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Carbon stocks in the mangrove ecosystem of Rufiji River Delta, Tanzania

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Abstract. *Lupembe IB, Munishi PKT. 2019. Carbon stocks in the mangrove ecosystem of Rufiji River Delta, Tanzania. Bonorowo Wetlands 9: 32-41.* Carbon sequestration is one of the most important ecosystem services provided by mangrove ecosystems. Despite this, most Tanzanian carbon storage research has focused on terrestrial environments. Carbon and volume prediction models for the mangrove ecosystem in Tanzania's Rufiji River Delta were constructed in this study. The created models were utilized to calculate carbon emissions. At various depths, the importance of soil organic carbon as a carbon storage was also evaluated. Using linear regression, a damaging sample of 50 trees spanning various DBH size classes was used to create biomass and volume, prediction models. Wet oxidation was used to determine the amount of organic carbon in the soil. Biomass models for stems, branches, roots, leaves, and twigs and volume prediction models for total volume were constructed. At P0.05 and P0.001, respectively, all linear and power form models constructed were significant. At 0-15 cm, 15-30 cm, and 30-60 cm, organic carbon was 39.61 t ha-1, 28.04 t ha-1, and 32.85 t ha-1, respectively. The surface layer (0-15 cm) had considerably more soil organic carbon (39.61 t ha-1) than that at 15-30 cm (28.04 t ha-1) and 30-60 cm (32.85 t ha-1) depths (P0.05). The most biomass C was contributed by Rhizophora mucronata (39.87%), followed by Avicennia marina (39.86%). (28.06%). The smallest contributions came from Sonneratia alba (2.58%) and Lumnitzera racemosa (1.98%). Rhizophora mucronata contributed 39.3% of the overall volume, whereas Avicennia marina contributed 27.1%. Overall, soil organic carbon (61.6%) was nearly twice that of vegetation carbon (38.4%), highlighting the importance of soil as a carbon storage in mangrove ecosystems.

Keywords: Carbon stocks, mangrove ecosystem, Rufiji River Delta, Tanzania

INTRODUCTION

In fighting against climate change, reducing carbon emissions from deforestation and forest degradation in developing countries is critical (Gibbs et al., 2007). About 20% of global anthropogenic carbon dioxide emissions come from deforestation and land-use change (IPCC 2007). In tropical and subtropical forests, where carbon reserves are depleting at an alarming rate of 1-2 billion tonnes per year, the problem of carbon emissions is becoming increasingly urgent (Subedi et al., 2010). Carbon stocks of forest biomass have fallen by approximately 0,5 Gt per year for 2005-2010 worldwide, mainly due to a reduction in the global forest area (FAO 2010). The one method proposed to reduce these emissions in the developing countries is the Reducing Emissions from Deforestation and forest Degradation (REDD+) (Burgess et al. 2010). Moreover, the UNFCCC mechanism for the post-Kyoto implementation is now on track to reduce deforestation as an important means of reducing Green House Gas (GHG) emissions (Hannah and Lovejoy 2011).

More than 650 billion tonnes, 44% in biomass, 11% in deadwood and litter, and 45% in the soil is stored in the world's forests (FAO 2010). Forests secrete and store more carbon than any other terrestrial ecosystem and constitute a significant natural climate change 'brake' (Gibbs et al., 2007). Mangrove forests may be a key strategy in various climate mitigation strategies like REDD+ because of their large carbon sinks (Kauffman et al. 2011, Kauffman and Donato, 2012). Mangroves are reported to have a large carbon stock per unit area and have a high potential for sedimentary carbon storage (Twilley et al. 1992).

Mangroves are one of the most productive ecosystems on the planet, and they play a critical part in the global carbon cycle (Twilley et al. 1992; Bouillon et al. 2008; Tibor et al. 2014). However, conversion to agriculture, aquaculture, tourism, urban growth, and overexploitation contribute to the continuous deterioration of mangrove ecosystems (Alongi 2002). The rapid removal and deterioration of mangroves could have detrimental repercussions for the movement of materials into marine systems and alter the composition of the atmosphere and climate (Giri et al., 2011).

The study's specific goals were: (i) to construct and to use allometric models for estimating carbon stocks in the Rufiji River Delta's mangroves, (ii) to build and to use volume prediction models for volume estimation in the Rufiji River Delta's mangroves, (iii) to determine the stocks of soil organic carbon (SOC) in the mangrove ecosystem.

