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Carbon Stocks Assessment in a Disturbed and Undisturbed Mangrove Forest in Ghana

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Abstract: Mangroves and other blue carbon ecosystems have long been recognised for their carbon sink function, yet the organic carbon stocks of mangroves in many countries in Africa remain to be assessed. This study evaluates the impact of traditional forest conservation on long-term carbon sequestration in a non-degraded (Amanzule) and a degraded (Kakum) mangrove forest system in Ghana (West Africa). The amount of carbon stored in mangrove trees was estimated from diameter-based allometric equations. Tree (above- and below-ground) carbon was ~34-fold higher in the Amanzule forest (mean = 0.89 ± 0.10 t/ha) than in the Kakum forest (mean = 0.026 ± 0.019 t/ha). Soil carbon density was estimated as organic carbon and bulk density at specific depths in both forests. Soil organic carbon density was ~5-fold higher in the Amanzule forest (mean = 2935.79 ± 266 t/ha) than the Kakum forest (mean = 554.01 ± 83 t/ha). The variation in the vertical distribution of soil carbon was not significant in either forest ($F = 0.57$; $p > 0.05$). These findings underscore the role of traditional conservation on mangrove carbon stocks and the need to consider the governance of coastal ecosystems when estimating blue carbon.

Keywords: mangrove forest; stock carbon; Ghana; Kakum; Amanzule



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1. Introduction

It has been well established that the level of carbon dioxide (CO₂) in the atmosphere is rising at an alarming rate ≈ 2.36 ppm per year over the past six decades [1]. This increasing amount of atmospheric CO₂ is the leading cause of global climate change, responsible for increased drought, intense flooding, and sea level rise with dire consequences for critical life-supporting ecosystems and agricultural production among other impacts on human livelihoods [2–4].

There is currently a broad consensus among the scientific community that conservation of ecosystems that serve as natural carbon sinks can reduce the level of CO₂ in the atmosphere [5–9]. These ecosystems include some, but not all, inland forests, mangroves, salt marshes, and seagrass beds which capture CO₂ through photosynthesis, thus trapping carbon in their living biomass above and below ground, as well as in dead tissues buried in the sediments. Together, the above-ground, below-ground and sediment-bound dead tissues of these blue ecosystems hold around 2000 Gt of carbon, which is over 2.5 times the amount of carbon that is currently held in the atmosphere [10].

In particular, mangrove ecosystems along the world's coastlines hold three billion metric tons of carbon. Except for the tundra and peatlands, mangroves store more blue carbon per unit area than any other ecosystem in the world [11–14]. This is possible because mangrove forest sediments do not become saturated with carbon [15]. Rather, the rate of carbon sequestration increases over time with the accretion of sediment within mangrove forests [11,16]. Furthermore, the carbon trapped within sediments underlying mangrove forests is held for a longer period than in other plant-dominated systems (see, for example,

McLeod et al. [15]). Due to these effects, mangroves account for $\approx 30\%$ of the coastal carbon stored in tropical and sub-tropical areas [17].

Despite the benefits highlighted above, mangrove ecosystems worldwide are threatened by multiple stressors, ranging from local pollution to destruction through dredging, filling and excavation for various agricultural and industrial uses [15,18–20]. These destructive activities are causing rapid loss of mangroves around the world, at a global rate of $\approx 0.2\%$ per year [11] and account for $\approx 62\%$ of global mangrove lost between 2000 and 2016 [21]. As a result, global mangrove cover is estimated to be reduced by 5.89% within a span of two decades (1996–2016) [22], while in Africa the decline was 17% [23]. This destruction has catastrophic consequences for coastal and indigenous communities who depend on mangrove resources for jobs, food and future opportunities [24]. Regarding global climate change in particular, mangrove forests can become sources of carbon that could add to the already high-level CO_2 in the atmosphere when degraded [25–28]. For example, decomposition of dead mangrove biomass alone releases about 53–57 Pg of carbon per year into the atmosphere [29]. This, together with other disturbance regimes in mangroves account for 18% of CO_2 emissions from tropical coastal areas [30]. Therefore, the protection of mangrove forests against degradation is considered an important strategy to prevent losses of coastal blue carbon into the atmosphere [31].

Currently, the strategy for reducing emissions from deforestation and forest degradation (REDD) seeks, among others, to encourage countries to (i) slow, halt and reverse forest loss and degradation; (ii) increase the removal of greenhouse gases from the atmosphere through forest conservation, management and expansion; and (iii) share research outcomes, experiences and lessons learned from efforts to reduce emissions from deforestation and forest degradation in developing countries (REDD+) [32,33]. As a key component, the strategy encourages countries to share data on cost-effective activities for addressing the drivers of deforestation. Ghana is a party to this REDD+ initiative [34] hence this present report is an important contribution towards the REDD+ initiative.

