Land Use Cover Types and Forest Management Options for Carbon in Mabira Central Forest Reserve

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Contents

Abstract

Mabira Central Forest Reserve (CFR), one of the biggest forest reserves in Uganda, has increasingly undergone encroachments and deforestation. This chapter presents the implications of a range of forest management options for carbon stocks in the Mabira CFR. The effects of forest management options were reviewed by comparing above-ground biomass (AGB), carbon, and soil organic carbon (SOC) in three management zones. The chapter attempts to provide estimates of AGB and carbon stocks (t/ha) of forest (trees) and SOC using

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sampling techniques and allometric equations. AGB and carbon were obtained from a count of 143 trees, measuring parameters of diameter at breast height (DBH), crown diameter (CW), and height (H) with tree coordinates. It also makes use of the Velle (Estimation of standing stock of woody biomass in areas where little or no baseline data are available. A study based on field measurements in Uganda. Norges Landbrukshoegskole, Ås, 1995) allometric equations developed for Uganda to estimate AGB.

The strict nature reserve management zone was noted to sink the highest volume of carbon of approximately 6,771,092.34 tonnes, as compared to the recreation zone (2,196,467.59 tonnes) and production zone (458,903.57 tonnes). A statistically significant relationship was identified between AGB and carbon. SOC varied with soil depth, with the soil surface of 0–10 cm depth registering the highest mean of 2.78% across all the management zones. Soil depth and land use/cover types also had a statistically significant effect on the percentage of SOC ($P = 0.05$). A statistically significant difference at the 95% significance level was also identified between the mean carbon stocks from one level of management zones to another. Recommendations include: demarcating forest boundaries to minimize encroachment, enforcement of forestry policy for sustainable development, promote reforestation, and increase human resources for efficient monitoring of the forest compartments.

Keywords

Above-ground biomass · Allometric equations · Soil organic carbon · Land use/cover change

Introduction: Land Use Change and Carbon

Representing 33% of the global land area (FAO 2011) and containing more carbon per unit area than any other land cover type (Hairiah et al. 2011), forests comprise the biggest percentage of biomass and play a big role in mitigating greenhouse gas emissions, especially carbon dioxide. According to the FAO (2010), biomass is the organic matter both above and below the ground. Forest biomass assessment is very important for national development planning, as well as scientific studies of ecosystem productivity and carbon budgets (Parresol 1999; Zheng et al. 2004). Considering climate change trends, there is a growing need for information on forest carbon stocks. Olson et al. (1983), Thornes (2002), and Schimel et al. (2001) point out that forests contain nearly 85% of the global above-ground carbon, and 40% of the below-ground terrestrial carbon stocks (Brown and Lugo 1984; Dixon et al. 1994). Land use/cover change (LUCC) has led to destruction of habitats, forests, exposed land to erosion, and affected human well-being (Foley et al. 2005; Kerr et al. 2007; Ellis and Pontius 2007; Arsanjani 2012). Alterations caused by LUCC account for the release of greenhouse gases into the atmosphere, resulting into global warming. Further effects are manifest in climate variability and change (Hashim and Hashim 2016). Studies by Watson et al. (2000), UNEP (2002), and Lambin and Geist (2008) have cautioned about instant and threatening effects of LUCC on agriculture, biodiversity, human health, and well-being. Despite its importance, accurate statistics on LUCC are not available in tropical countries (Ochoa-Gaona and Gonzalez-Espinosa 2000). Agriculture is still the most significant driver of global deforestation. Given the importance to the planet's future of both agriculture and forests, there is an urgent need to promote positive interactions between these two land uses (FAO 2016).

