences the distribution of vegetation [25]. Montane areas with shorter elevation gradients are characterized by compressed vegetation zonation and appearance of cloud montane forests in lower elevations [26] [27]. Soil texture discontinuity and micro-climate variation are influenced by short elevation gradients than longer gradients [27]. Besides this, the human population plays important role in determining the distribution of plant species and carbon storage [19]. A recent study by Adhikari *et al.* [28] showed that carbon stocks are highest on steep eastern and southern slopes of the Taita Hills, which are too laborious for agricultural practices, and thus remained in natural condition.

Kilimanjaro and the Taita Hills are located 100 km apart with similar climate characteristics although they have a very different geology; the Taita Hills are ancient crystalline mountains and Kilimanjaro is a more recent volcanic mountain. This geological difference impacts on the nature of soils and biodiversity in the areas [29]. The Taita Hills are the northern-most part of the Eastern Arc Mountain chain that is characterized by significant numbers of endemic species of plants and animals [29]. Both mountain areas are characterized by high human population growth and expanding small-scale agriculture which potentially affects carbon storage in croplands on the inhabited slopes. With the current and growing demand for balancing carbon storage, sustainable livelihoods and conservation of biodiversity, there is need to increase aboveground carbon sequestration in croplands [2].

The aim of this study was to assess the aboveground carbon and how its distribution is influenced by environmental variables on croplands on the inhabited slopes of Mount Kilimanjaro and the Taita Hills. The specific research questions were: 1) is there a difference in carbon storage between sites and different types

of croplands? 2) which species contribute more AGC on the inhabited slopes of Mount Kilimanjaro and the Taita Hills? and 3) which environmental variables best explain the distribution of AGC along the elevation gradients?

2. Methodology

2.1. Study Area

2.1.1. The Taita Hills

The Taita Hills are located in southern Kenya, approximately 300 km southeast of Nairobi (Figure 1). The highest point in the Taita Hills is Vuria at 2208 m a.s.l. The area experiences two rainy seasons a year: long rains fall from March to May and short rains from October to December. Annual is in the range 1100 and 1400 mm yr^{-1}, increasing with altitude and on wetter, eastern aspects, compared with 500 mm yr^{-1} in the surrounding plains [30]. The mean temperature varies from 21°C in August to 26°C in February, compared with 23°C - 27°C in the plains [31]. The study transect is located in the wetter south-eastern and southern parts of the Taita Hills.

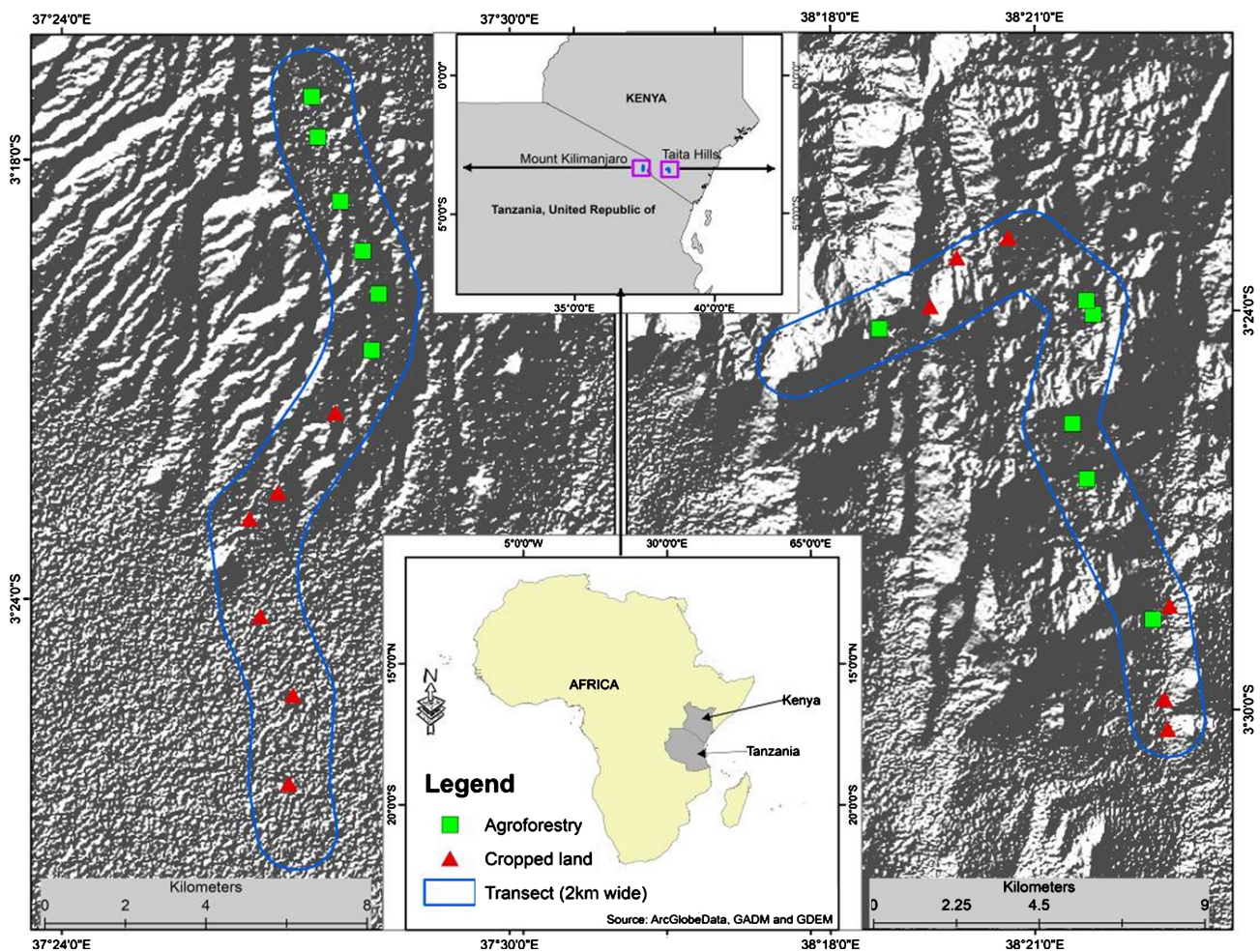The Taita Hills can be distinguished by three agro-ecological zones based on

Figure 1. Transect and plot locations on Mount Kilimanjaro (left) and the Taita Hills (right).

the crop-suitability of soils and climate: Lower Highland (LH)—maize, peas, potatoes, cabbages, cauliflower, kales, carrots, beetroot, spinach, lettuce, plums, passion fruit; Lower Midland (LM)—maize, sorghum, millet, sunflower, beans (tepary), cowpeas, black and green grams, chicken peas, pumpkin; Upper Midland zones (UM)—coffee, avocado, onions, cabbages, macadamia nuts, castor, bananas, pawpaws, citrus, sunflower and maize [32].

The three main forest types in the Taita Hills are indigenous montane forests, plantation forests of *Eucalyptus spp., Pinus spp.* and *Cypressus lusitanica*, and woodlands consisting of both native and exotic species [32]. The total area of indigenous forest remaining is approximately 8 km^2, plantation forests cover 26 km^2, woodlands 64 km^2, and cropland 375 km^2 [7]. Of the cropped areas, 70% is continuous cropland (little tree cover), and 30% is agroforestry [7], in which typical species are exotic *Grevillea robusta*, *Mangifera indica*, *Persea americana*, and native species such as *Prunus africana* [6].

2.1.2. Mount Kilimanjaro

Mount Kilimanjaro is located in north-eastern Tanzania, approximately 300 km south from Nairobi (**Figure 1**). Annual rainfall varies with altitude; about 1200 to 2000 mm yr^{-1} is received in the highland area; 1000 to 1200 mm yr^{-1} in the midlands and 400 to 900 mm yr^{-1} in the lowlands. The montane zone, which is dominated by agroforestry systems above 1800 m, receives the highest rainfall. Due to the fertile volcanic soils and favourable climate the area is densely settled and supports agriculture. Similarly, as in the Taita Hills, the eastern and southern parts receive more rainfall. Mount Kilimanjaro has three distinct agro-ecological zones: the highland zone occurring between 1200 and 1800 m characterized predominantly coffee-banana belt; the midland area, occurring between 900 and 1200 m, is predominantly a maize-bean belt, and; the lowlands that extend 700 to 900 m [33]. A half-mile narrow forest strip occurs above the coffee-banana belt, which was established in 1941 as a buffer forest along the lower edge of the montane forest to provide local people with timber and non-timber forest products, preventing incursion into the National Park [33].