MATERIALS AND METHODS

Study site description

This research was carried out in the mangrove ecosystem in the Rufiji River Delta, Rufiji District, Tanzania (Figure 1). The delta, which is situated between latitudes 7°50' and 8°03' S and longitudes 39°15' and

32°17'E7.47° E, comprises 53,255 acres (Semesi 1989 as reported by Mwalyosi 2002). It is situated about 178 km south of Dar es Salaam. Tropical forest and grassland vegetation cover the majority of the Rufiji District. The Rufiji River Delta is part of the Rufiji River basin, 177.000 km^2 in size (Mwalyosi, 2002; Taylor et al., 2003). The Delta is home to East Africa's biggest region of estuarine mangroves, which supply nursery grounds for over 80% of Tanzania's prawn fishing business (Pethick and Spencer 1990). *Rhizophora mucronata* Poir., *Sonneratia alba* J.E. Smith., *Ceriops tagal* (Perr.) C.B. Robinson., *Avicennia marina* (Forsk.) Vierh., and *Bruguiera gymnorrhiza* (L.) Savigny is common mangrove species in the Rufiji River Delta (Mwalyosi 2002). *Lumnitzera racemosa* Wild., *Heritiera littoralis* Aiton, and *Xylocarpus granatum* Koen are other species.

Rufiji District has a year-round temperature range of 13 to 41°C, with two rainy seasons ranging from 750 to 1250 mm: short rains (October-December) and long rains (February-May). The district's population is over 182,000 people, with the Ndengereko the leading ethnic group (Mkindi and Meena 2005). In the Rufiji floodplain and Delta, agriculture is the primary source of income (93% of households). Rice is the primary diet for 76% of the households in the lower Rufiji River Valley and was grown with different crops. *Oryza sativa* (rice), *Zea mays* (maize), *Ipomoea batatas* (sweet potatoes), *Eleusine coracana* (millet), and fruits such as *Mangifera indica* (mangoes), *Citrus sinensis* (oranges), *Ananas comosus* (pineapples), *Carica papaya* (papaya), and *Artocarpus heterophyllus* (jack fruit) are primarily grown for subsistence. Still, a small% age is grown for (Mkindi and Meena 2005).

Sampling design

This study used a stratified random sampling design for carbon inventory, as MacDicken (1997) recommended and Kauffman and Donato (2012), which deliver more precise estimates than alternative designs. According to species distribution, the study area was divided into six strata. As a result, each stratum was designated by the dominating species or species type. *Heritiera littoralis, Avicennia marina, Rhizophora mucronata, Ceriops tagal, Sonneratia alba,* and *Bruguiera gymnorrhiza* represented these strata. Transects were created at right angles to the boundaries of the mangrove forest in each stratum from the forest margins. Plots were 100-150 meters apart, while transects were 500-750 meters apart. Accessibility issues caused by mud and canals required such distance alterations (Mattia and Malimbwi 1999). *Xylocarpus granatum and Lumnitzera racemosa*, the other two species, do not form strata/pure stands in the studied region. As a result, when they were discovered in different strata during inventory, they were included and purposefully selected during destructive sampling. The strata were allocated using vegetation maps mixed with ground-truthing. Each stratum's sampling plots were laid systematically, with the starting point chosen at random.

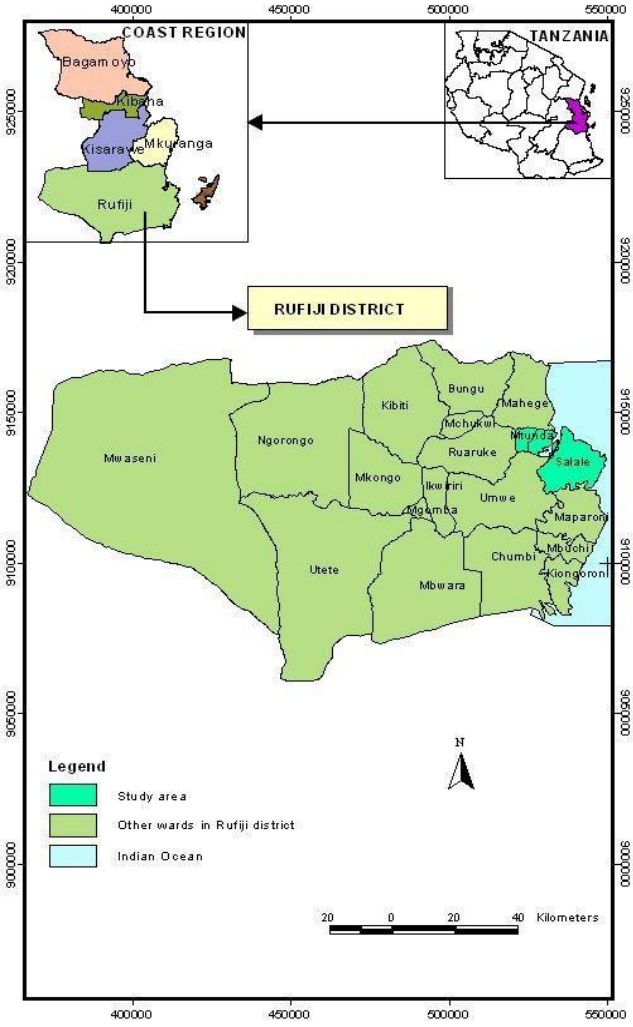

Figure 1. Location of the study site in the Rufiji River Delta, Rufiji District, Tanzania