In Ghana, mangrove ecosystem management is done through communal ownership where traditional leaders and local customary practices inform the use of mangrove forests [35,36]. Hence, except for mangroves in protected areas, local customs and traditional law enforcement determine the exploitation of mangrove forests [37,38]. In some rural communities, mangroves are protected, seen as no-go areas providing linkage with gods, ancestors and spiritual powers [37,39]. In urban, cosmopolitan areas, on the other hand, mangroves are used indiscriminately, often exploited for fuel wood [40]. It is unknown how these different management regimes influence the carbon stock in mangrove ecosystems. Furthermore, the mangrove forest biomass and carbon stock in Ghana have not been comprehensively documented [41].

The present study aims to assess tree density, above- and below-ground carbon as well as the total carbon stock of two different mangrove forests in Ghana: the Amanzule mangrove forest in a remote community conserved through several traditional systems [37] and the Kakum mangrove forest in an urban area threatened by deforestation and other anthropogenic influences [42,43]. The ultimate goal of this study is to provide information necessary for national carbon inventories and nature conservation strategies in support of the objectives of REDD+.

2. Materials and Methods

2.1. Study Area

Two estuarine mangroves systems were selected for this study (Figure 1): the Amanzule mangrove forests in the Western Region of Ghana ($4^\circ 46' 31''$ N; $2^\circ 00' 19''$ W), and the Kakum mangrove system in the Central Region of the country ($5^\circ 05' 01.4''$ N; $1^\circ 18' 48.3''$ W). The Amanzule estuary mangrove forest is located in the equatorial climate zone with major rainfall periods occurring from May to June and October to November each year. The average annual rainfall is 1600 mm with a relative humidity of 87.5%, and a mean annual

temperature of 26 °C [44]. The soil type of the forest is mainly forest oxysols and forest ochrosols–oxysols intergrades [45].

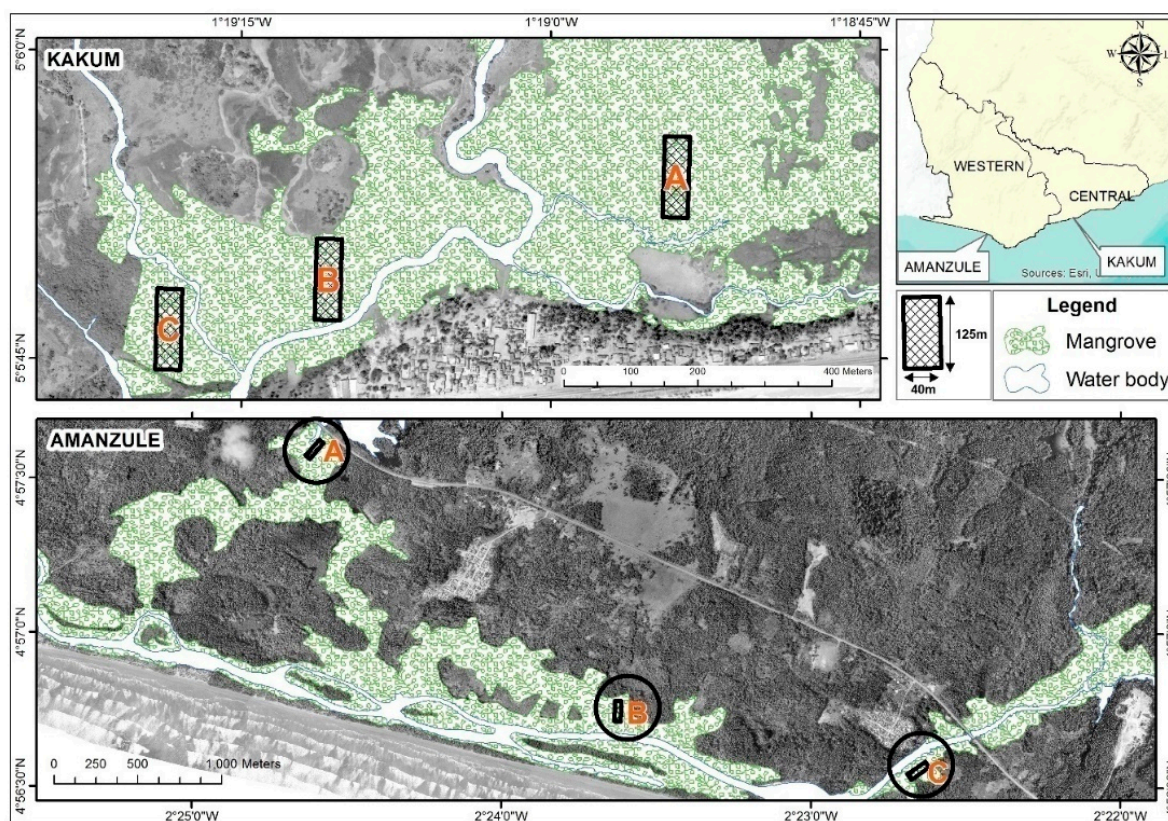


Figure 1. Study areas showing sampling locations.

Kakum is located in the dry equatorial zone of Ghana with coastal savannah as the major vegetation type. The area experiences high rainfall with the wettest periods in May/June and September/October each year. The mean annual rainfall is about 1000 mm with the average monthly temperature ranging between 24 °C to 30 °C [44]. The topography of the Kakum forest is flat with forest ochrosols as the dominant soil type [45,46].