The study is conducted along two transects encompassing a wide range of environmental, land use and social conditions. On both Mount Kilimanjaro and Taita Hills, the study transects are located on wetter, eastern aspects (**Figure 1**).

2.2. Methods

2.2.1. Sampling Plots

The primary data collection and analytical framework is presented in a flow diagram. A standard size plot of 1 ha [34] was used for sampling biometric parameters for trees with diameter at breast height (dbh) ≥ 10 cm. Stratified random sampling was used to partition the study area into agroforestry and cropped lands. However, the distribution of plots in agroforestry areas and cropped land were random along the elevation gradients of Mount Kilimanjaro and the Taita Hills. Within these stratifications, plots were distributed randomly using simple

random sampling; six plots were distributed in agroforestry areas and another six in cropped lands. These plots were located within the 1 km buffer (either side) of the study transect that runs along the elevation gradients on Kilimanjaro and the Taita Hills both having transect length of 20 km. In the Taita Hills the transect runs from Mwatate at 840 m to Vuria at an elevation of 1900 m (**Figure 1**). In Kilimanjaro the transect runs from Miwaleni at 730 m through Kawawa to Kirua-Vunjo at an elevation of 1800 m, near the boundary of the National Park (TANAPA). For each tree, DBH was measured at 1.3 m, and tree height was measured using a hypsometer. Tree species were identified with the assistance of botanists from the National Museums of Kenya.

2.2.2. Estimation of Plot Carbon

The Above-Ground Biomass (AGB) was estimated using the DBH and tree height recorded and the Wood Specific Gravity (WSG) (g/cm^3) derived from the Global Wood Density Database [35] [36] for the tree species; either at species level or genus, or family depending on the available information. With these parameters, an allometric model [37] was used for estimating AGB.

$$\text{AGB} = 0.0673 \times \left(\rho \times D^2 H \right)^{0.976} \tag{1}$$

Where ρ is the Wood Specific Gravity, D^2 is the dbh, and H is the height of the tree. According to [37], the above model performed well across forest types and bioclimatic conditions. After deriving the AGB for each tree, data was aggregated to plot level from which 50% of AGB was assumed to be the above-ground carbon storage in a plot [37] [38] [39]. The standard unit for the amount of the above-ground carbon in this study is expressed in Megagram Carbon per hectare (Mg C ha^{-1}).

2.2.3. Environmental Variables

To understand the relationships between environment, soil, vegetation and AGC a series of soil and biophysical variables were used as predictor variables to explain the patterns of AGC stored across the altitudinal gradient, and within the major land-uses. Biophysical variables used were Enhanced Vegetation Indices (EVI) from the Moderate Resolution Imaging Spectroradiometer (MODIS) 16-days interval for the year 2012 downloaded from the National Aeronautics and Space Administration (NASA) Earth Observing System Data and Information System (**Table 1**) for both Kilimanjaro and the Taita Hills. The mean for the 16-days interval for the year was used for analysis. MODIS-EVI was chosen because EVI minimizes canopy background variations and maintains sensitivity over dense vegetation conditions [40]. MODIS-EVI layers were downloaded in October 2014. The major land-use was acquired from field observation between May and August 2012.

Based on studies that were previously conducted on environmental controls over the aboveground biomass [41] [42], physical and soil variables were selected. Physical variable consisted of elevation (digital elevation model, DEM

Table 1. The environmental variables abbreviated and described of their units of measurement, spatial resolution and their sources.

Environmental factors	Variable	Abbr.	Unit of Measurement	Spatial Resolution	Source of data
Edaphic factors six layers mean estimate for depths; 2.5, 10, 22.5, 45, 80, and 150 cm depths	Soil organic carbon	SOC	C/permilles	930 m	isric.org
	Cation exchange capacity	CEC	cmolc/kg	930 m	isric.org
	pH	pH			isric.org
	Bulk density	BLD	kg/m³	930 m	isric.org
Physical factor	Elevation	Elev	meter	30 m	Geonetwork portal
	Slope angle	Slope	Degree	30 m	Derived from elevation
	Enhanced vegetation index MODIS-EVI 16 days interval	EVI	0 - 1 index	659 m	NASA
Human population	Population density	PopDen	Person/km²	1 km	
Cropland	Cropped land	These are areas predominated by mono-cropping system and sparsely populated			
	Agroforestry	These are areas with fruit trees, and other trees; mixed crops both cash and food crops; moderate to densely populated			

30 m) and slope; the latter was derived from DEM. Four edaphic variables were selected and downloaded from ISRIC (SoilGrids 1 km) for the analysis; these included the cation exchange capacity (CEC), soil pH, soil organic carbon (SOC) and soil bulk density (BLD) (Table 1).

2.2.4. Data Extraction and Statistical Modelling

Point values were extracted from the environmental variable layers using point analyses tool in ArcGIS 10. These were aggregated under major land use systems for Kilimanjaro and the Taita Hills for statistical analysis using the R programme [43]. Data relationships were described using univariate statistics and portrayed as series of boxplots to describe the amount of variation in agroforestry and cropped land in Kilimanjaro and the Taita Hills. Fischer's F-test (var test) was used to test the significance of the variation of data, and Student's t-test (t test) was used to test the significance difference in the data means between agroforestry and cropped land within sites; agroforestry, and cropped land between sites. Standard error of mean of AGC was calculated with R programme for the sites and different types of cropland. A Generalized Linear Model (GLM) was used to assess the relationships of AGC with the environmental variables. Where data points were non-linear, 2nd or 3rd order of polynomials were used to fit the model relation. Akaike Information Criterion (AIC) scores were used to rank the model relationship by sites and explain the distribution of AGC and various land-uses. AGC was upscaled for visualization of distribution along the Kilimanjaro and the Taita Hills transects using the GLM function in R and extrapolation in ArcGIS on the surface of environmental variables. Spatial map visualization of variables was performed using ArcGIS 10.2.

3. Results

3.1. Aboveground Carbon on Sites

The mean Aboveground Carbon (AGC) along the Kilimanjaro transect is 39.06 $\pm$ 6.48 Mg C ha^{-1} (mean $\pm$ SE) and along the Taita Hills transect the mean is 28.82 $\pm$ 5.82 Mg C ha^{-1}; both areas having comparable variation and means (Table 2). The mean of AGC in cropped land in Kilimanjaro is 19.67 $\pm$ 5.18 Mg C ha^{-1} which is a third of the mean AGC in agroforestry 58.45 $\pm$ 2.75 Mg C ha^{-1}. Significant difference in variation, and the mean were observed on AGC between agroforestry and cropped land in Kilimanjaro (F = 17.41, p = 0.007), and (t = 4.62, p = 0.001) respectively (Table 2).

Distribution of AGC is in agroforestry area in Kilimanjaro has median tends towards the 1st quartile 52.95. In cropped land, the median tends slightly towards the 3rd quartile (30.43) (Figure 2). The mean of AGC in cropped land in the Taita Hills is 13.69 $\pm$ 1.54 Mg C ha^{-1}; less than a third of the mean AGC in agroforestry 43.95 $\pm$ 7.4 Mg C ha^{-1}. In agroforestry area, the median tends towards the 1st quartile 52.95 but in cropped land, the median tends slightly towards the 3rd quartile (30.43) (Figure 2). The variation of AGC in cropped land and agroforestry in the Taita Hills does not differ significantly; however, their means are significantly different (t = 4.86, p = 0.001) (Figure 2 and Figure 3, Table 2). Thus, the mean of AGC in agroforestry from the Kilimanjaro is 30%

Table 2. The univariate statistics (mean and standard error), Fischer's and Student's t test for AGC distribution in cropped land and agroforestry areas in Kilimanjaro and the Taita Hills.