Sample size determination

Before the fieldwork, a pilot study was conducted to assess the study area's DBH size classes and species distribution. The number of sampling plots was selected using the size of the forest and a predetermined sampling intensity of 0.01%, resulting in 59 plots (equation 1).

$$N = (TA * Si)/Ps * 100) \quad (1)$$

Where: N: Number of sample plots, TA: Total area of the forest, Si: Sampling intensity, Ps: Plot size.

Data collection for aboveground carbon estimation

With a randomly chosen starting position, a total of 59 rectangular plots measuring 20 m x 40 m (Munishi et al. 2010b) were established methodically (Malimbwi et al. 1994). Each plot was broken into eight 10 m × 10 m subplots for convenient parameter measurements. For R. mucronata, all trees having a DBH of less than 5 cm in each subplot had their DBH measured using a diameter tape at 1.3 m from the ground and 30 cm above the highest prop root (Komiyama et al. 2005). With the help of a local

botanist and a mangrove ecosystem management plan, these trees were identified by their native and scientific names. Three to five sample trees were measured for total height in each plot, after which a height/diameter connection was constructed, and the equation was used to predict the height of all other trees measured for DBH only.

Model development

The allometric models were created using a destructive sampling method. For the construction of the biomass and volume models, 50 trees were felled at random. A pilot study determined that the selected trees had a 5 to 56 cm diameter at breast height. These trees were felled, divided into stems and branches, and then cut into little billets with top and bottom diameters roughly the same (Figure 2). The billets were measured for mid diameters and length independently for volume estimations (Figure 3). Following that, the billets were weighed and recorded for fresh weight using a hanging scale with a capacity of 100 kg. Tree billets that could be easily lifted were weighed after tied together with a sisal rope. Branches were given the same treatment as stems. Finally, small sample discs about 2 cm thick were cut from each sample tree's stems, roots, and branches to determine wet to dry weight conversion factors, as advised by Malimbwi et al. (1994); Munishi et al. (2010a); Ebuy et al. (2011); Ong and Gong (2013). Huber's formula was used to calculate the volume of each part (equation 2). Twigs and leaves were collected and weighed fresh then small samples were taken for laboratory examination. By adding the volumes of the individual billets, the total volume of the stems and branches was calculated.

$$V = \pi d^2/40000 * L \quad \ldots\ldots (2)$$

Where:
V: volume (m^3)
d : diameter of the billet (cm)
L: Length of the billet (m)

Estimation of root biomass

The surface soils around the stump were dug with spades, shovels, and hoes to expose all roots. The root collar diameter (RCD) was measured on all roots. All roots were excavated and measured for new weights for stumps that were straightforward to unearth (Figure 4). Only three roots were calculated for the remaining stumps for fresh weights: small, medium, and large. The roots were taken from the stump, cleansed to eliminate mud, and then cut into little billets that were weighed and recorded fresh. For laboratory study of wet to dry conversion factors, small samples of around 2 cm thick were obtained (Snowdon et al. 2002; Ritson and Sochacki 2003).

Collection and handling of soil samples

Three types of variables were assessed to obtain an accurate inventory of organic carbon stocks in the organic soil: soil depth (cm), soil bulk density (g cm^{-3}), and organic carbon concentrations (% C) inside the sample, as recommended by Pearson et al. (2007) and Murdyarso et al. (2010). A 98.125 cm^3 steel core sampler collected soil samples from each plot center at three depths: 0-15 cm, 15-30 cm, and 30-60 cm. Undisturbed soil cores, as indicated by Munishi and Shear (2004), were taken to assess soil bulk density. The soil corer was pushed into the soil to the depths listed above before being removed. The soil samples were placed in plastic sealable tubes, labeled, weighed, and transferred to the soil organic carbon examination laboratory.