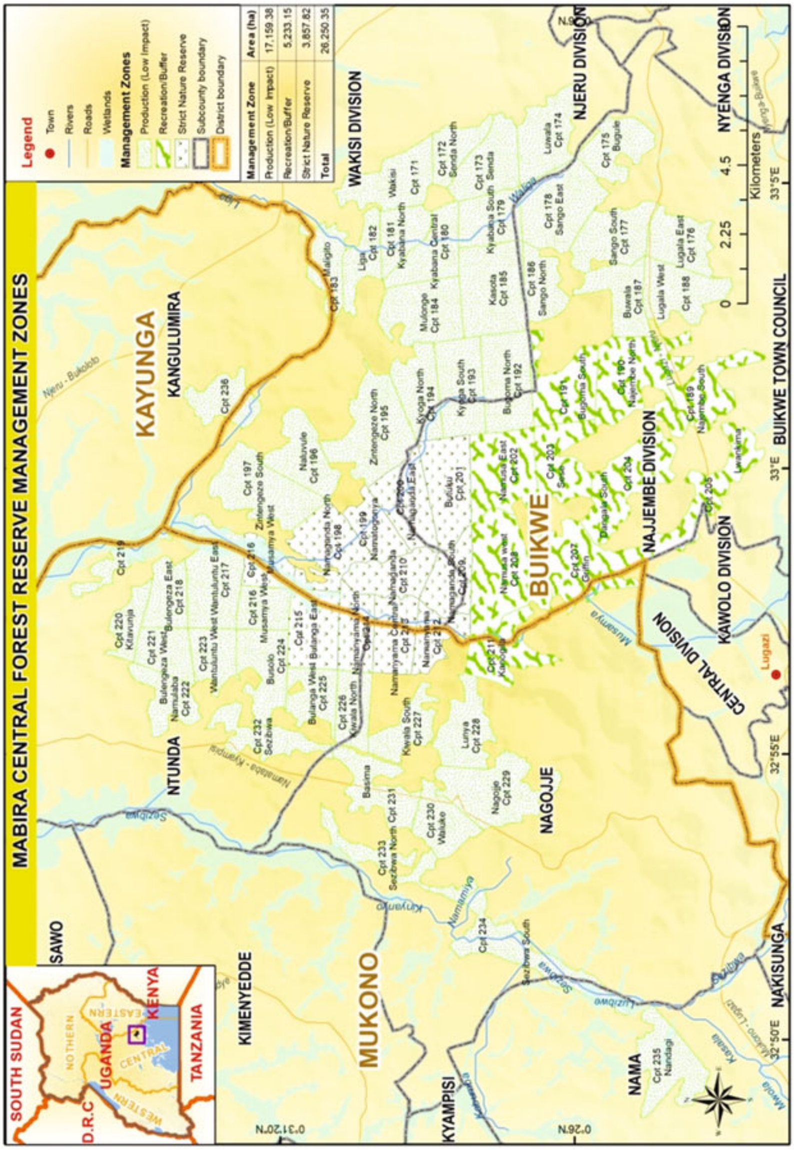
The rate of deforestation, estimated at 0.4–0.7% per year (Shrestha et al. 2004; Parry et al. 2007), constitutes immense environmental stress. Between 2000 and 2010, 13 million ha of world forest were lost (FAO 2010), implying an increase in the amount of carbon dioxide into the atmosphere. According to Baccini et al. (2012) and Harris et al. (2012), deforestation and forest degradation contribute about 20% of the greenhouse emissions. Land use change leads to alterations in carbon storage in soils and vegetation. Consequently, it strongly influences emissions and fixation of carbon in these ecosystems (Jandl et al. 2007). Jjagwe et al. (2017) identify the significant drivers of land use/cover changes in and around the Mabira CFR as: high household size, loss of soil fertility, poor agricultural practices, establishment of roadside markets, industrialization, and the unclear CFR boundary. Against the above background, that the main aim here is to estimate and compare total tree biomass and carbon stocks among the three management zones of the Mabira CFR.

Mabira Central Forest Reserve: Location and Management

Mabira Central Forest Reserve (CFR) is currently the largest natural rainforest region found in the Lake Victoria crescent of Uganda, spanning the districts of Mukono, Buikwe, and Kayunga (Fig. 1). It lies 54 east and 26 km west of the cities of Kampala and Jinja, respectively. It covers about 26,250 ha and is situated between 32 52°–33 07° E and 0 24°–0 35° N, at an altitude of 1070–1340 m above sea level. The topography is characterized by gently undulating plains that have numerous flat topped hills and wide shadow valleys. Temperatures are fairly constant throughout the year, with an average of 26 °C. It has two peak rain seasons between March–May and September–November. Rainfall ranges between 1250 and 1400 mm per annum.

The forest is globally recognized as an important conservation biome rich in biodiversity, with over 300 bird species (Lepp et al. 2011) and 365 plant species (Howard and Davenport 1996). Currently, the forest has 27 enclaves; considering its proximity to Kampala city, the area has attractions for commercial utilization. Uganda's population growth rate of 3.2%, as per the 2002 population census (UBOS 2010), is one of the highest globally.

Mabira CFR was gazetted as a CFR in the 1900 under the Buganda agreement. It has been protected as a Forest Reserve since 1932 and is currently managed by the National Forest Authority (NFA). Forest management is under three main zones, namely: the strict nature reserve where no extraction is permitted except for research activities; the recreation buffer zone where activities like ecotourism and limited harvesting are permitted; and the production zone which accommodates agriculture, livestock grazing, legal and unregulated harvesting of timber. The forest has



Management Zone	Area (ha)
Production (Low Impact)	17,159.38
Recreation/Buffer	5,233.15
Strict Nature Reserve	3,857.82
Total	26,250.35