The Amanzule forest is part of the Amanzule wetlands regarded as the dwelling place of the gods by local communities. As a consequence of this traditional belief, the Amanzule forest has been under protection for many years [44], managed by local traditional norms and customs even though the forest has no formal conservation status [37]. In contrast, the Kakum mangrove forest is intensely exploited for fuel wood and other domestic uses [42].

Three sampling plots (herein referred to as plots), each measuring 125 m × 40 m were established in each mangrove forest. Each plot was divided into 18 subplots of 10 m × 10 m per plot (herein referred to as subplots) (Figure 2). The plots were sited in areas previously determined to have dense mangrove cover [47]. To ensure comparability, the plots in both forests were located close to the low water mark, with plot A furthest from the low water mark and plot C closest to the low water mark.

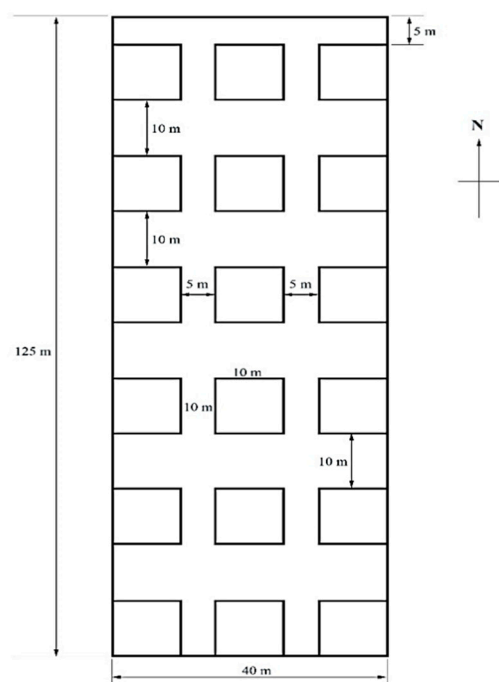


Figure 2. Schematic layout of sampling plots used in the study.

2.2. Data Collection and Analyses

Data were collected during low tide to ensure easy access to plots. Carbon stock within the selected mangroves was assessed based on three measures: total above-ground carbon (A_C), total below-ground carbon (B_C), and total organic carbon (S_C) in different layers of soil following the method of Kauffman and Donato [48]. The above- and below-ground carbon refer to the amount of carbon stored in living plant tissues above and below the soil, respectively [49]. The above- and below-ground carbons were estimated using Equation (1):

$$A_C \text{ or } B_C = W \times f \quad (1)$$

where W is tree biomass, and f is the biomass-to-carbon conversion factor of 0.46 and 0.39 respectively, for above- and below-ground biomass [50]. The above- and below-ground biomass of each tree was determined using Equations (2) and (3), respectively [51]:

$$W_{top} = 0.251 \times p \times D^{2.46} \quad (2)$$

and

$$W_R = 0.199 \times p^{0.899} \times D^{2.22} \quad (3)$$

where W_{top} is above-ground biomass, W_R is below-ground biomass, D is tree diameter at breast height, and p is the specific wood density based on conservative estimates by Howard et al. [50] for different mangrove species. The tree diameter at breast height was determined at 1.37 m above ground using a Vernier calliper for smaller trunks. For larger tree trunks, the circumference was measured with a tape and the value divided by π to obtain the diameter. In the case of *Rhizophora* spp. the diameter was measured at 30 cm above the highest stilt root.

The organic carbon content of the soil (S_C) was measured from soil samples collected with an auger and a rectangular soil sampler (volume: 120 cm³) at depths of 0–15 cm, 16–30 cm, 31–50 cm, and 51–100 cm, following the method of Kauffman and Donato [8]. Samples were stored in opaque polyethene bags and transported to the laboratory for analysis.

In the laboratory, each layer of the soil was dried in the oven at 105 °C to constant weight, and ground in a porcelain mortar. The homogenized samples were sieved through a 0.5 mm mesh to remove root parts and analysed for organic carbon content using the modified dichromate oxidation method of Bajgai et al. [52]. Following oxidation, the organic carbon concentration was calculated using Equation (4) [53]:

$$O_C = \frac{[A \times N_{FAS} \times (0.003)]}{Dw} \times 100 \quad (4)$$

where O_C is the weight of carbon per unit weight of soil layer, A is the volume (mL) of dichromate consumed during boiling, N_{FAS} is the normality (0.2 N) of the ferrous ammonium sulphate solution used in the oxidation, whilst Dw is the weight (g) of the dried homogenised soil. The total weight of organic carbon occurring within each soil layer (Kg C m^{-2}) was calculated using Equation (5):

$$S_C = [B \times T \times O_C] \quad (5)$$

where T is the thickness (m) of the soil layer and B is the bulk density (kg m^{-3}) of the soil layer sampled. The total carbon stock (Kg C ha^{-1}) from each of the plots was determined by summing the total above-ground carbon (A_C), below-ground carbon (B_C) and carbon in the different soil layers (S_C).