Determination of soil organic carbon (SOC)

The soil cores were taken from the tubes in the laboratory, and the wet mass was measured. Cerón-Bretón et al. (2011) oven dried the materials to a constant weight at 103 ± 2°C. For each sample, soil BD was calculated as a ratio of oven-dry weight to soil core volume (98.125 cm^3). Soil samples were air-dried and then crushed to determine C concentrations. After that, the samples were sieved through a 2-mm filter to eliminate any gravels, roots, or other debris. SOC content was determined using the Wet Oxidation method (through the Walkley-Black method). Total soil carbon storage per unit area was calculated by multiplying the organic carbon content of the soil by the bulk density and depth of the soil (equation 3).

$$\text{Total C (t C ha}^{-1}) = (\text{soil B.D (g cm}^{-3}) \times \text{soil depth (cm)} \times \%C) \quad \ldots\ldots (3)$$

Data analysis

Development of allometric models

The stem, branch, and root discs from the field were soaked in water for eight days before being weighed for green weight in the lab. After that, all samples were oven-dried to a consistent dry weight at 105°C. The basic density of the samples was estimated as a ratio of mass (g) to volume (L) (cm^3). The water displacement method was used to determine the volume of the samples. The biomass ratio for the stem and branch samples was computed by dividing the oven-dry weight by the green weight of the wood samples (Malimbwi et al. 1994; Munishi and Shear 2004, Munishi et al. 2010a), and then averaging by component and by species. The leaves and twigs samples were oven-dried to a consistent weight at 70°C. The biomass ratio (equation 4) was used to calculate the biomass of stems, branches, leaves, and twigs based on their green weights (Snowdon et al., 2002).

$$\text{Biomass (kg)} = \text{Green weight (kg)} \times \text{Biomass ratio} \quad \ldots (4)$$

Estimation of root biomass

Root samples were oven-dried at 80°C to a consistent weight in the lab. Because just a few roots were measured in the field for fresh weight, an RCD-biomass connection was created to estimate the biomass of the remaining roots (equation 5). To obtain biomass prediction models, the estimated biomass was regressed on DBH.

$$B = \text{Exp}\{-5.241+2.527 \ln(RCD)\}, (R^2 = 0.81, SE = 0.83, N = 52) \quad \ldots\ldots (5)$$

Where: B: biomass (kg), RCD: root collar diameter (cm)

Figure 2. Cross-cutting a tree of *Avicennia marina* into manageable billets in Rufiji River Delta, Tanzania (Photo: Lupembe 2013)

Figure 3. Recording diameters of billets before weighing in Rufiji River Delta, Tanzania (Photo: Lupembe 2013)

Figure 4. Pulling out a root stump of *Ceriops tagal* in Rufiji River Delta, Tanzania (Photo: Lupembe 2013)

Fitting and selection criteria for the best fit models

Biomass and volume data were processed using a Statistical Packages for Social Sciences and a Microsoft Excel spreadsheet running on Windows 7. (SPSS Version 16 software). To generate biomass/carbon and volume prediction models, the biomass and volume were regressed against DBH, a combination of DBH and height, and DBH, height, and wood density (Malimbwi et al. 1994; Munishi et al. 2001; Munishi et al. 2010b). The best fit models for the biomass and volume components were determined using least squares regression analysis. The models with the greatest fit were chosen based on the following criteria: lowest standard error of estimate (SEE), highest coefficient of determination (R2), and best performance in graphical analysis of residuals.

The following general kinds of biomass/volume equations were fitted and tested in the development of the biomass and volume models:

(i) $Ln(Y) = b_o + b_1 Ln(DBH)$ …… (6)
(ii) $Ln(Y) = b_o + b_1 Ln(DBH) + b_2 Ln(H)$ …….... (7)
(iii) $Y = b_o + b_1(DBH^2 H)$ ……..…….. (8)
(iv) $Ln(Y)=b_o+b_1Ln(dDBH^2H)$ ……..…… (9)
(v) $Y=aX^b$ ……..…… ….…… (10)

Where: Y: biomass (kg $stem^{-1}$) or volume (m^3 $stem^{-1}$), DBH: diameter at breast height (cm), H: total tree height (m), d: wood basic density (g cm^{-3}), and a, b, b_0, b_1 and b_2 are regression constants.

Computation of biomass and volume

The plot tree diameter data were utilized to predict biomass/carbon storage and volume using allometric models constructed with DBH as a predictor variable (Malimbwi et al. 1994; Munishi et al. 2010a). Because it is expected that around half of biomass is carbon, the amount of carbon was calculated by multiplying the plot biomass by 0.50. (Malimbwi et al. 1994; Munishi et al. 2001; Munishi and Shear 2004; Basuki et al. 2009).