Fig. 1 A map showing the management zones of Mabira CFR and environs

undergone dramatic changes, especially since the early 1970s, in the form of encroachments and deforestation. These activities resulted from the desire by the government of the time to expand agriculture and permit free settlement anywhere. This forest region is estimated to have quite a high population density, with some places having an average of up to 15,122 people/sq. km in Parishes like Nakazadde (Schwarz and Fakultät für Geomatik, Hochschule Karlsruhe-Technik und Wirtschaft 2010) and an average of seven members per household. Over 80% of the population is heavily dependent on the forest ecosystem for their livelihood (Bush et al. 2004) in form of agriculture, lumbering, and brick laying. Studies by NFA (2009) indicate that population pressure coupled with high levels of poverty continue to constrain the remaining forest cover by way of conversion to other land uses. The high resistance over the proposal by government in 2007 to convert 7186 ha of forest to sugar production by the Sugar Corporation of Uganda Limited (SCOUL) is a case in point.

As a means to improve management in the forest reserve, several mechanisms have been devised in the revised forest management plan (MWE 2017), which include but not limited to: yield control and harvest, Collaborative Forest Management (CFM), licenses, silviculture, and rehabilitating encroachments. Despite the few success stories where CFM has been adopted, it is noteworthy that in the many communities where CFM agreements are implemented, no tangible economic benefits have been realized (Turyahabwe et al. 2012).

Estimating Biomass and Soil Organic Carbon Stocks in Mabira CFR

Estimating Above-Ground Biomass and Carbon Stocks

In order to determine the above-ground biomass (AGB) stocks, living biomass was considered. Studies by Djomo et al. (2010) and Brown (2002) have identified challenges of using the direct/destructive approach to estimate biomass. Consequently, we applied the indirect approach to estimate biomass content. The approach is not time consuming, cheap, and nondestructive, as borne out in studies by Tackenberg (2007), Chen et al. (2009), and Henry et al. (2011). The use of generalized allometric equations is proven and reliable in estimating AGB and carbon stocks and a number of them have been developed for different purposes, species, and regions.

More than 95% of the variation in AGB is explained by diameter at breast height (DBH) alone (Brown 2002). Studies by Djomo et al. (2010, 2016) and Ngomanda et al. (2014) show that the input of tree height improves the quality of AGB estimation. Biomass equations have been preferred, if a representative sample of tree-wise data is acquired (Brown 1997; Basuki et al. 2009; Djomo et al. 2010; Beets et al. 2012; Chave et al. 2014; Ngomanda et al. 2014; Mokria et al. 2015).

A team of eight people was employed in this process to survey management zones and take tree measurements. An NFA official with a security guard per management zone led the team in this exercise. Three management zones were

Table 1 Sampled compartments

Management zone	Name and compartment number	Number of trees
Strict nature reserve	Compartment 209	63
	Compartment 212	
Recreation/buffer zone	Compartment 208	50
Production zone	Compartment 211	30
Total number of trees samples		**143**

Fig. 2 Measurements for tree parameters

surveyed, each representing unique but homogeneous blocks. From the three zones, four compartments were considered as summarized in Table 1.

Resource utilization and management in the respective zones varies. Under the strict nature reserve, no extraction is permitted except for research activities, undertaken under very restrictive measures. Whereas the recreation buffer zone permits activities like ecotourism and limited harvesting, the production zone accommodates agriculture, livestock grazing, legal and unregulated harvesting of timber.

Field sites were randomly selected, taking 20 square plots of 30 m × 30 m from the strict nature reserve, where 63 trees were sampled. The same number of square plots of 50 m × 50 m was considered from the recreation/buffer and production zones, where measurements of 50 and 30 trees were taken, respectively. The plot sizes varied, considering variations in tree densities and sampling intensity. Consequently, bigger plot sizes were designated in areas where the trees were more scattered (recreation/buffer zone) to enable capturing of more trees for assessment. Tree measurements by height, diameter at breast height (DBH), canopy, and coordinates were taken and recorded. The tools used in determining AGB included GPS receivers, Suunto clinometers, a compass, caliper, and diameter tape (Fig. 2).

The measurements taken were then used to calculate biomass using allometry. For trees with multi-stems, the quadratic mean diameter (QMD) was calculated using Eq. (1) below:

$$\mathrm{QMD} = \sqrt{(\pi * BA)/(4 * N)} \tag{1}$$

Table 2 Constants for the varying diameter classes used to convert field vegetation measures

Diameter class	Constants			
	a	b	c	D
DBH <20 cm	−0.85989	1.5445	0.50663	0.333346
20 ≥ DBH ≤ 60 cm	−1.750891	1.943912	0.473731	0.245776
DBH ≥60 cm	−2.166502	2.032931	0.31292	0.436348

After Velle (1995)

Where:

QMD is quadratic mean diameter.
BA is total basal area = ba1 + ba2 + ba3... ba_N is the number of stems.