The mangrove tree populations in the two study areas were characterised based on species density, relative density, total basal area, and relative dominance. The stand density of each subplot (number of trees per hectare) was calculated as:

$$\text{Tree Density} = \frac{\text{No. of trees of a species}}{0.01 \text{ ha}} \quad (6)$$

The mean total density ($\pm$ s.d.) of trees in each plot was obtained based on the number of trees in the subplots.

The basal area (m^2) of each tree was computed as $\text{DBH}^2 \times 7.854^{-5}$ following [42] and the total tree basal area ($\text{TBA m}^2 \text{ ha}^{-1}$) as:

$$\text{TBA} = \frac{\text{Sum of the basal area for all tree species}}{\text{Area of sampling plot (m}^2\text{)}} \quad (7)$$

2.3. Statistics Used

The sampling was designed to investigate three major factors that are likely to influence the results. These factors were the type of forest management (conservation vs. exploitation), location of sampling area within the forests, and subplots. The vegetation structure in each mangrove forest was assessed using the density and basal area of the tree species. The basal area of tree species from the sampling locations was compared using a two-way analysis of variance (two-way ANOVA) with forest type and sampling plot as the sources of variance.

Possible differences in the biological characteristics of the individual species in different forest systems were assessed using a two-way ANOVA with forest type and sampling plot as the sources of variance. Total above-ground carbon (A_C), total below-ground carbon (B_C), and soil organic carbon (S_C) measured in the different forest systems were also compared using a two-way ANOVA. Organic carbon concentration in the different layers of soil from each forest was compared. Tukey's test ($\alpha = 0.05$) was performed to determine which pairs of means were significantly different.

3. Results

3.1. Vegetation Composition and Structure

Three mangrove tree species, namely *Rhizophora mangle*, *Avicennia germinans* and *Laguncularia racemosa* were found in the Kakum and Amanzule forests. *Avicennia germi-*

nans was the dominant species in the Kakum forest with 86.8% cover whereas *R. mangle* dominated the Amanzule forest with a cover of 85.9%. Notably, *R. mangle* was the tallest tree in both forests while *L. racemosa* was the shortest tree (Table 1). Tree girth sizes were significantly different among species in the Kakum forest with *A. germinans* and *L. racemosa* having the biggest and smallest girth sizes respectively ($F = 7.59$; $p < 0.05$).

Table 1. Mean ($\pm$ s.e.) height and diameter at breast height (DBH) of trees in the two mangrove forest systems.

Species	Kakum Forest			Amanzule Forest		
	Height (m)	DBH (cm)	N	Height (m)	DBH (cm)	N
<i>R. mangle</i>	2.89 ± 0.05^a	2.94 ± 0.06^a	115	8.09 ± 0.07^a	10.31 ± 0.25^a	1174
<i>A. germinans</i>	2.74 ± 0.01^b	3.00 ± 0.02^b	1912	5.75 ± 0.14^b	7.80 ± 0.42^b	180
<i>L. racemosa</i>	2.25 ± 0.05^c	2.76 ± 0.05^c	176	3.65 ± 0.17^c	4.13 ± 0.25^c	13

Values with different superscripts in a column are statistically different ($p < 0.05$). N = number of trees measured.

Girth sizes differed significantly among trees in the Amanzule forest with *R. mangle* and *L. racemosa* having the biggest and smallest girth sizes respectively (Table 1). The three mangrove species were taller and had greater trunk diameters in the Amanzule forest than in the Kakum forest. Basal area of *A. germinans* differed between forests and among plots ($p = 0.000$ for both). Basal area of *R. mangle* and *L. racemosa* differed significantly among plots but not between sites ($p = 0.217$; $p = 0.253$ respectively).

Kakum had a higher mean tree density than Amanzule (Table 2). The mean tree biomass in the Amanzule forest (mean AG + BG biomass = $1.21 \pm 4.6 \text{ t ha}^{-1}$) was greater than in the Kakum forest (mean AG + BG biomass = $0.03 \pm 0.02 \text{ t ha}^{-1}$); $t(1366) = 9.46$, $p = 0.00$). In the Kakum forest, tree biomass was similar for plots A and B whereas plot C had the highest tree density and biomass. In Amanzule forest, plot C had the highest tree density and lowest tree biomass. The highest tree biomass was recorded in plot A in the Amanzule forest (Table 2).

Table 2. Mean ($\pm$ s.d.) stand density and tree biomass in the Kakum (KA) and Amanzule (AM) mangrove forests.

Plot	Mean Stand Density (no./ha)		Mean Tree Biomass (t/ha)	
	KA	AM	KA	AM
A	3300 ± 2203.47	1333.33 ± 569.83	0.025 ± 0.02^a	5.42 ± 9.96^a
B	3866.67 ± 2152.97	2388.89 ± 1260.7	0.025 ± 0.02^a	0.37 ± 0.79^b
C	5272.22 ± 2325.26	3883.33 ± 955.63	0.029 ± 0.02^b	0.29 ± 0.36^c

Values with different superscripts in a column are statistically different ($p < 0.05$).