Stem density and basal area computations

The DBH tally from the sample plots was used to determine the average stocking for the mangrove species (equation 11);

$N = (1/n)\ (x_i/a_i)$ ……..…….. (11)

Where: N: average number of stems per hectare, n: number of plots, x_i: number of stems in plot I, a_i: area of plot i.

The mean basal area (m^2 ha^{-1}) was estimated from sample plot area and DBH tally (equation 12);

$G = (1/n)\ (gi)/a$ ……..…….. (12)

Where: G: Basal area per hectare

$g_i = (\pi/4)/d_i^2$

Where: a and d_i area sample plot area (ha) and diameter of the i^{th} stem in the plot respectively for n plots.

RESULTS AND DISCUSSION

Allometric models for carbon prediction

Table 1 shows the allometric equations for the dry weight of stems and roots, which generally fit the data well and had more than 80% coefficients of determination. All of the models were statistically significant ($p<0.05$). Although substantial, the biomass/carbon prediction models for branches, leaves, and twigs were not as powerful as the stems and roots. Munishi et al. (2010a) found that the biomass/carbon prediction models created for branches and twigs in Miombo woods were not strong but significant.

Wood basic density

Stems had a basic density of 0.33 to 0.69 g cm^{-3}, with a mean of 0.59 ± 0.042 g cm^{-3} (Table 2). Wood basic density for branches ranged from 0.32 to 0.65 g cm^{-3}, with a mean of 0.57 ± 0.038 g cm^{-3}. Basic density for roots varied from 0.18 ± 0.021 to 0.72 ± 0.037 g cm^{-3}, with a mean of 0.47 ± 0.055 g cm^{-3}. Roots had a lower fundamental density than branches for the overall pattern (Table 2). The roots of *R. mucronata*, on the other hand, showed a greater basic density (0.72 ± 0.037 g cm^{-3}) than the stems and branches. The basic root density of *L. racemosa* was the lowest, at 0.18 ± 0.021 g cm^{-3}.

Biomass characteristics of the mangrove species in Rufiji River Delta

The biomass of mangrove species was concentrated in trunks (55.63%) rather than branches (9.62%), leaves, and twigs (2.80%). The BGB (31.95%) was roughly half that of the AGB. The biomass of stilt roots in *R. mucronata* was likewise higher than some branches and leaves. Compared to other mangrove species, *R. mucronata* and *A. marina* showed the most significant regressions. The strongest relationships with DBH were stems and BGB ($R=0.9$, $P<0.01$). The biomass of branches, leaves and twigs had a weak positive connection with DBH ($R=0.6$, $P<0.01$). Carbon contents of the mangrove ecosystem in Rufiji River Delta.

The Rufiji River Delta's total C stock was estimated to be 160.15 t ha^{-1}. The soil contributed the most carbon to the overall carbon pool, with 98.57 t ha^{-1}. Soil C alone accounted for around 62% of the ecosystem's overall C estimates. A total of 40.5 t ha^{-1} of aboveground carbon was estimated (25.29%). Stems made the most contribution (55.34%), followed by branches (8.22%). Leaves and twigs supplied the least to total aboveground C stocks (2.21%). The Rufiji River Delta's belowground C pool (roots) was calculated to be 21.08 t ha^{-1}, or 13.16% of the overall C stock (Figure 5). In the Rufiji River Delta, Tanzania, belowground C (roots and soils) accounted for 74.71% of the total C supply.

Proportional contribution to c stocks by different species

On a hectare basis, the following tree species contributed to total carbon stocks: R. *mucronata* (39.87%) stored the most carbon per unit area, followed by *A. marina* (28.06%), *B. gymnorrhiza* (15.61%), *H. littoralis* (4.90%), *C. tagal* (4.11%), and *S. alba* (2.58%). *L. racemosa* provided the least total carbon stocks (1.98%) (Figure 6).

Carbon Storage at Different DBH size classes

In different DBH classes, mangrove species have variable carbon storage capabilities (Figure 6). DBH class 25-29.9 cm provided the most carbon, accounting for 30.85% of total carbon stores, followed by DBH class >34.9 cm, which produced 23.25% of total carbon stocks. DBH class 5-9.9 cm (4.08%) contributed the least carbon, followed by DBH class 10-14.9 cm (5.76%). This means that little trees may not provide much carbon to the ecosystem, but they are critical in preserving future carbon reserves.