To estimate AGB, a number of models were explored and tested in relation to the variables. Models which included the diameter as predictor variable, a combination of diameter and tree height, diameter and crown diameter, and finally the diameter, tree height, and crown diameter were tested. These models are the most commonly used for allometry development (Brown et al. 1989; Chave et al. 2005; 2014; Djomo et al. 2010, 2016). The generalized allometric equation by Velle (1995) equations developed for Uganda to estimate AGB was applied as stated in Eq. (2).

$$\mathrm{Ln}\ (\mathrm{PWF}) = \mathrm{a} + \mathrm{b} * \mathrm{Ln}\ (\mathrm{D}) + \mathrm{c} * \mathrm{Ln}\ (\mathrm{HT}) + \mathrm{d} * \mathrm{Ln}\ (\mathrm{CR}) \qquad (2)$$

Where:

PWF is fresh weight of a stem and branches in kg
D is DBH in cm
HT is height of the tree in m
CR is the width of the crown in meters.
a, b, c, and d are constants for all the pooled trees which may vary according to the diameter class as indicated in Table 2 below.

The application of the generalized allometric equation is avouched by its use even in highly diverse systems, where more than 95% of the variation in AGB is explained by DBH alone (Brown 2002). The fresh weight was then converted to dry weight for biomass detection by taking 50% of the wet weight (Gates et al. 1982). Below-ground biomass (BGB) was estimated by taking 20% of AGB (Mokany et al. 2006). From this, the total biomass per tree and per hectare was also calculated. Subsequently, carbon was converted into carbon sequestered (CO equivalents) by multiplying it with a factor of (44/12), which is the carbon dioxide-carbon molecular weight ratio (Penman et al. 2003). To assess the variation in biomass and carbon stocks for the different management zones, Anova for XLSTAST (version 3.1.3) was applied.

The UBOS 2017 shapefile was used to estimate the total size of areas covered by the three management zones as indicated in Fig. 1. Data collected were analyzed using XLSTAST. The biomass was converted to carbon (C) by assuming a 50% biomass to carbon content (Brown 1997; Losi et al. 2003; Penman et al. 2003; Change 2006; FAO 2005).

Estimating Soil Organic Carbon

According to Rau et al. (2011), the excavation of soil pits has been identified as a widely applicable and universally accepted method for the assessment of soil organic carbon (SOC). Samples of 50 m × 50 m plots up to 30 cm deep for the SOC pool were taken from the three management zones of the Mabira CFR and environs. Four dominant land use types, viz.: built-up area, plantations (sugarcane and/tea), subsistence farming, and forest were considered in each management zone. From each zone, 44 samples were taken, considering at least 3 points in each land use/cover type. A total of 132 soil samples were extracted from the 44 spots, taking three replicates from soil depth of 0–10 cm, 10–20 cm, and 20–30 cm. On completion of sample collection, the unwanted materials like stones, granules, plant parts, leaves, etc. were discarded. The soil samples were kept in polythene bags, tightly closed and well labeled. The bags were stored at 5 °C to limit microbial degradation, oxidation, and volatilization activities.

In the laboratory, samples were air dried and sieved through a 2-mm sieve. The sieved sample was used for SOC estimation. The samples were analyzed using wet oxidation method (Walkley and Black 1934), using potassium dichromate ($K_2Cr_2O_7$) and concentrated sulfuric acid (H_2SO_4). The samples were oven dried and a sample reagent mixture was prepared using standard laboratory procedures. The mixture was titrated with ferrous ammonium sulfate to determine the amount of organic carbon. Back titration was then performed until the color of the solution turned brown, which marked the end point. A standardization blank (without soil) was also run in the same way. Equation (3) was used to extract the carbon content.

$$\mathbf{BT - ST(0.3 \times 5)/0.3 \times 9.8} \tag{3}$$

Where:

BT = blank titer, which was considered at 9.8
ST = unused dichromate

All data were analyzed using SPSS statistical software version 16.0. Analysis of variance (ANOVA) was carried out using the two-factor randomized complete plot design. Significant F-values were obtained; differences between individual means were tested using the least significant difference (LSD) test. To assess variations in biomass and carbon stocks for the different management zones, Anova for XLSTAST (version 3.1.3) was applied.

AGB and Carbon Stocks

Average AGB and AGC based on tree parameters comprising height, DBH, and crown diameter, as presented in Table 3 were 890.9 and 445.63 kg, respectively. Biomass and carbon totals of 1069.1 and 534.6 kg, respectively are also evident. A linear relationship between biomass and carbon stocks is presented in Fig. 3. The R-Squared statistic indicates that the model as fitted explains 100.0% of the variability in carbon stocks (tonnes per hectare). The correlation coefficient is 1.0, signifying a perfectly strong relationship between the two variables. Since the P-value is greater than 0.05, there is no indication of serial autocorrelation in the residuals at the 95.0% confidence level. BGB was estimated by applying the 20% conversion rate to AGB (Mokany et al. 2006). Similarly, 50% of the BGB is taken as the estimation for BGC, results of which are presented in Table 3.