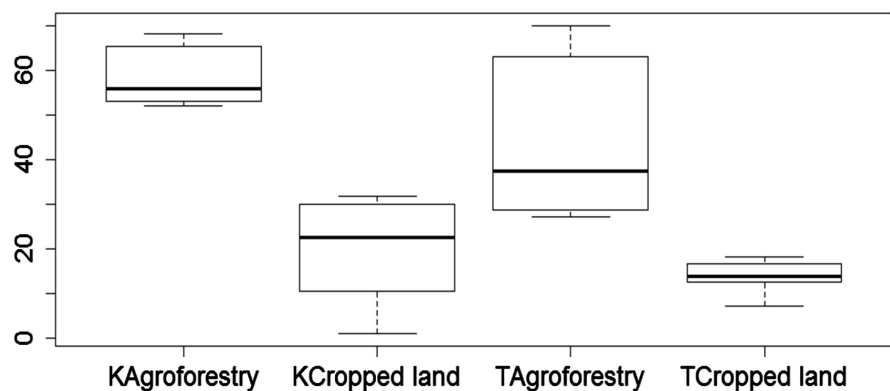| Comparison		Mean $\pm$ SE		Fischer's F test		Student's t test	
		Kilimanjaro	Taita	F	p	t	p
Between sites	Agroforestry	58.45 $\pm$ 2.75	43.95 $\pm$ 7.4	9.36	0.03	1.95	0.08
	Cropped land	19.67 $\pm$ 5.18	13.69 $\pm$ 1.54	10.92	0.02	0.58	0.57
Within site	Cropped land vs Agroforestry AGC	Kilimanjaro		17.41	0.01	4.62	0.00
		Taita		5.87	0.08	4.86	0.00

Figure 2. AGC (Mg C/ha) boxplot for cropped land and agroforestry areas in Kilimanjaro (prefix K) and Taita Hills (prefix T).

greater that of Taita Hills. This shows significant difference in variation (F = 9.36, p = 0.028) but their means are not significantly different (**Figure 2**, **Figure 3**, **Table 2**). The variation of AGC in the cropped lands in the two sites are significantly different (F = 10.92, p = 0.020) while their means is not significantly different (**Figure 2**, **Table 2**). The mean and median of AGC data in agroforestry areas in the Taita Hills are very close 31.98 ± 7.40 Mg C ha^{-1} (median 32.56). The boxplot indicate plots with small and large amount of AGC in agroforestry are heterogeneous but plots with moderate amount of AGC are homogeneous along the elevation gradient (**Figure 2**, **Table 2**).

Most of the AGC data in cropped land are distributed towards the 1st quartile (13.24); thus, the mean (22.43 ± 5.49) and median (15.62) of AGC are not close. However, variation of AGC data for cropped lands in the Taita Hills is both below the 1st and 3rd quartiles (**Figure 2**, **Table 2**). The AGC in agroforestry on Kilimanjaro area is more than agroforestry in the Taita Hills; Tukey's pairwise comparisons shows the two sites are significantly different in the amount of AGC (**Table 2**). No significant difference is observed in the amount of AGC in cropped lands on Kilimanjaro and the Taita Hills.

3.2. AGC vs Environmental Variables in Types of Cropland

The response of AGC with EVI in agroforestry in Kilimanjaro is very significant and the relationship is fitted by the 2nd order of polynomial (R^2 = 0.92, p = 0.020) (**Figure 3**, **Table 3**). The relationship of AGC and CEC in agroforestry in Kilimanjaro is significant and the relationship is fitted by the 2nd order of polynomial (R^2 = 0.91, p = 0.027) (**Figure 3**, **Table 3**). The response of AGC with BLD in agroforestry in Kilimanjaro shows significant relationship (R^2 = 0.87, p = 0.045), fitted by the 2nd order of polynomial (**Figure 3**, **Table 3**). The relationship between AGC in agroforestry from the Taita Hills with the above variables are strong but are not significantly related (**Figure 3**, **Table 3**). The response of AGC to EVI, CEC and BLD in cropped lands on Kilimanjaro and the Taita Hills are weak and does not show significant relationships (**Figure 3**, **Table 3**).

The relationship of AGC and pH in agroforestry in the Taita Hills is very strong and significant (R^2 = 0.98, p = 0.031), fitted by the 3rd order of polynomial (**Figure 3**, **Table 3**). A significant relationship occurs between AGC and SOC in cropped land in the Taita Hills (R^2 = 0.70, p = 0.00), fitted by 1st order of polynomial. On the other side, the relationship of SOC and AGC in cropped land on Kilimanjaro is weak and not significant (**Figure 3**, **Table 3**).