Table 1. Carbon prediction models for stems, branches, roots, and leaves and twigs in Rufiji mangrove ecosystem, Rufiji River Delta, Tanzania

Component	Model	R^2	SE	P-value
Stems	B=Exp{-1.949+2.226ln(DBH)}	0.81	0.4573	<0.05
Branches	B=Exp{-3.463+2.103ln(DBH)}	0.57	0.7606	<0.05
Roots	B=Exp{-2.758+2.328ln(DBH)}	0.85	0.4130	<0.05
Leaves and twigs	B=Exp{-4.081+1.881ln(DBH)}	0.38	1.0670	<0.05

Note: B: biomass, R^2: coefficient of determination, SE: standard error from the ANOVA of regressions

Table 2. Basic density (mean ± SE) of the mangrove species in Rufiji River Delta, Tanzania

Species	Stems (g cm^{-3})	Branches (g cm^{-3})	Roots (g cm^{-3})
Heritiera littoralis	0.59 ± 0.018	0.54 ± 0.009	0.42 ± 0.004
Rhizophora mucronata	0.67 ± 0.006	0.62 ± 0.022	0.72 ± 0.037
Bruguiera gymnorrhiza	0.69 ± 0.007	0.63 ± 0.025	0.52 ± 0.009
Ceriops tagal	0.68 ± 0.012	0.65 ± 0.008	0.57 ± 0.022
Xylocarpus granatum	0.55 ± 0.011	0.56 ± 0.014	0.49 ± 0.006
Sonneratia alba	0.57 ± 0.004	0.56 ± 0.017	0.38 ± 0.006
Lumnitzera racemosa	0.33 ± 0.009	0.32 ± 0.012	0.18 ± 0.021
Avicennia marina	0.65 ± 0.011	0.64 ± 0.025	0.50 ± 0.012
Mean	0.59 ± 0.042	0.57 ± 0.038	0.47 ± 0.055

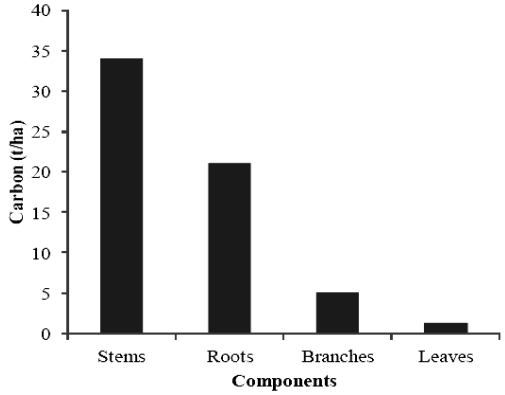

Figure 5. Carbon stocks as contributed by different tree components in the mangrove ecosystem of Rufiji River Delta, Tanzania

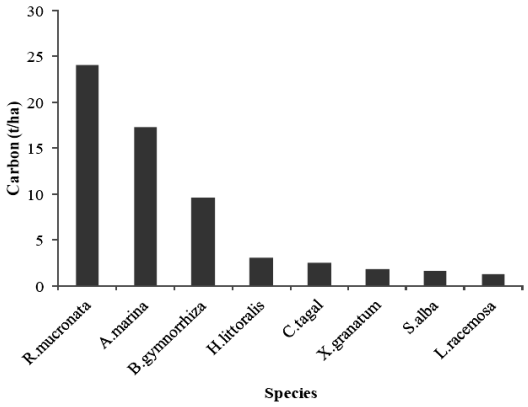

Figure 6. Carbon stocks as contributed by different mangrove species in Rufiji River Delta, Tanzania

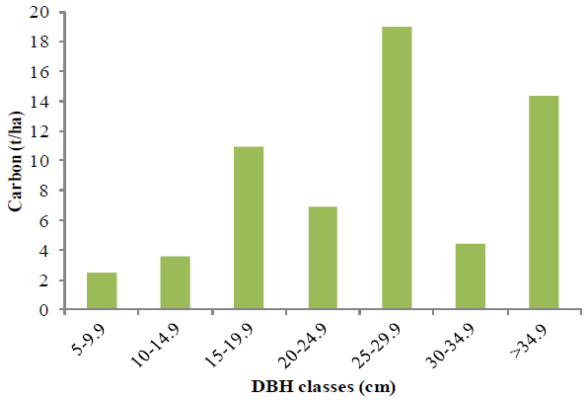

Figure 7. Mangrove tree carbon storage at different DBH classes in Rufiji River Delta, Tanzania

Wood volume, stocking rate, and basal area estimation for the mangroves of Rufiji River Delta, Tanzania

For linear models (P<0.05) and a power model (<P0.001), all produced volume equations were significant (Table 3). The first two equations simply employed DBH as a predictor variable, but the third equation included DBH and height. DBH class 5-9.9 cm had the most stocking (37.45%), followed by DBH class 15-19.9 cm (21.33%). Several trees with a DBH of less than 5 cm, particularly for *C. tagal*. DBH class 30-34.9 cm (2.12%) produced the lowest stocking, suggesting the presence of huge trees. DBH class 25-29.9 cm (30.12%) had the highest basal area, whereas DBH class 5-9.9 cm had the lowest basal area (5.46%) (Figure 7).