Variations of biomass and carbon stocks were noted in the different management zones. The highest average total AGB was found in the strict nature reserve, where values of the multiparameters of DBH, height and crown diameter were highest as well. The production zone, which had scattered trees with smaller parameters registered the lowest average total AGB (Table 4). Whereas the strict nature reserve had the highest carbon stocks, the production zone registered the least (Tables 5 and 6).

The ANOVA (Table 7) decomposes the variance of carbon stocks (kg per tree) into two components: a between-group and within-group components. The F-ratio, which in this case is 13.97, is a ratio of the between-group estimate to the within-group estimate. Since the P-value of the F-test is less than 0.05, there is a statistically significant difference between the mean carbon stocks (tonnes per hectare) from one management zone to another at the 5% significance level. To determine which means are significantly different from others, multiple range tests were selected from the list of tabular options.

The multiple comparison procedure is applied (Table 8) to determine which means are significantly different from others. The bottom half of the output shows the estimated difference between each pair of means. An asterisk to signify statistically significant differences at the 95.0% confidence level has been placed next to the pairs. In the table, two homogenous groups are identified using columns of Xs. Within each column, the levels containing Xs form a group of means within which there are no statistically significant differences. According to Fisher's least significant difference (LSD) procedure used to discriminate among the means, there is a 5% risk of calling each pair of means significantly different when the actual difference is 0 (Fig. 4).

A comparison of tree carbon stocks and sequestration per management zone was also done, and it was revealed that the highest carbon is in the strict nature reserve and least in the production zone as shown in Table 9.

It is noticeable from Tables 9 and 10 that carbon sinking varies between the management zones. Table 10 shows that the strict nature reserve management zone sinks the highest volume of carbon of approximately 6,771,092.34 tonnes, despite its small coverage in comparison to the recreation/buffer (2,196,467.59 tonnes) and production zones (458,903.57 tonnes).

Table 3 Variations between tree biomass and carbon

	AGB (kg)	AGC (kg)	BGB (kg)	BGC (kg)	Total biomass (kg)	Total carbon (kg)	Carbon sequestered
Count	143	143	143	143	143	143	143
Average	890.9	445.63	178.1	89.09	1069.1	534.6	1960
Standard deviation	1437.8	718.91	287.6	143.78	1725.3	862.7	3163.2
Coeff. of variation (%)	161.38	161.38	161.38	161.38	161.38	161.38	161.38
Minimum	24.1	12.06	4.8	2.4	28.9	14.5	53.1
Maximum	10,121.2	5060.61	2024.2	1012.1	12,145.5	6072.7	22,266.7
Range	10,097.1	5048.6	2019.4	1009.7	12,116.5	6058.1	22,213.6
Coeff. skewness	0.35	0.35	0.35	0.35	0.35	0.35	0.35
Stnd. kurtosis	17.94	17.94	17.94	17.94	17.94	17.94	17.94

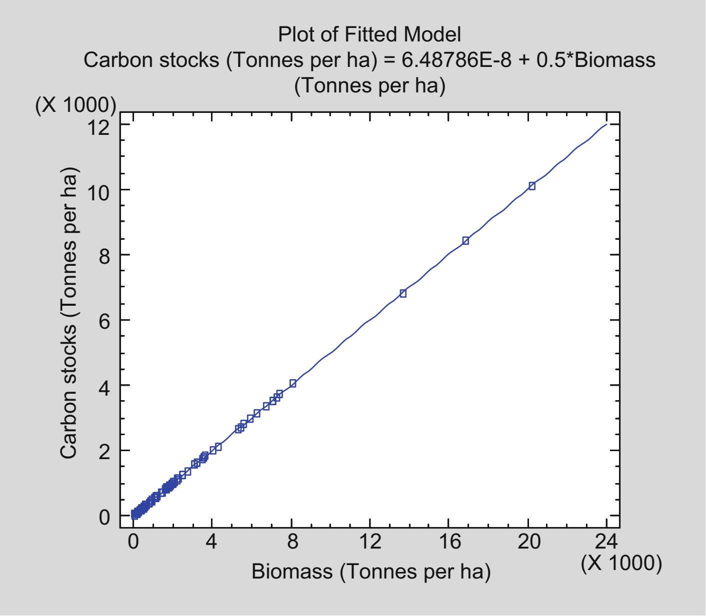


Fig. 3 Relationship between biomass and carbon

Table 4 Summary statistics for average tree biomass stocks (kg)