3.3. AGC vs Woody Plant Species along Elevation Gradients

The distribution of the AGC among the woody plant species on the slope of Mount Kilimanjaro is predominated by *Albizia gummifera* with carbon storage of 8.6 MgC/ha; this is followed by *Persea americana* (3.5 MgC/ha) and *Ficus sycomorus* (3.3 MgC/ha) (**Figure 4(a)**). In the Taita Hills, the predominant woody species is *Grevillea robusta* with AGC of 4.6 MgC/ha; followed by *Mangifera*
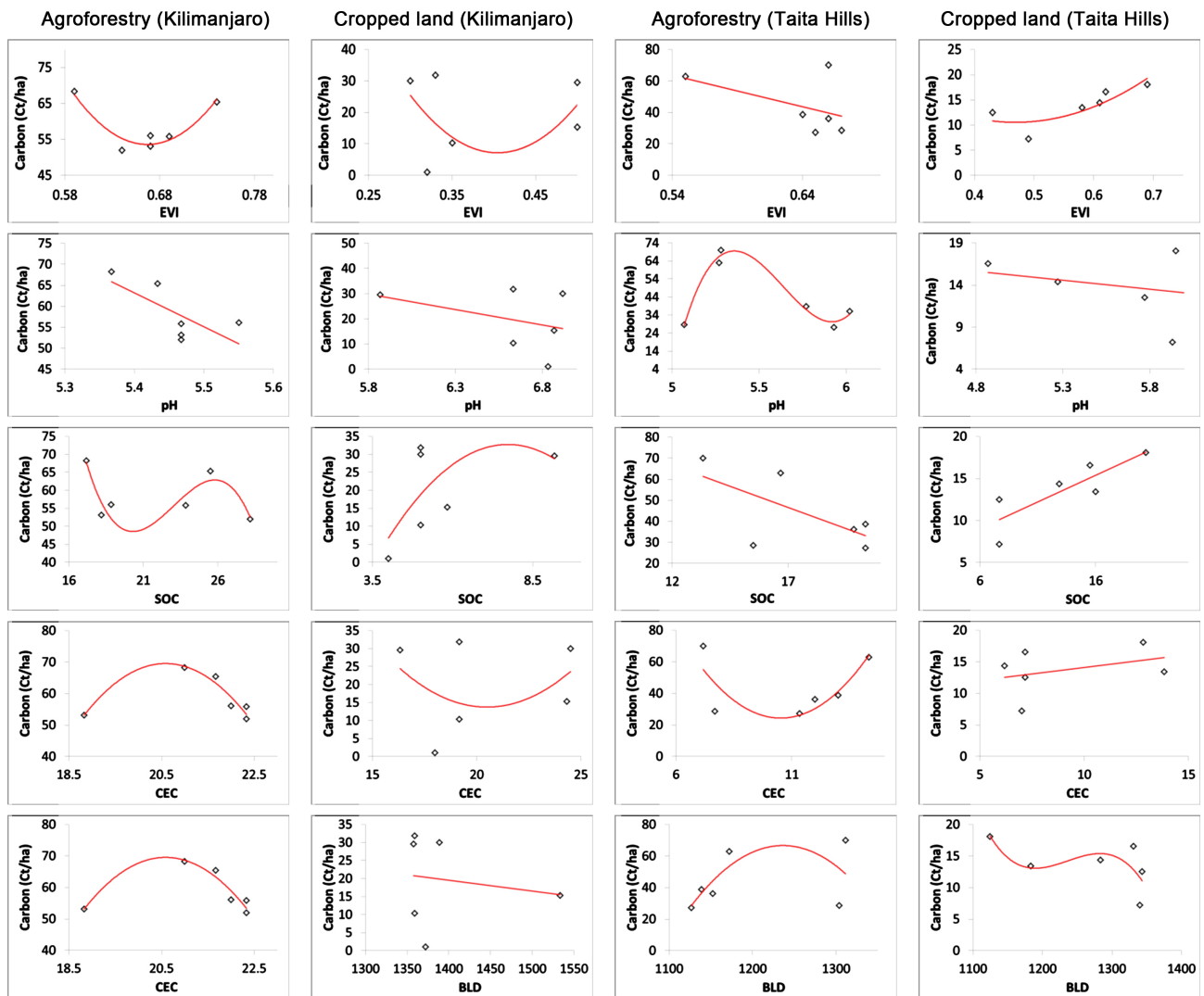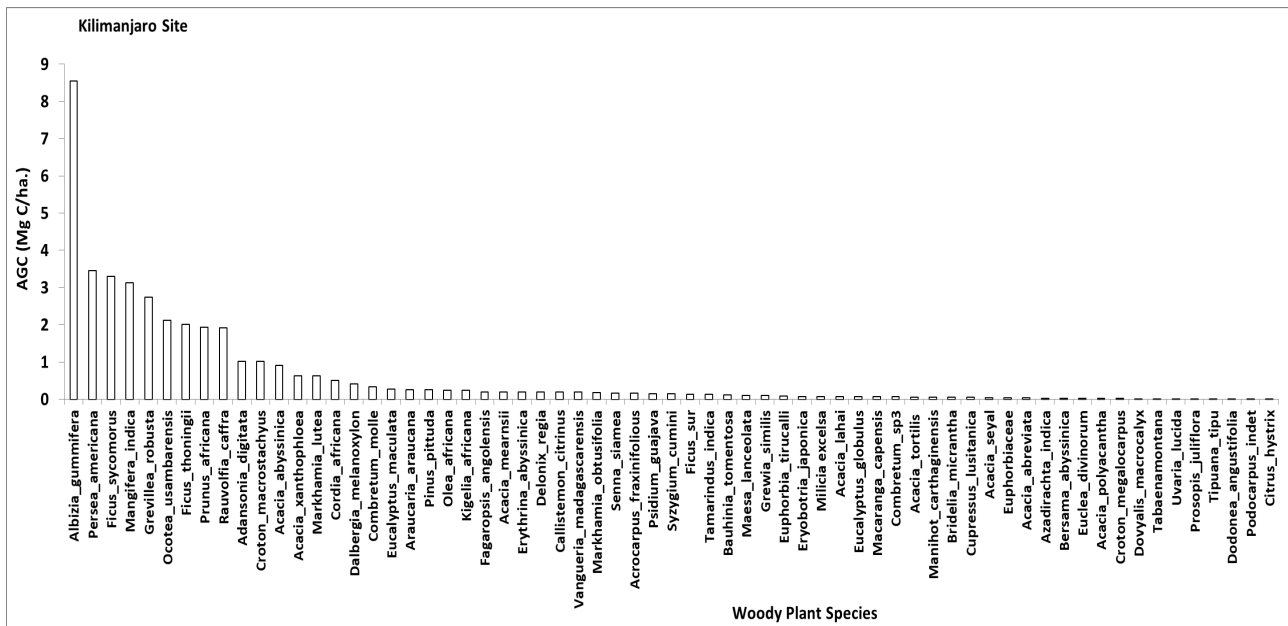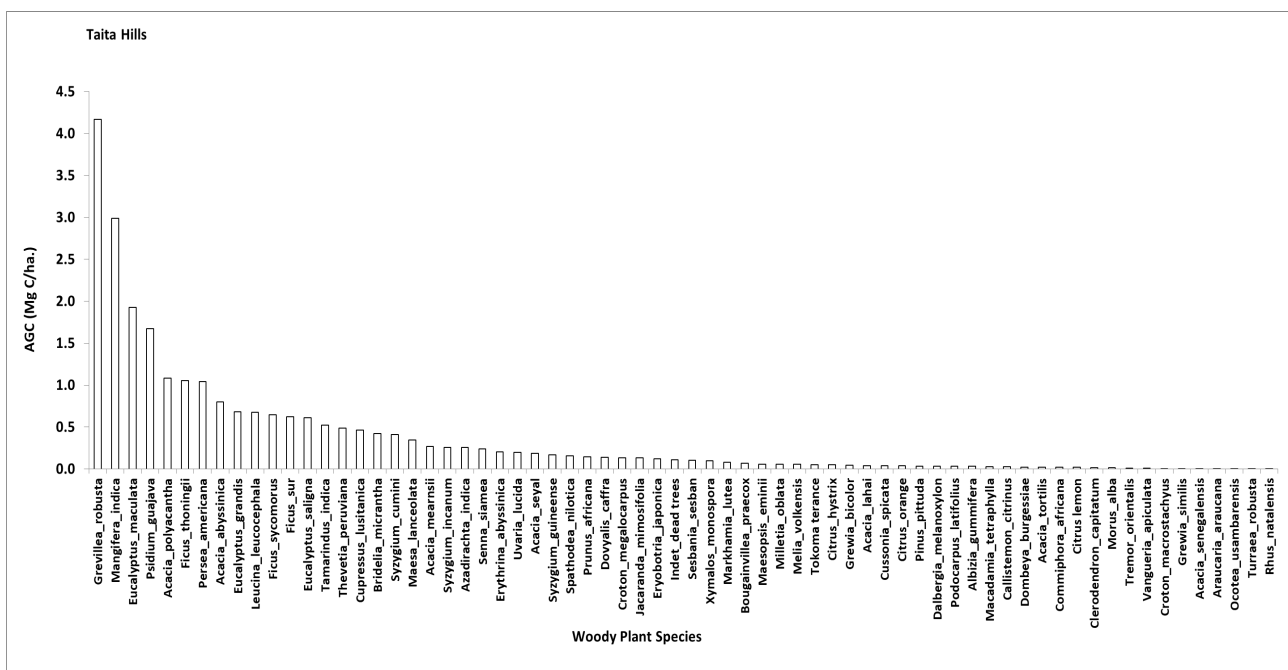
Figure 3. Linear and polynomial (2nd and 3rd) fitted models for relationships of AGC with environmental variables in agroforestry and cropped land in Kilimanjaro and the Taita Hills.

Table 3. Model relationships of AGC with environmental variables in agroforestry and cropped land in Kilimanjaro and the Taita Hills.

Environmental Variable	Cropland	Kilimanjaro				Taita			
		Fit. Order	R^2	p	AIC	Fit. Order	R^2	p	AIC
EVI	Agroforestry	x^2	0.92	0.020	31	x^2	0.26	0.639	57
	Cropped land	x^2	0.14	0.805	54	x^2	0.72	0.152	32
pH	Agroforestry	x	0.50	0.115	41	x^3	0.98	0.031	38
	Cropped land	x	0.14	0.458	52	x	0.10	0.540	37
SOC	Agroforestry	x^3	0.81	0.272	39	x	0.43	0.160	53
	Cropped land	x^2	0.36	0.507	52	x	0.70	0.038	31
CEC	Agroforestry	x^2	0.91	0.027	32	x^2	0.64	0.213	53
	Cropped land	x^2	0.12	0.820	54	x	0.14	0.474	37
BLD	Agroforestry	x^2	0.87	0.045	35	x^2	0.29	0.599	57
	Cropped land	x	0.03	0.760	52	x^3	0.50	0.652	38

(a)

(b)

Figure 4. (a) The distribution of AGC among the Woody Plant Species on the inhabited slopes of Mount Kilimanjaro; (b) The distribution of AGC among the Woody Plant Species on the inhabited slopes of Taita Hills.

indica (2.6 MgC/ha), and; *Eucalyptus maculata* with 1.7 MgC/ha (**Figure 4(b)**). *A. gummifera* has the highest AGC in agroforestry on Kilimanjaro with 7.7 MgC/ha; while on the Taita Hills, *G. robusta* predominated with an AGC of 7.6 MgC/ha. AGC on cropped land on the slope of Mount Kilimanjaro and the Taita Hills is predominated by *M. indica* with an estimated AGC of 3.2 MgC/ha and 2.3 MgC/ha, in respective sites. The distribution of AGC among the Woody

Plant Species between Mount Kilimanjaro and the Taita Hills was significantly varied (p = 0.00, F = 2.92); while, their mean was not significantly different.

The AGC increases with the increase in woody plant species richness and stock density on both Mount Kilimanjaro and the Taita Hills slopes. The increase of square root of AGC in Mount Kilimanjaro is more varied with the increase in woody species richness hence no significant relationship observed (F = 2.25, R^2 = 0.10, p = 0.17) (**Figure 5(a)**). The square root of AGC increases significantly with the increase in stock density of the woody species in Kilimanjaro (F = 7.81, R^2 = 0.44, p = 0.02) (**Figure 5(a)**). However, assessment of the relationship of stock density and woody species richness in Kilimanjaro indicate an estimated 77% correlation.