The current analysis calculated a volume of 168.85 ± 8.299 m^3 ha^{-1}. The most abundant species was R. mucronata (39.26%), followed by *A. marina* (27.10%). *L. racemosa* and *S. alba* contributed the lowest, 2.24% and 2.47%, respectively (Table 5). The volume of trees in the DBH class 25-29.9 cm made up 30.13% of the overall tree volume. 5.43% and 6.75% of the wood volume were given by DBH classes 5-9.9 cm and 10-14.9 cm, respectively (Table 4). Trees with smaller diameters had lesser volume per unit area, while larger ones had higher volumes per unit area.

Soil organic carbon

The soil's bulky density (BD) ranged from 0.53 to 1.17 g cm^{-3}, with a mean of 0.89 ± 0.17 g cm^{-3}. Between sampling stations, there were no significant differences in soil BD (P>0.05). With a mean of 2.52 ± 0.272, carbon concentrations varied from 0.72 to 5.88%. There was no significant variation in carbon concentration between 15-30 and 30-60 cm layers (P>0.05). The top (0-15 cm) layer, on the other hand, had a considerably greater% C than the different layers (P<0.05). The pH of the soil varied from 2.34 to 7.46, with a mean of 5.78 ± 0.214. (Figure 8). This means that the soils were very strongly acidic to mildly alkaline, with clay as the predominant soil texture.

The average depth of soil organic C storage in the mangrove habitat was 33.5 ± 3.356 t ha^{-1} (Figure 8). Overall, the average soil organic C of the Rufiji River Delta mangrove habitat was 98.57 t ha^{-1} at all depths. The surface layer (0-15 cm) had a higher amount of soil organic C (39.61 ± 2.979 t ha^{-1}) than the lower layers, with a total of 39.61 ± 2.979 t ha^{-1}. The mean soil organic C in the middle layer (15-30 cm) was 28.04 ± 1.817 t ha^{-1}, lower than the mean soil organic C in the bottom layer (30-60 cm) of 32.85 ± 2.579 t ha^{-1}. This disparity is due partly to the nature of mangrove soils, which are extremely unstable and soft compared to terrestrial ecosystem soils. In mangrove habitats, soils of various layers are frequently mixed. The surface layer of soil organic C differed significantly from the middle and lowest layers (<P0.05). The middle layer's soil organic C did not differ significantly from the bottom layer's (P>0.05).

Table 3. Volume equations for estimating total volumes for the mangrove trees of Rufiji River Delta, Tanzania

Model	R^2	SE	P-value
V=0.04357DBH-0.54967	0.92	0.125	<0.05
$V=0.000716DBH^{2.0037}$	0.94	0.114	<0.001
$V=0.1025+0.0000297DBH^2H$	0.89	0.148	<0.05

Note: R^2 and SE are as defined in table 1

Table 4. Mean (± SE) stem density (N), basal area (G), and volume (V) in the mangroves of Rufiji River Delta, Tanzania

DBH Classes	N (stems ha^{-1})	G (m2 ha^{-1})	V (m3 ha^{-1})
5-9.9	273 ± 8	1.00 ± 0.001	9.17 ± 0.027
10-14.9	105 ± 5	1.24 ± 0.002	11.40 ± 0.013
15-19.9	155 ± 6	3.52 ± 0.003	32.44 ± 0.034
20-24.9	53 ± 3	2.08 ± 0.006	19.15 ± 0.019
25-29.9	98 ± 5	5.51 ± 0.005	50.88 ± 0.041
30-34.9	15 ± 2	1.23 ± 0.016	11.39 ± 0.007
>34.9	29 ± 3	3.72 ± 0.071	34.43 ± 0.048
Total	729 ± 34	18.30 ± 0.639	168.85 ± 5.903

Table 5. Wood volume (mean ± SE) for different mangrove species of Rufiji River Delta, Tanzania

Species	Volume (m^3 ha^{-1})	%
Rhizophora mucronate	66.29 ± 0.159	39.26
Avicennia marina	45.76 ± 0.259	27.10
Bruguiera gymnorrhiza	27.13 ± 0.148	16.07
Heritiera littoralis	8.97 ± 0.145	5.32
Ceriops tagal	7.74 ± 0.097	4.58
Xylocarpus granatum	5.00 ± 0.377	2.96
Sonneratia alba	4.18 ± 0.789	2.47
Lumnitzera racemose	3.78 ± 0.126	2.24
Total	168.85 ± 8.299	100.00