Management zones	Count	Average biomass (kg)	Standard deviation	Coeff. of variation (%)	Minimum	Maximum
Production zone	30	181.436	319.433	176.059	24.124	1783.39
Recreation/buffer zone	50	506.0548	627.4903	123.9965	36.3592	3117.55
Strict nature reserve	63	1534.23	1895.35	123.537	37.1147	10,121.2
Total	143	887.516	1439.42	162.186	24.124	10,121.2

It is also important to compare SOC in forest environments. Comparison for variations of soil organic carbon in Mabira forest was done basing on the SOC percentage content. It was noted that there was no variation in the mean SOC for the three management zones. In terms of soil depth, the 0–10 cm and 10–20 cm soil layers had relatively similar variations of least square means for carbon than the 20–30 cm soil layer. The highest SOC was observed in the soil surface of 0–10 cm depth, with the highest mean of 2.78% across all the management zones. As expected, soil organic matter decreases with depth and varies with land use/cover type. Whereas the forest and subsistence farming land use/cover types had relatively higher means of SOC (with legumes and bananas as dominant crops), low mean variations for

Table 5 Descriptive statistics for carbon stocks (kg per tree) by management zones

Description								
Carbon								
					95% Confidence interval for mean			
	N	Mean	Std. deviation	Std. error	Lower bound	Upper bound	Min.	Max.
Strict nature reserve	63	920.54	1137.21	143.275	634.14	1206.94	22	6073
Recreation buffer	50	303.63	376.49	53.244	196.63	410.63	22	1871
Production zone	30	108.86	191.66	34.992	37.29	180.43	14	1070
Total	143	534.56	862.69	72.142	391.95	677.17	14	6073

Table 6 Variance of carbon stocks (kg per tree) by management zone

Source of variations	Sum of squares	d.f.	Mean square	F-ratio	Sig.
Between groups	1.749E7	2	8,744,327.239	13.881	0.000
Within groups	8.819E7	140	629,941.672		
Total (corr.)	1.057E8	142			

Table 7 Analysis of variance for carbon stocks (kg per tree) – type III sums of squares

Source	Sum of squares	d.f.	Mean square	F-ratio	*P*-value
Main effects					
Management zones	4.89	2	2.44	13.97	0.0000
Residual	2.45	140	1.75		
Total (corrected)	2.94	142			

All F-ratios are based on the residual mean square error

carbon were recorded in both the tea and sugarcane plantations, and built-up areas (Table 11 and Fig. 5).

Among the three factors (soil depth, management zones, land use/cover types) assessed for SOC variations, it was soil depth and land use/cover types that had a statistically significant effect on the percentage of carbon ($P = 0.05$), as presented in Table 12.

Discussion

Velle (1995) allometric equation was adopted and here combinations of tree parameters are applied. Similar recommendations for specific diameter–height allometries are made in studies by Feldpausch et al. (2011) and Banin et al. (2012). According to Sharifi et al. (2016), blending parameters may give better results. Although DBH was found to be a significant parameter in determining AGB and C (Dudley and

Table 8 Multiple range tests for carbon stocks (tonnes per hectare) by management zones – method: 95.0% LSD

Level			Count	Mean	Homogeneous groups	
Production zone			30	181.43	X	
Recreation/buffer zone			50	496.30	X	
Strict nature reserve			63	1534.23	X	
Multiple comparisons						
Carbon LSD						
(I) Zone	(J) Zone	Mean difference (I–J)	Std. error	Sig.	95% confidence interval	
					Lower bound	Upper bound
SNR	Recreation buffer	616.90[a]	150.326	0.000	319.70	914.11
	Production zone	811.67[a]	176.06	0.000	463.60	1159.76
Recreation buffer	SNR	−616.90[a]	150.33	0.000	−914.11	−319.70
	Production zone	194.77	183.30	0.290	−167.61	557.15
Production zone	SNR	−811.68[a]	176.06	0.000	−1159.76	−463.60
	Recreation buffer	−194.77	183.30	0.290	−557.15	167.61

[a] The mean difference is significant at the 0.05 level

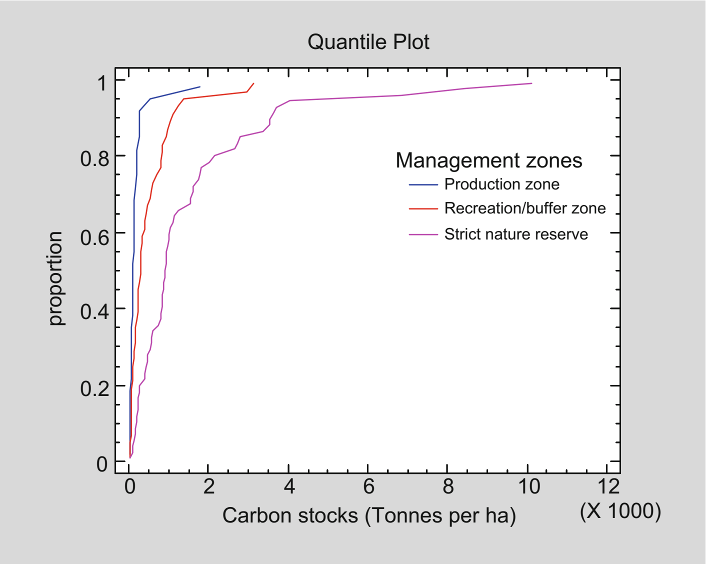


Fig. 4 Carbon stocks in the different management zones, indicating highest carbon concentrations in the strict nature reserve