AGC increases significantly with the increase in woody species richness (F = 15.62, R^2 = 0.66, p = 0.00) and stock density (F = 20.19, R^2 = 0.72, p = 0.00) on the slopes of the Taita Hills (**Figure 5(b)**). Earlier analysis of the woody species
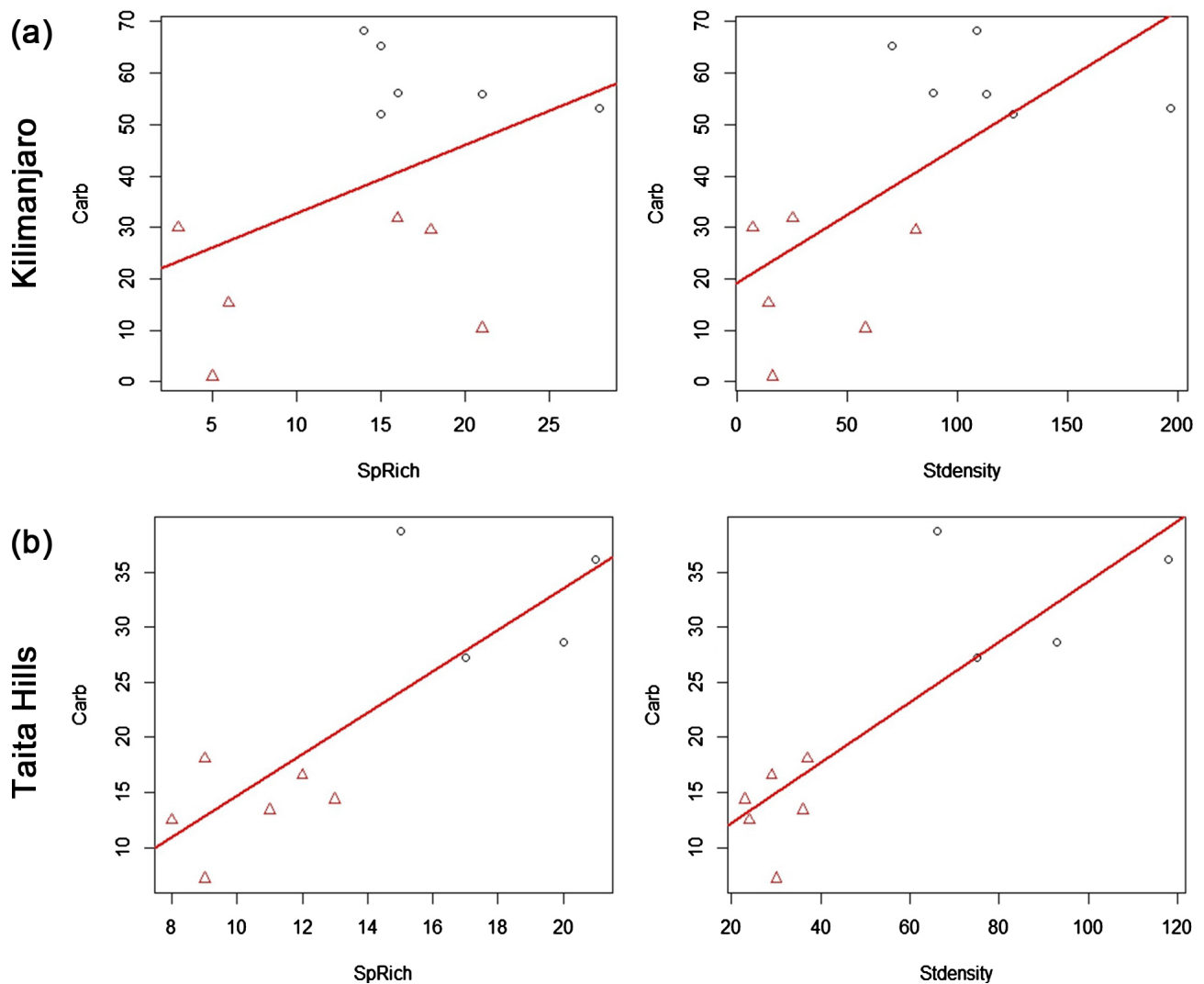

Figure 5. The relationship of AGC (Carb) with the species richness (SpRich) and stock density (abundance); (a) on the slope of Mount Kilimanjaro; (b) on the slopes of the Taita Hills.

stock density and species richness for the Taita Hills shows the two variables significantly and highly correlated ($R^2 = 0.95$, F = 89.93, p = 0.00).

3.4. AGC Prediction Models along Elevation Gradients

The relationship of AGC with environmental variables was explored under univariate and multivariate model relationships. The influence of environmental variables on AGC distribution varies on the inhabited slopes of Mount Kilimanjaro and the Taita Hills. At both sites, AGC increases with the increase in elevation, slope, and edaphic variables (CEC and SOC) EVI and population density, while, AGC decreases with the decrease in edaphic variables such as soil pH and BLD. However, difference could be observed on the level of significance of the relationship. Variation in elevation gradient is significantly attributed to 72% of AGC variation in Kilimanjaro (p = 0.00) but no significant relationship was observed in the Taita Hills. The variation of slope angle is significantly linked to about 73% of AGC distribution in the Taita Hills but not on Kilimanjaro (Table 4). The transect in the inhabited areas of Mount Kilimanjaro has a more or less continuous elevation gradients but the Taita Hills is more interrupted forming steep areas (high slope angles). The inhabited elevation of Mount Kilimanjaro has home gardens observed established towards the middle of the transect increasing in cover towards the end of transect. Less steep areas of the Taita Hills are dominated by annual crop cultivation but as the slope angle increases and land become steeper, the areas are preserved with natural vegetation and/or planted trees.

In particular, the variation of AGC with SOC indicates significant relationships in both Kilimanjaro ($R^2 = 0.72$, p = 0.00) and the Taita Hills ($R^2 = 0.56$, p = 0.01) (Figure 6, Table 4). In Kilimanjaro, AGC relates significantly with Soil BLD ($R^2 = 0.72$, p = 0.00) and pH ($R^2 = 0.80$, p = 0.00) but not in the Taita Hills (Figure 6, Table 4). While, AGC does not relate significantly with CEC in both inhabited slopes of Mount Kilimanjaro and the Taita Hills. Increase of AGC is significant with the increase of EVI on the inhabited slopes of Mount Kilimanjaro ($R^2 = 0.68$, p = 0.00) and the Taita Hills ($R^2 = 0.41$, p = 0.05). Population density apparently significantly affects AGC distribution only in the Taita Hills ($R^2 = 0.42$, p = 0.04) but not on the slopes of Mount Kilimanjaro (Figure 6, Table 4).