A. germinans and *R. mangle* had the highest densities in the Kakum and Amanzule forests respectively. This is reflected in the high total basal area observed for the respective species in both forests (Table 3). Species with the least densities were *R. mangle* (Kakum forest) and *L. racemosa* (Amanzule forest). Whereas *R. mangle* was about 10 times greater in Amanzule than in Kakum, *L. racemosa* was ~14 times higher in Kakum than in Amanzule (Tables 3 and 4)

Table 3. Mean ($\pm$ s.e.) species density and basal area of trees in the Kakum (KA) and Amanzule (AM) mangrove forests.

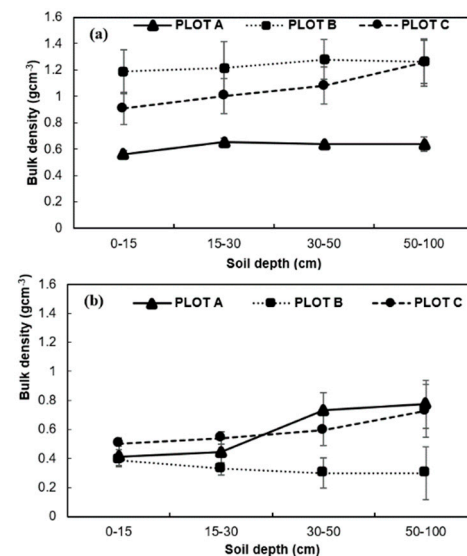
Species	Mean Species Density (Trees/ha)				Total Basal Area (m^2/ha)	
	KA	N	AM	N	KA	AM
<i>R. mangle</i>	212.96 ± 33.34	115	2174.07 ± 33.05	1174	0.15	30.43
<i>A. germinans</i>	2712.96 ± 423.05	1912	333.33 ± 54.11	180	2.67	2.44
<i>L. racemosa</i>	325.93 ± 50.95	176	24.07 ± 3.89	13	0.20	0.03

Table 4. Two-way ANOVA comparing biological characteristics of mangrove species found in forest protected by traditional customs (Amanzule) and forest exposed to consumptive exploitation (Kakum).

Tree Species	Biological Characteristic	Source of Variance	SS	df	MS	F	p-Value
<i>Rhizophora mangle</i>	Basal Area	Forest (F)	0.001	1	0.001	1.523	0.217
		Sampling plot (P)	0.397	2	0.199	230.336	0.000
		F × P	1.17×10^{-6}	1	1.17×10^{-6}	0.001	0.971
<i>Avicennia germinans</i>	Basal Area	Forest (F)	0.002	1	0.002	122.854	0.000
		Sampling plot (P)	0.002	2	0.001	58.421	0.000
		F × P	0.002	1	0.002	105.812	0.000
<i>Laguncularia racemosa</i>	Basal Area	Forest (F)	6.904×10^{-6}	1	6.904×10^{-6}	62.938	0.253
		Sampling plot (P)	1.641×10^{-8}	1	1.641×10^{-8}	0.150	0.001
		F × P	0.00	0	-	-	-

3.2. Soil Bulk Density

Mangrove sediments were ~2-fold heavier in the Kakum forest (mean: $0.97 \pm 0.07 \text{ g cm}^{-3}$) than in the Amanzule forest (mean: $0.50 \pm 0.08 \text{ g cm}^{-3}$), $F(2, 18) = 32$, $p < 0.05$ (Figure 3). A two-way ANOVA indicated that there were significant differences between the bulk densities of sediment at different soil depths in both forests (Kakum: $F(2, 9) = 47.7$, $p = 0.000$; Amanzule: $F(2, 9) = 5.9$, $p = 0.023$) (Tukey's post hoc test, $p < 0.05$).

**Figure 3.** Variations in soil bulk density in (a) Kakum and (b) Amanzule mangrove forests.

Generally mean bulk density increased with depth in both forests. However, the increase was not statistically significant in either forest ($F = 0.57$; $p > 0.05$) (Figure 3).

3.3. Carbon Stock Estimates

Soil organic carbon densities were ~5-fold higher in the Amanzule forest than in the Kakum forest. There was no significant vertical variation in soil organic content in either forest (Figure 4). Soil carbon density ranged from $462 \pm 308 \text{ t/ha}$ (at 0–15 cm depth) to $648 \pm 378 \text{ t/ha}$ (50–100 cm depth) in the Kakum forest and from $2797 \pm 973 \text{ t/ha}$ (0–15 cm depth) to $3119 \pm 1009 \text{ t/ha}$ (50–100 cm depth) in the Amanzule forest.