Table 9 Average biomass, carbon, and carbon sequestered per tree in the management zones of Mabira CFR

Management zone	Biomass/kg	Carbon stock/kg	Carbon sequestered
Strict nature reserve	1841 ± 321.7	920.5 ± 160.8	3375 ± 589.7
Recreation/buffer	607.2 ± 106.5	303.6 ± 53	1113 ± 195
Production	217.7 ± 54.2	108.9 ± 27.1	399.2 ± 99.4

Fownes 1992), it was also noted that higher estimations of AGB and carbon were indicated where DBH and H were combined. It was also noted that a coefficient of 1.0 indicated a perfectly strong relationship between AGB and carbon. Such a significant logarithmic relationship was also identified by Clark et al. (2001) and Krisnawati et al. (2012).

The results reveal a positive relationship between land use/cover and carbon sequestration, since the strict nature reserve has more AGB stocks. Therefore, conservation of forests with large carbon stocks would reduce carbon dioxide emissions than the production zone, where pockets of degradation are evident, despite isolated afforestation and reforestation attempts. The findings are in keeping with Sharma et al. (2010), implying that preserving old growth strands maintains large amounts of carbon stocks and also promotes sequestration of much more carbon than exotic forests.

The strict nature reserve covering 3857 ha sinks approximately 6,771,092.34 tonnes. However, government plans to reduce this area to 3189 ha and increase the production

Table 10 Total tree carbon estimates per management zone

Management zone	Estimated coverage (ha)	Average tree counts per hectare	Average tree carbon (kg)	Total carbon per hectare (kg)	Average carbon per management zone	Average carbon per hectare (tonnes)	Average carbon sequestered (tonnes) per zone
Strict nature reserve	3857.82	520	920.5	478,680	1,846,661,548	1,846,661.55	6,771,092.34
Recreation/ buffer	5233.15	337	303.6	114,469.6	599,036,614.3	599,036.61	2,196,467.58
Production	17,159.38	67	108.8	7293.7	125,155,501.8	125,155.50	458,903.57

Table 11 Least squares means for SOC with 95.0% confidence intervals

Level	Count	Mean (%)	Std. error	Lower limit	Upper limit
Grand mean	132	2.17994			
Soil depth					
0–10 cm	44	2.78	0.16	2.47	3.09
10–20 cm	44	2.17	0.15	1.87	2.47
20–30 cm	44	1.59	0.15	1.28	1.89
Management zones					
Production zone	24	2.25	0.21	1.82	2.67
Recreation/buffer zone	60	2.11	0.12	1.88	2.35
Strict nature reserve	48	2.18	0.14	1.88	2.47
Land use/cover types					
Built-up	24	1.88	0.19	1.49	2.26
Forest	36	2.81	0.15	2.52	3.10
Subsistence farming	40	2.45	0.14	2.17	2.73
Sugarcane plantation	26	1.86	0.19	1.50	2.25
Tea plantation	6	1.89	0.38	1.14	2.63

zone to 26,785 ha (NFA 2017). This would reduce the carbon sink and pave the way for further global warming, related to unsustainable agricultural practices, which include deforestation, bush burning, overgrazing, monoculture, and overcultivation, all of which degrade the environment.

Soils are the main terrestrial carbon sink; the conservation of soil carbon reduces carbon emissions, as well as the risks of climate change. Land use and cover change are noted to significantly influence carbon variations. Under the strict nature reserve, where the dominant land cover type is forest, most of the activities are conservational, hence more carbon stocks, as opposed to the plantation area, which is more commercial with lower carbon stocks. This is in keeping with studies by Desjardins et al. (2004) and Meyer et al. (2012). Furthermore, SOC was found highest in the top layer of soil (0–10 cm). This is explained by the rapid decomposition of forest litter, which provides abundant organic matter. This is corroborated by studies by Mendoza-Vega et al. (2003) and Chowdhury et al. (2007), where more SOC was identified as located at the soil depth of 0–14 cm. Furthermore, the highest and lowest AGC concentration was identified in the strictly managed and production zones, respectively. This is in conformity with findings by Brakas and Aune (2011), who noted that AGC stocks were very low in degraded, as opposed to preserved forests.