The multivariate response of AGC to elevation and slope showed significant relationship in Kilimanjaro (KCarbMod1) ($R^2 = 0.72$, p = 0.00) and the Taita Hills (TCarbMod1) ($R^2 = 0.73$, p = 0.01) (Table 4). However, multivariate response of AGC to these environmental variables is relatively similar to the univariate response to the elevation in Kilimanjaro and to the slope angle in the Taita Hills. When quadratic function is introduced on the elevation in KCarbMod1 (thus, KCarbMod2) in Kilimanjaro, the response of AGC is increased significantly to about 84% (Table 4). In the case for the Taita Hills, response of AGC increased significantly but with a small margin. However, when population
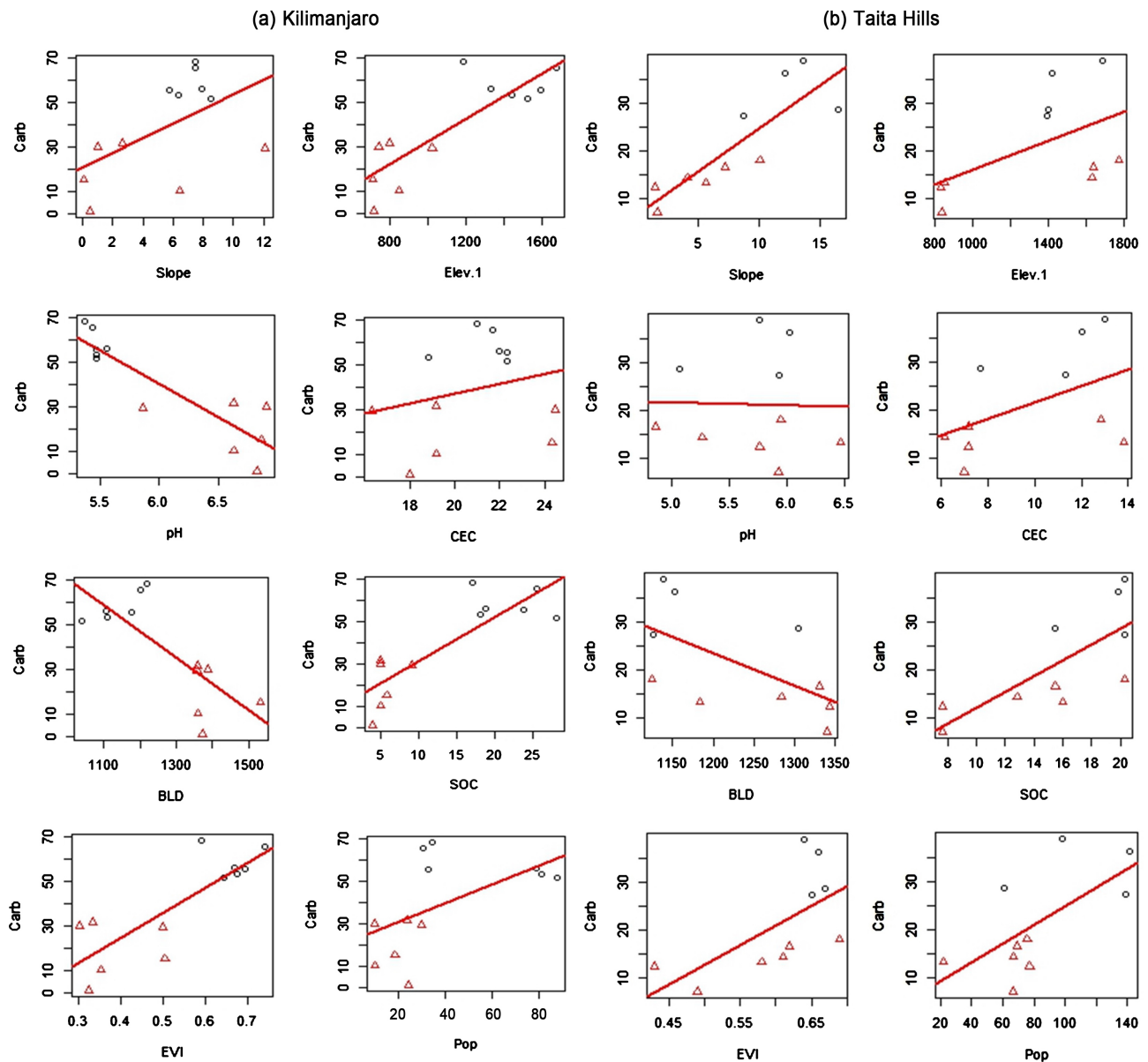
Figure 6. Relationship of AGC with environmental variables (physical and soil variables) on the inhabited slopes of Mount Kilimanjaro and the Taita Hills.

density is added to the model TCarbMod1 (thus, TCarbMod3), the response of AGC increases significantly to about 89% (p = 0.00). This implies, other than the slope which seems to be the most important variable influencing AGC in the Taita Hills, population density has effect on the distribution of AGC to an extent. AGC response to the inclusion of population density in KCarbMod1 is not significant. AGC multivariate response to edaphic variables (pH, CEC, BLD and SOC) (KCarbMod3) is very significant (R^2 = 0.90, p = 0.00) on Kilimanjaro but not in the Taita Hills (Table 4). The combination of KCarbMod1 with KCarbMod3/7; thus KCarbMod4 (Table 4) shows AGC responds significantly (R^2 = 0.94, p = 0.03) on Kilimanjaro but not in the Taita Hills. However, response of AGC to KCarbMod4 is relatively similar to the response to KCarbMod3.

Table 4. Prediction, univariate and multivariate model relationship of the Above Ground Carbon Storage (AGC/Carb) with environmental variables on the inhabited slopes of Kilimanjaro and Taita Hills.

Site		Models	RSE	DF	Mult. R^2	F	p-value	AIC
Taita Hills	Univariate	TCarbMod_Elev < −lm(Carb~Elev)	0.27	8	0.27	2.94	0.13	77.61
		TCarbMod_Slope < −lm(Carb~Slope)	5.94	8	0.73	21.27	0.00	67.77
		TCarbMod_pH < −lm(Carb~pH)	11.35	8	0.00	0.01	0.95	80.73
		TCarbMod_SOC < −lm(Carb~SOC)	7.53	8	0.56	10.18	0.01	72.53
		TCarbMod_CEC < −lm(Carb~CEC)	9.95	8	0.23	2.43	0.16	78.09
		TCarbMod_BLD < −lm(Carb~BLD)	9.08	8	0.36	4.49	0.07	76.28
		TCarbMod_Pop < −lm(Carb~Pop)	8.64	8	0.42	5.83	0.04	75.27
		TCarbMod_EVI < −lm(Carb~EVI)	8.71	8	0.41	5.59	0.05	75.44
	Multivariate	TCarbMod1 < −lm(Carb~Elev + Slope)	6.34	7	0.73	9.32	0.01	69.75
		TCarbMod2 < −lm(Carb~Elev + I(Elev^2) + Slope)	6.49	6	0.76	6.15	0.03	70.69
		TCarbMod3 < −lm(Carb~Elev + Slope + Pop)	4.36	6	0.89	16.12	0.00	62.70
		TCarbMod5 < −lm(Carb~Elev + I(Elev^2) + Slope + Pop)	4.70	5	0.89	10.41	0.01	64.41
Kilimanjaro	Univariate	KCarbMod_Elev < −lm(Carb~Elev)	12.54	10	0.72	25.24	0.00	98.56
		KCarbMod_Slope < −lm(Carb~Slope)	19.76	10	0.30	4.20	0.07	109.47
		KCarbMod_EVI < −lm(Carb~EVI)	13.32	10	0.68	21.27	0.00	100.00
		KCarbMod_pH < −lm(Carb~pH)	10.62	10	0.80	39.14	0.00	94.58
		KCarbMod_SOC < −lm(Carb~SOC)	12.44	10	0.72	25.82	0.00	98.37
		KCarbMod_CEC < −lm(Carb~CEC)	22.78	10	0.06	0.68	0.43	112.9
		KCarbMod_BLD < −lm(Carb~BLD)	14.90	10	0.60	14.97	0.00	102.7
		KCarbMod_Pop < −lm(Carb~Pop)	19.67	10	0.30	4.33	0.06	109.36
	Multivariate	KCarbMod1 < −lm(Carb~Elev + Slope)	13.2	9	0.72	11.41	0.00	100.53
		KCarbMod2 < −lm(Carb~Elev + I(Elev^2) + Slope)	10.60	8	0.84	13.77	0.00	98.05
		KCarbMod3 < −lm(Carb~SOC + CEC + pH + BLD)	8.79	7	0.90	16.19	0.00	91.75
		KCarbMod4 < −lm(Carb~SOC + CEC + pH + BLD + Elev.1 + I(Elev.1^2) + Slope)	9.35	4	0.94	8.50	0.03	92.51

3.5. Statistical and Visual Validation of AGC Prediction Model

The evaluation considers models that show significant relationship with the distribution of AGC on the inhabited slopes of Mount Kilimanjaro and the Taita Hills. The AIC indicates the model KCarbMod3/7 performs best in explaining the distribution of AGC on Kilimanjaro (AIC = 87.20). AGC predicted by KCarbMod3/7 and AGC recorded in plots significantly associate by 94% (R = 0.94, p = 0.00) on Kilimanjaro transect (Table 5). In the Taita Hills, the model TCarbMod3 performs best in explaining the response of AGC (AIC = 71.11) and apparently associate with the high proportion of AGC recorded on site (R = 0.79, p = 0.01) than other models (Table 5). This is followed by SOC model

Table 5. Evaluation of predicted AGC by correlation with the observed plot AGC on the slopes of Mount Kilimanjaro. PredCarb is the predicted AGC and PlotCarb is the observed plot AGC.