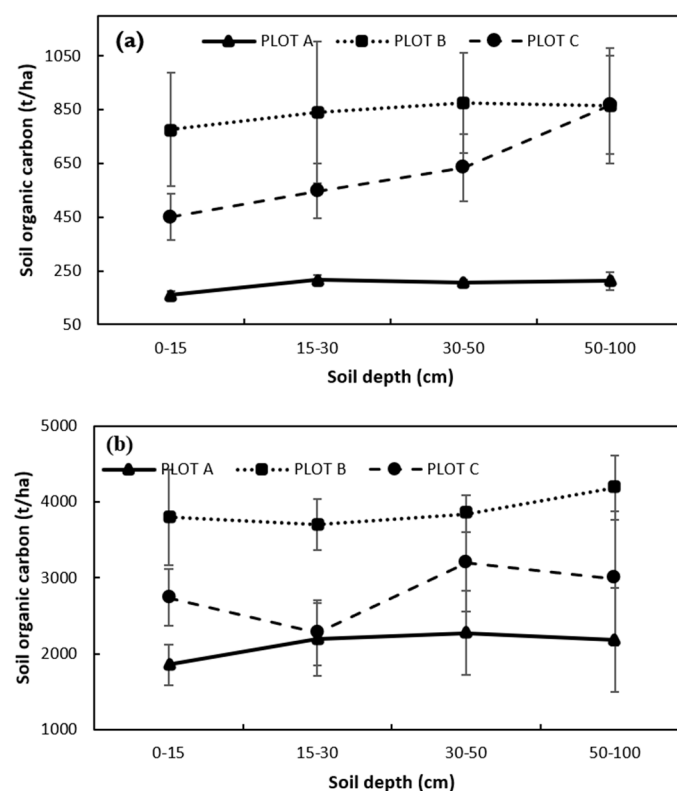


Figure 4. Variations in mean ($\pm$ s.e.) soil organic carbon density in (a) Kakum and (b) Amanzule mangrove forests.

The amount of organic carbon stored at specific depths differed between Kakum and Amanzule forests and among plots within each forest (Table 5).

Table 5. Two-way ANOVA comparing organic carbon in different layers of soil found in forest protected by traditional customs (Amanzule) and forest exposed to consumptive exploitation (Kakum).

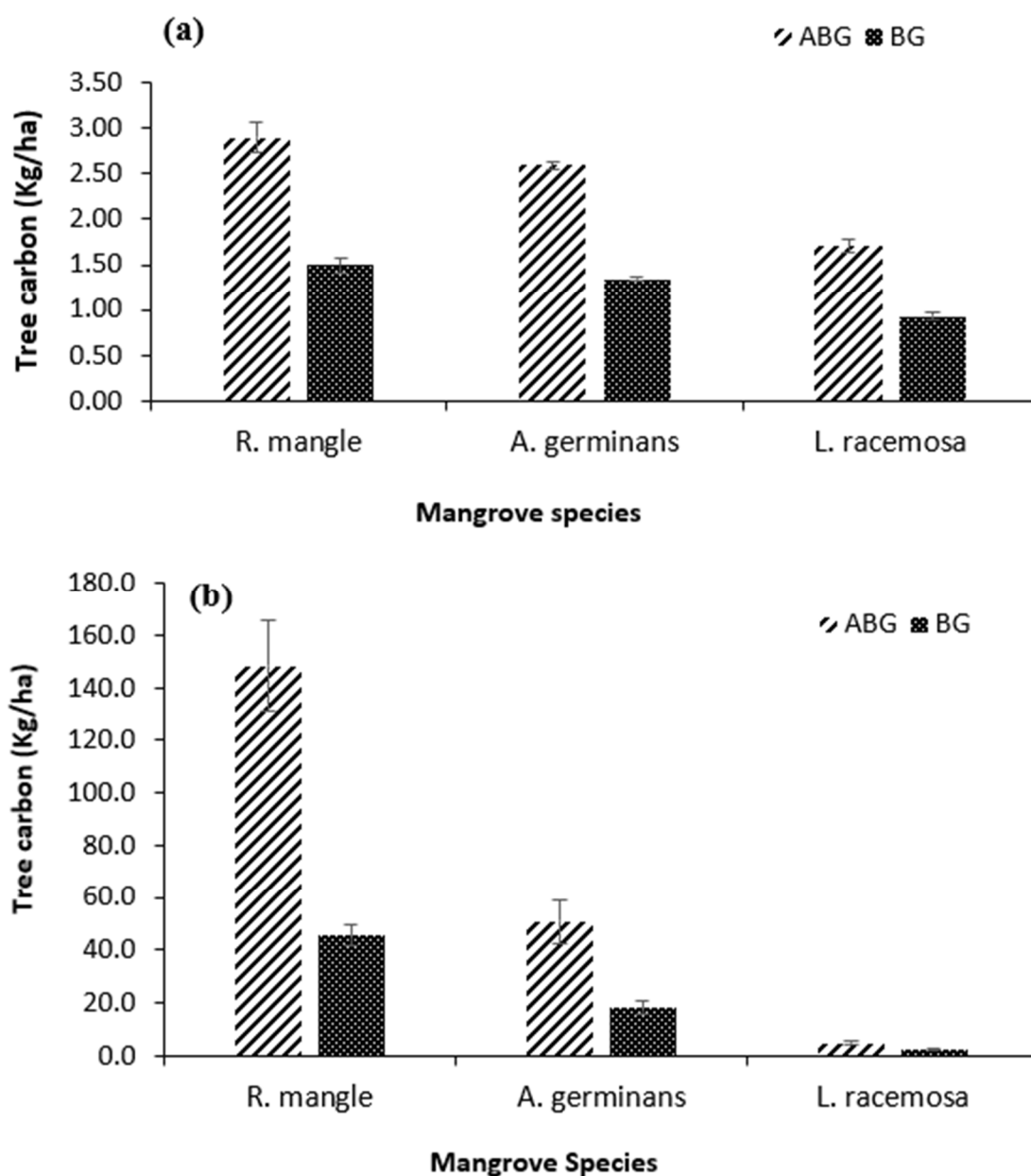
Depth of Soil Layer	Source of Variance	SS	df	MS	F	p-Value
0–15 cm	Type of forest management (F)	490,919.765	1	490,919.765	74.712	0.000
	Sampling Area (A)	98,489.604	2	49,244.802	7.494	0.002
	F $\times$ A	26,556.127	2	13,278.064	2.021	0.150
16–30 cm	Type of forest management (F)	430,583.129	1	430,583.129	71.114	0.000
	Sampling Area (A)	76,805.348	2	38,402.674	6.342	0.005
	F $\times$ A	21,297.150	2	10,648.575	1.759	0.190
31–50 cm	Type of forest management (F)	576,121.481	1	576,121.481	69.939	0.000
	Sampling Area (A)	76,311.015	2	38,155.508	4.632	0.018
	F $\times$ A	12,190.145	2	6095.073	0.740	0.486
51–100 cm	Type of forest management (F)	549,407.088	1	549,407.088	36.369	0.000
	Sampling Area (A)	106,337.977	2	53,168.988	3.520	0.042
	F $\times$ A	32,895.955	2	16,447.977	1.089	0.350