Land management practices can significantly affect the content and distribution of SOC in different vegetation types (Li et al. 2014; Zhang et al. 2014; Baritz et al. 2010). The highest SOC concentrations were noted in the production zone and lowest in the recreation/buffer zone. By implication, if well managed through conservation attempts such as afforestation, reforestation, longer fallows and mulching, agricultural soils have a great potential for carbon sinking. Studies by

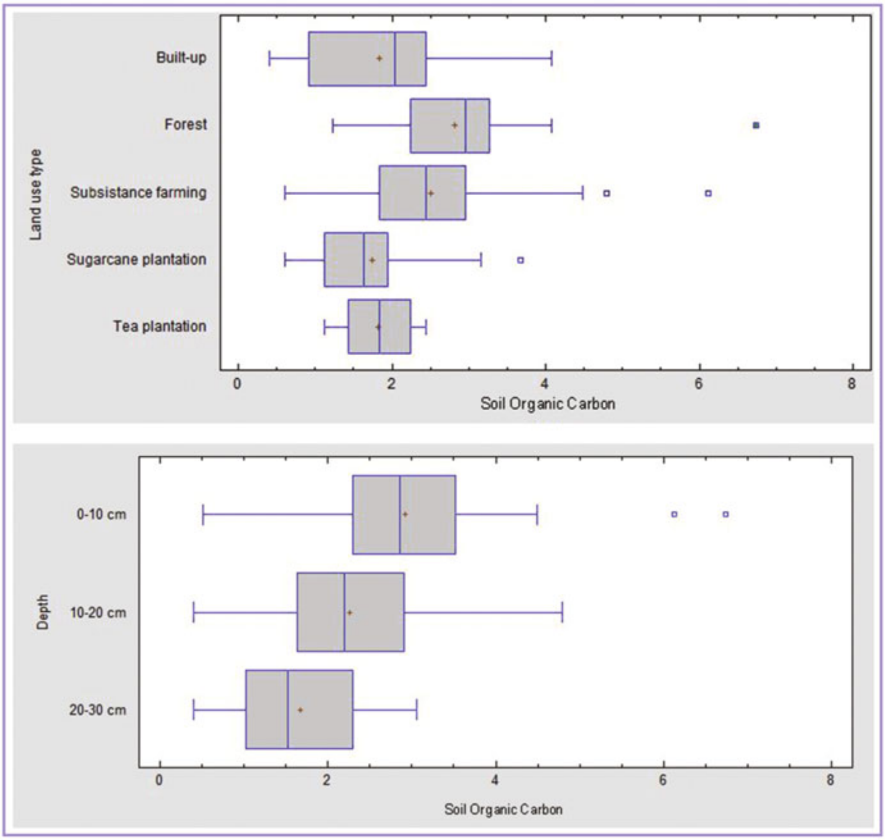


Fig. 5 Percentage SOC variations per land use/cover type, management zone, and soil depth

Table 12 Analysis of variance for SOC – type III sums of squares

Source	Sum of squares	d.f.	Mean square	F-ratio	*P*-value
Main effects					
Soil depth	31.0391	2	15.5195	19.89	0.0000[a]
Management zone	0.282212	2	0.141106	0.18	0.8348
Land use type	17.1589	4	4.28971	5.50	0.0004[a]
Residual	95.985	123	0.780366		
Total (corrected)	152.692	131			

All F-ratios are based on the residual mean square error
[a]Significant at 0.05% level of significance

McKinley et al. (2011) and Ryan et al. (2010) indicate that reducing the amount of forest harvest can decrease carbon losses to the atmosphere. As stated by Schwilk et al. (2009) and Stephens et al. (2012), forest disturbances can lead to additional soil carbon losses through soil erosion inducement.

Conclusion

The main aim of this chapter was to assess the effect of forest management options on biomass and SOC variations in Mabira CFR. AGB and carbon stocks (t/ha) of forest (trees) and SOC were estimated using allometric equations and sampling techniques. A multiparameter assessment of DBH, H, and crown diameter, and soil samples of 0–30 depth provided replicable results for tree strand AGB and SOC.

The highest AGB was evident in areas where forest was still intact (strict nature reserve), as opposed to the degraded and encroached areas (production zone). SOC varied with soil depth and land use/cover types. Another important revelation in this chapter is that SOC concentration is greatest in the production zone. By implication, if well managed through conservation measures such as afforestation, reforestation, longer fallow periods, and mulching, SOC in legume enhanced agricultural soils have a great potential as carbon sinks. The lowest SOC was noted in the recreation/buffer zone (0.4%). Land use type, AGB, and forest management in the different zones are identified as the key drivers of carbon stock variations in Mabira CFR. Priority should be given to reducing deforestation and restore degraded areas. This can be achieved through demarcating forest boundaries to minimize encroachment, enforcement of policy on forestry for sustainable development, and promotion of reforestation programs.

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