Model Relationship		PredCarb vs PlotCarb		
		R	p-value	AIC
Univariate Model	KCarbMod_Elev < −lm(Carb~Elev)	0.83	0.00	99.79
	KCarbMod_pH < −lm(Carb~pH)	0.90	0.00	94.29
	KCarbMod_BLD < −lm(Carb~BLD)	0.79	0.00	102.21
	KCarbMod_SOC < −lm(Carb~SOC)	0.86	0.00	97.42
	KCarbMod_EVI < −lm(Carb~EVI)	0.86	0.00	97.51
	TCarbMod_Slope < −lm(Carb~Slope)	0.57	0.10	77.04
	TCarbMod_SOC < −lm(Carb~SOC)	0.77	0.01	71.58
	TCarbMod_EVI < −lm(Carb~EVI)	0.67	0.03	74.79
	TCarbMod_Pop < −lm(Carb~Pop)	0.05	0.89	80.71
Multivariate Model	KCarbMod1 < −lm(Carb~Elev + Slope)	0.83	0.00	99.60
	KCarbMod2 < −lm(Carb~Elev + I(Elev^2) + Slope)	0.83	0.00	99.87
	KCarbMod3/7 < −lm(Carb~SOC + CEC + pH + BLD)	0.94	0.00	87.20
	KCarbMod4/12 < −lm(Carb~SOC + CEC + pH + BLD + Elev.1 + I(Elev.1^2) + Slope)	0.92	0.00	91.33
	TCarbMod1 < −lm(Carb~Elev + Slope)	0.56	0.09	77.00
	TCarbMod2 < −lm(Carb~Elev + I(Elev^2) + Slope)	0.64	0.05	75.49
	TCarbMod3 < −lm(Carb~Elev + Slope + Pop)	0.79	0.01	71.11
	TCarbMod5 < −lm(Carb~Elev + I(Elev^2) + Slope + Pop)	0.13	0.73	80.57

(AIC = 71.58) with the predicted AGC correlates with 77% of AGC recorded on plots frim the Taita Hills (R = 0.77, p = 0.01) (Table 5).

The visual inspections of spatial models generated from the statistical models (univariate and multivariate) tend to validate some of the AGC univariate and multivariate response. Most of the spatially predicted AGC shows poor prediction on the lower elevations of the transect on the inhabited slopes on Mount Kilimanjaro. The predicted AGC values are visually incomparable with the plot AGC values in the lower elevation except for pH model. Some of the models such as univariate elevation, pH and EVI tend to generate spatial AGC that compares with the values of plot AGC in the upper elevation. The univariate pH and EVI apparently performs better in spatially predicting AGC on the slopes of Mount Kilimanjaro.

Spatially predicted AGC in the Taita Hills by the univariate TCarbMod_SOC and multivariate model consisting of elevation, slope and population (TCarbMod3) has visually comparable spatial model (Figure 7, Table 5). Spatial prediction of AGC by TCarbMod_EVI has close visual pattern of AGC distribution with TCarbMod_SOC and TCarbMod3. The spatial AGC model from univariate
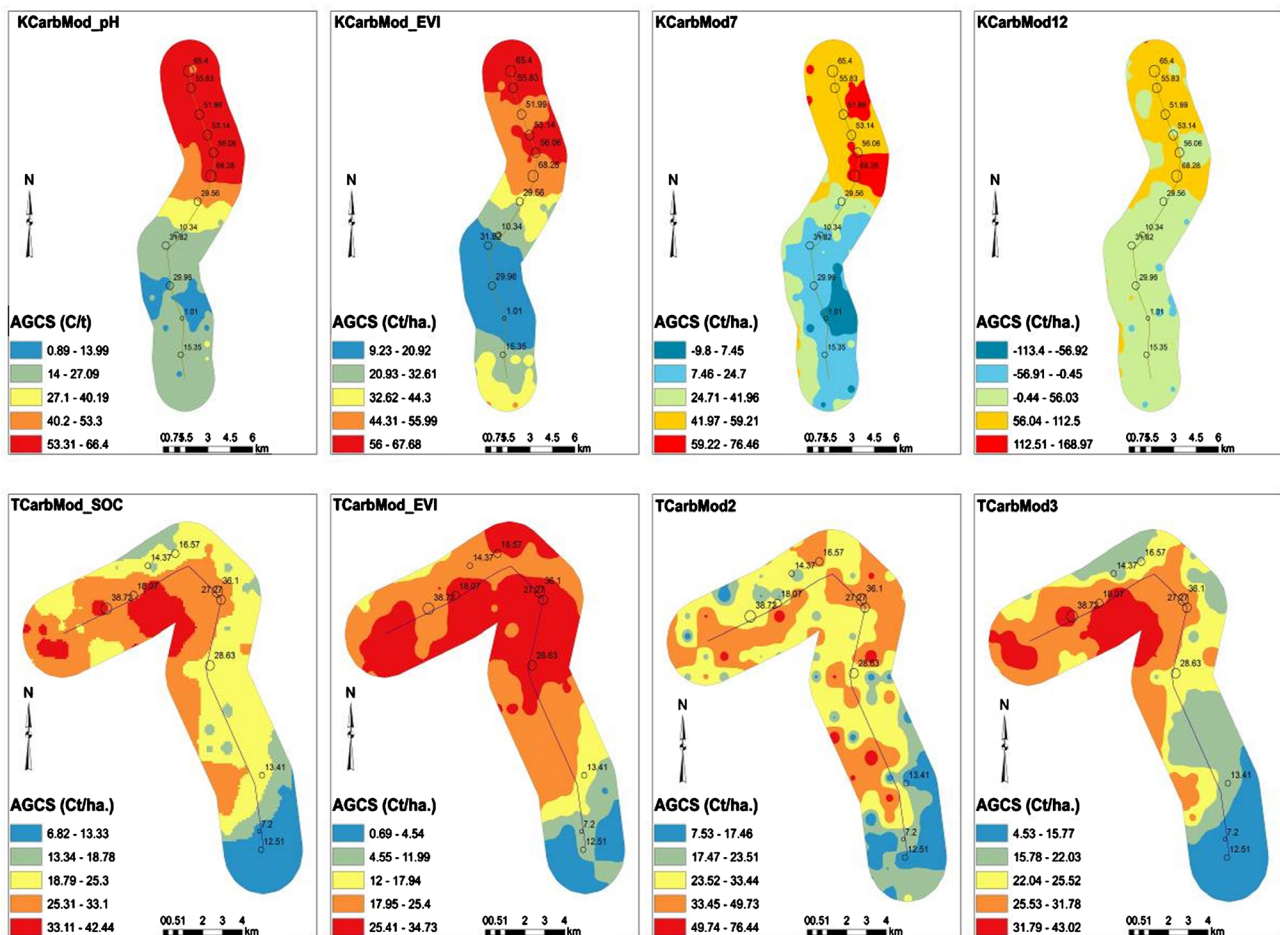
Figure 7. Spatial model prediction of aboveground carbon storage AGCS based on the univariate and multivariate models for Mount Kilimanjaro and the Taita Hills. Prefix T refers to the Taita Hills and K is Kilimanjaro. CarbMod refers to Carbon Model. The univariate models have variable identity at the end; for example slope (TCarbMod_Slope). The multivariate models include KCarbMod3/7 (SOC + CEC + pH + BLD), and KCarbMod4/12 (SOC + CEC + pH + BLD + Elevation + I(Elevation^2) + Slope). The multivariate models for Taita include: TCarbMod2 (Elevation + I(Elevation^2) + Slope), TCarbMod3 (Elevation + Slope + Population density).

slope, TCarbMod1 and TCarbMod2 are also comparable visually and this could probably be because they have slope as a factor in the multivariate models (**Figure 7**, **Table 5**). However, models TCarbMod_SOC, TCarbMod_EVI and TCarbMod3 (**Figure 7**, **Table 5**) has predicted AGC values and observed plot AGC comparable which makes them better models for predicting AGC spatial on the inhabited slopes of the Taita Hills.