Rhizophora mangle had the highest carbon density per tree in both forests followed by *A. germinans* and *L. racemosa* (Table 6; Figure 4). *Rhizophora mangle* contained about 100 times; *A. germinans* contained about 36 times and *L. racemosa* contained about 5 times more carbon in the Amanzule forest than in the Kakum forest (Table 6).

Table 6. Mean ($\pm$ s.d.) carbon density (kg) per tree for each species.

	Kakum	N	Amanzule	N
<i>R. mangle</i>	2.37 $\pm$ 1.44	115	209.27 $\pm$ 3602.39	1174
<i>A. germinans</i>	2.12 $\pm$ 1.55	1912	73.67 $\pm$ 498.63	180
<i>L. racemosa</i>	1.42 $\pm$ 0.83	176	5.97 $\pm$ 10.91	13

Estimated above-ground carbon density was higher than estimated below-ground carbon density for all tree species in both forests. Average above-and below-ground tree carbon densities were about 28 times and 17 times higher, respectively, in Amanzule forest than in Kakum forest (Figure 5). Above-ground tree carbon was ~1.9-fold and 2.7-fold higher than below-ground tree carbon for all species in Kakum and Amanzule respectively. Significant differences ($F = 31.41$; $p = 0.00$) occurred in carbon density among mangrove species in both forests.

**Figure 5.** Mean tree carbon density of mangrove species at (a) Kakum (b) Amanzule mangrove forests.

Tree carbon is lower in the Kakum forest (0.03 ± 0.02 t/ha) relative to the Amanzule forest (0.89 ± 1.65 t/ha). Spatially, tree carbon differed significantly across sampling plots in the Kakum ($F = 11.49$; $p < 0.05$) and Amanzule ($F = 144.83$; $p < 0.05$) forests (Tables 7 and 8). A two-way ANOVA revealed that tree carbon density was significantly affected by the forest type and sampling plot for both above-ground, $F(2, 3564) = 239.1$, $p = 0.00$, and below ground, $F(2, 3564) = 337.7$, $p = 0.00$ carbon (Table 8). Soil carbon was lower in the Kakum forest than in the Amanzule forest. In both forests, soil carbon was higher than tree carbon. Soil carbon was ~5-fold higher in Amanzule forest (2935.79 ± 266 t/ha) than in Kakum forest (554.01 ± 83) whereas tree carbon was ~34-fold higher in Amanzule (0.89 ± 0.10 t/ha) than in Kakum (0.026 ± 0.019 t/ha).

Table 7. Mean ($\pm$ s.e.) tree and soil carbon densities in the Kakum and Amanzule mangrove forests.

	Tree Carbon (t/ha)		Soil Carbon (t/ha)	
	Kakum	Amanzule	Kakum	Amanzule
PLOT A	0.03 ± 0.02	2.39 ± 4.43	198.06 ± 25.93	2124.66 ± 184.81
PLOT B	0.02 ± 0.02	0.16 ± 0.35	838.92 ± 44.88	3881.38 ± 211.50
PLOT C	0.03 ± 0.02	0.13 ± 0.16	624.98 ± 178.67	2798.65 ± 396.68

Table 8. Two-way ANOVA comparing above- and below-ground tree carbon found in Amanzule and Kakum forests.