4. Discussion

Carbon storage in the aboveground living biomass of trees forms the largest pool and the most directly impacted by deforestation and degradation [44]. Tropical montane forests have in the last centuries and decades been converted to other land uses or degraded [45]. Cropland established on previously sparsely vegetated or highly disturbed lands can result in a net gain in both biomass and soil carbon [46]. Permanent cropland is considered to be a broad category that con-

sists of cropped land, agroforestry and rice paddies [1]. Cropped land consists of the annual crops and or mono-cropping systems; while, agroforestry is characterized by mixed annual and perennial crops with fruit trees and trees of socio-economic benefits in the background. One of the key issues addressed in this study concerns the above-ground carbon stored in different types of cropped lands and agroforestry systems along the densely inhabited slopes of Mount Kilimanjaro and the Taita Hills.

The inhabited montane area of Mount Kilimanjaro has 39.06 ± 6.48 Mg C ha^{-1} and the Taita Hills 28.82 ± 5.82 Mg C ha^{-1} occurring within the mean range of AGC in East Africa ranging between 0.6 Mg C ha^{-1} in permanent cropland [9] to 91.5 Mg C ha^{-1} in agroforestry system [20]. A recent study in the Taita Hills suggest cropland has an average of 9.1 Mg C ha^{-1} in areas above 1220 m a.s.l. and 2.3 Mg C ha^{-1} below 1220 m a.s.l. which is considerably lower than our result [7]. Agroforestry areas have higher amounts of mean AGC with Kilimanjaro storing higher amount of AGC (58.45 ± 2.75 Mg C ha^{-1}) than the Taita Hills (31.98 ± 7.40 Mg C ha^{-1}). This is certainly higher than the amount of carbon indicated for different types of agroforestry [46]. On the other hand, cropped lands in Kilimanjaro have AGC of 19.67 ± 5.18 Mg C ha^{-1} and then Taita Hills cropped lands estimated at 13.69 ± 1.54 Mg C ha^{-1}. AGC in the two sites are higher than the amount of AGC estimated in most cropland in East Africa between 1.6 to 4.8 Mg C ha^{-1} [21] and the amounts of carbon storage in sub-humid and semi-arid ecoregions [47]. However, AGC in the woodlots in the cropland areas range from 39.4 to 123 Mg C ha^{-1} [9] which is higher than AGC in ordinary agroforestry areas. Pellikka *et al.* [7] found increase in carbon stocks in croplands over 1200 m.

AGC in cropped lands on Kilimanjaro and the Taita Hills is lower than agroforestry values it is higher than in other croplands in the region. The amount of AGC in cropped land and agroforestry areas on the slopes of Mount Kilimanjaro differ significantly in their means and variation, while in the Taita Hills significant difference was only observed on the variation. This difference could be brought about by the high amount of AGC in the agroforestry trees and some indigenous trees retained when forest in montane areas is converted into cropland [46]. The difference in AGC in cropped land and agroforestry areas in the two sites also depends on the crop type, management practices, and soil and climate variables in the croplands [48]. Cropped lands consist of treeless mono-crop stand with few trees on hedges; while, agroforestry systems are characterized by vegetation structure that falls below the thresholds used for the Intergovernmental Panel on Climate Change Forest Land Category [2].

In this study, AGC is not only compared between sites but also analyzed against elevation gradients within each and between the sites. Most studies indicate the above-ground biomass and carbon stock significantly decreases with the increase in elevation [38]; and varies strongly between and within continents [47]. Elevational gradient causes great variation in vegetation structure and car-

bon stock among sites [26] [41] [28]. For instance, in short elevational gradients (<2000 m a.s.l.), as in the case of the Taita Hills, vegetation zones are more compressed and edaphic discontinuities stronger in short distance due to steep topography and microclimate variation than in long elevational gradients (>2000 m a.s.l.) [26]. Due to variation of morpho-species of woody plant species with elevation gradient in site, about 59% of AGC significantly varies with the woody plant species in Ipeti'-Embera' in eastern Panama Province, Panama [49]. Similarly this relationship is observed on the slopes of the Taita Hills where about 66% of AGC is explained significantly by the distribution of the woody plant species richness along elevation gradients. This relationship is absent on the slopes of Mount Kilimanjaro probably because of the predominance of banana plantation for shading coffee. Even though AGC distribution is affected differently by elevation gradients and slope angle on Kilimanjaro and the Taita Hills, similar study in Udzungwa and Usambara confirms significant influence of slope angle and elevation on AGC [38].

Climate (precipitation and temperature) and soil factors vary with elevation gradients [41] [42]. Through this interaction, elevation gradients intercorrelate with the climate and soil variables depending on the type of elevation gradient. AGC varies significantly with variation of soil pH, BLD and SOC on the slopes of Mount Kilimanjaro while AGC does not vary with the edaphic variables in the Taita Hills. However, population density seems to associate with about 42% of AGC distribution on the slopes of the Taita Hills. Evaluation of univariate and multivariate models statistically and spatially show that soil pH is the strongest and most significant predictor for AGC by 80% on the slopes of Mount Kilimanjaro, while in the Taita Hills, three variables (elevation, slope and population density) simultaneously affect the distribution of AGC on the inhabited slopes of the area.

The analysis of this work depended on secondary remotely sensed environmental variables at a resolution of 0.5 - 1 km. This resolution might have not been sensitive to variation of soil and climate factors that could change drastically within a short distance on the inhabited slopes of Mountain areas. In order to minimize errors that could emerge from generalization of environmental variables at this resolution, sampling points more than 1 km apart were considered in the analysis. This implies the numbers of sampling points were reduced and this together with the secondary environmental variables would potentially affect precision of the results. Variation in the average amount of carbon storage between this study and others can also be impacted on by sampling designs adopted by different researchers. Thus, future consideration of standardized field measurements of environmental variables and increasing the number of sample size would improve the results.

This research has wider application in understanding the drivers behind carbon storage, within agroforestry systems, biodiversity conservation and water conservation on the inhabited slopes of Mount Kilimanjaro and the Taita Hills.

Water balance is a variable which is affected by carbon storage (AGC and SOC) and should be a consideration in the water conservation policy and management of montane forest systems as a key hydrological resource [50]. Understanding factors that relate with the AGC at a local scale provide an efficient means of monitoring AGC in a large area of study for future conservation and for enhancing the management of agroforestry systems. Information on AGC on the inhabited slopes provide baseline for future assessment of carbon emissions through removal of the woody plants and loss of soil organic carbon through land degradation. Management of carbon sequestration within densely inhabited landscapes can be adopted through agroforestry development such as the careful selection of tree species that are preferred at a local site by local communities and have good storage potential. The study shows that most of the AGC is contributed by agroforestry exotic tree species but indigenous species constitute low percentage which potentially affects biodiversity conservation. Consideration of indigenous tree species in agroforestry policy will bring about a balance between biodiversity conservation and socio-economic of the local communities on the inhabited slopes of Mount Kilimanjaro and the Taita Hills.

5. Conclusion

The inhabited slopes of Mount Kilimanjaro and the Taita Hills have relatively similar amounts of AGC. Along the study transects the AGC varies significantly within different cropped land and agroforestry systems. The two sites differ on the predominant woody tree species that contribute more AGC on the inhabited slopes; *A. gummifera* and *G. robusta* contribute more to AGC on Mount Kilimanjaro and the Taita Hills, respectively. The elevation gradient significantly explains the distribution of AGC on slopes of Mount Kilimanjaro but slope angle seems to be significant on the slope of the Taita Hills. Most of soil variables explain significant variation of AGC on the slopes of Mount Kilimanjaro more than in the Taita Hills. However, SOC and EVI significantly explain the distribution of AGC on both sites but not so strongly in the Taita Hills. AGC distribution is significantly explained by multiple effects of elevation and slope angle on the slopes of the two sites. Population density together with elevation and slope angle apparently affect distribution of AGC in the Taita Hills but not on Kilimanjaro. Significant multiple effect of soil variables (pH, CEC, BLD and SOC) is only observed on the slopes of Mount Kilimanjaro. AGC distribution on the slopes of Mount Kilimanjaro can be predicted by univariate pH and EVI models. In the Taita Hills, univariate SOC, EVI models and multivariate model of elevation, slope and population predict AGC reliably. These insights on the factors that control AGC in mountain agroforestry system are keies to informing management that aims to strike a balance between biodiversity conservation and socio-economic livelihoods on the densely inhabited slopes of Mount Kilimanjaro and the Taita Hills; insights that are relevant more widely to other mountain ecosystems and communities.

Acknowledgements

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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