Carbon	Source of Variance	SS	df	MS	F	p-Value
Total above-ground carbon	Forest (F)	341,524,812.682	1	341,524,812.682	397.158	0.000
	Sampling plot (P)	410,660,717.821	2	205,330,358.910	238.778	0.000
	F $\times$ P	411,237,085.875	2	205,618,542.937	239.113	0.000
Total below-ground carbon	Forest (F)	29,728,701.454	1	29,728,701.454	599.290	0.000
	Sampling plot (P)	33,426,430.089	2	16,713,215.044	336.915	0.000
	F $\times$ P	33,504,196.857	2	16,752,098.429	337.699	0.000

4. Discussion and Conclusions

This study examined carbon storage in two mangrove ecosystems in Ghana—the protected Amanzule forest in the Western Region, and the unprotected Kakum forest in the Central Region of the country where there is unmitigated wood extraction. Above- and below-ground tree carbon was estimated from the diameter and density of the mangrove trees whereas soil organic carbon was calculated from soil samples.

The results show that the Amanzule forest had about thirty times more above-ground biomass than the Kakum forest. This corroborates the observation of Tamooch et al. [54] that logging and other anthropogenic disturbances reduce the health of mangrove forests and affect their overall carbon stock density. A greater part of the degraded Kakum mangrove forest is harvested for fuel wood and other subsistence uses due to lack of enforcement of traditional forest protection rules. Consequently, very few large trees remain in the forest. Mangrove trees in the Kakum forest were stunted as indicated by their low average height and diameter and as also observed by other workers (see [42,55]). In contrast, the Amanzule species were taller with wider girths, thus underscoring the beneficial effect of traditional protection on the health of natural ecosystems.

The high tree density observed in the Kakum forest is reflective of the open nature of the forest canopy. The trees are generally short and as such seedlings receive adequate warmth for growth. The apparent poor stature of the mangrove trees in the Kakum forest could be attributed to the prevailing soil type (ochrosols) which has low resistance to degradation, low nutrient levels and contains toxic concentration of aluminium see the reference [56]. These conditions, in concert with high bulk density (more mineral

particles) observed in Kakum forest, do not provide the best conditions for mangrove growth performance. Studies have shown that sediments characterised by high soil density are less porous and rich in mineral particles [57]. Such sediments restrict tree growth via their impact on soil aeration and water penetration. The relatively low density of mangrove trees observed in the Amanzule forest is attributable to the high tree canopy with big stem sizes and therefore there was little chance for the survival of seedlings. The big stem sizes of mangrove trees encountered in the Amanzule forest influenced the high carbon density values recorded and support the view of Donato et al. [58] and Assefa et al. [59] that the quantity of carbon stored is primarily determined by the size of the stand, canopy height and stature. For instance, the high soil carbon values recorded are characteristics of the high organic matter content and the forest oxysols–ochrosols intergrade soils dominating the Amanzule forest. This study has also shown that several years of carbon sequestration, devoid of intensive tillage, in the Kakum and Amanzule mangrove forests may have stored a great amount of carbon below ground (as peat) and accrete. We recorded high values of soil carbon, ~1000-fold higher than the values recorded for tree carbon in both forests. This is consistent with the general observation that soil C accounts for > 90% of total ecosystem C in mangrove forests [41,58,60]. The soil carbon recorded in this study is higher than global estimates [11] but similar to values reported for West-Central Africa see the reference [41].

The present study highlights the importance of non-degraded mangrove forests in capturing carbon. Forest degradation contributes to increasing levels of greenhouse gases in the atmosphere through the release of stored carbon in tree biomass. By implication, degraded coastal ecosystems such as mangroves are converted from net carbon sinks to net carbon sources. Therefore, carbon offsets through conservation of mangrove ecosystems could be far more cost-effective in addressing global carbon flux than current approaches focused on other terrestrial trees. Protection of mangrove ecosystems may also have enormous add-on benefits to fisheries and potentially limit coastal erosion.

This study contributes to carbon estimates for West-Central Africa as reported by Kauffman and Bhomia (2017). It confirms the carbon storage potential of mangrove ecosystems and highlights the impact of local cultural practices on mangrove carbon stocks. There is, therefore, an urgent need to consider the use of local tradition and governance approaches to improve conservation of mangrove ecosystems.

Given the high dependence of local inhabitants on services provided by mangroves, conservation measures and research towards the sustainable use of mangroves in Ghana must be prioritized in addition to sensitization and strengthening of local governance systems. The identification and scale-up of supplementary livelihood options for rural coastal communities, in the context of the blue economy, should be considered to reduce pressure on mangrove ecosystems. This study provides a snapshot of carbon stored in degraded and non-degraded mangrove forests without recourse to carbon flux caused by anthropogenic and ecological changes. Additionally, non-randomization of sampling plots in this study may account for a lower average carbon stocks value for the whole forest due to lower tree density in some areas outside of sampling plots. It will, therefore, be important to establish permanent plots to conduct longitudinal studies to generate data for the reporting of Ghana's nationally determined contribution of greenhouse gas emissions and removals as stipulated by the United Nations Framework Convention on Climate Change.

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