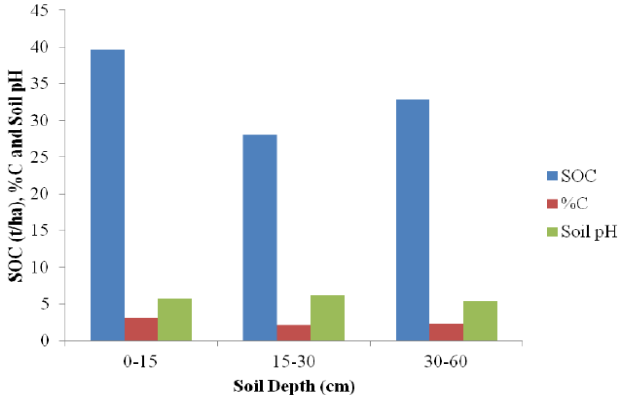

Figure 8. Soil organic carbon, carbon concentration, and soil pH at different depths in the mangrove ecosystem of Rufiji River Delta, Tanzania

Discussion

Carbon stocks in the mangrove ecosystem of Tanzania's Rufiji River Delta were assessed in this study. For the past 20 years, allometric models have been used to study carbon/biomass in mangroves (Komiyama 2005). Allometric models were created in this study by regressing biomass/volume against DBH and/or height as predictor variables. The generated models were used to predict the mangrove ecosystem's aboveground, belowground, and volume in the Rufiji River Delta. The importance of soil organic carbon as a carbon source was also examined.

Biomass/carbon prediction models for the mangroves of Rufiji River Delta.

Due to the limitations connected with height measurements in this species, this study exclusively used DBH to estimate biomass in the mangrove ecosystem of the Rufiji Delta. The DBH has been utilized as the only independent variable in several studies that have used regression to explore biomass in mangroves (Ong et al., 2004; Soares et al., 2005). However, other research estimated the aboveground biomass of mangrove species using formulae based on height and DBH (Suzuki and Tagawa 1983; Ross et al. 2001; Abohassan 2012). Other studies have used a combination of DBH, height, and particular wood gravity as predictor variables (Ross et al. 2001; Soares et al. 2005), and some studies have used a combination of DBH, height, and specific wood gravity as predictor variables (Ross et al. 2001; Soares et al. 2005). (Chave et al. 2005). The majority of research has encouraged using models in which tree biomass is determined solely by DBH measurements, which has the advantage of being practical because most inventories contain DBH measurements. DBH is also simple to measure accurately in the field (Segura and Kanninen 2005). Compared to stem and root biomass, the biomass of branches, leaves, and twigs was less predictable. Munishi et al. (2010a), Sawadogo et al. (2010), and Wang et al. (2010) have all found similar findings (2011). As a result, it is easier to anticipate the biomass of large woody components like stems and total aboveground biomass for smaller components like branches and twigs. The branches and leaves are extremely sensitive to light, water, nutrients, and soil conditions, such as microclimate and competition from neighbors (Sawadogo et al., 2010). Carbon biomass in the mangrove ecosystem of the Rufiji River Delta

According to Brown (2002), most hardwood forests contain aboveground biomass of 75-175 Mg ha^{-1} (or 38-90 Mg C ha^{-1}). The C estimations of the current study are within this range. The estimated aboveground C storage in the Rufiji River Delta (40.5 t C ha^{-1}) is comparable to the 98.4 t ha^{-1} recorded by Faridah-Hanum et al. (2012) in the Marudu Bay forest (approximately 49 t C ha^{-1}). *Rhizophora mucronata* had the largest biomass, accounting for almost half of the total TAGB. Suzuki and Tagawa (1983) found that stocking (density), basal area, and height significantly impacted total aboveground biomass. *Rhizophora mucronata* exhibited the maximum basal area (39.25%) and moderate stand density in the Rufiji River Delta. Ross et al. (2001) calculated aboveground biomass to be 22.28 5.18 t ha^{-1} in Dwarf forests and 56.02 11.96 t ha^{-1} in Fringe forests, equating to around 11 t C ha^{-1} and 28 t C ha^{-1}, respectively. Aboveground C stocks were found to be greater in the current study. However, if dead forests and trees with a diameter of less than 5 cm were included in the present study, the aboveground C could be considerably higher.

Tamooh et al. (2008) found that belowground C stocks (roots) in the Rufiji River Delta in Gazi Bay vary between 3.8 0.2 C t ha^{-1} and 17.9 0.6 C t ha^{-1}, 24.2 0.4 C t ha^{-1} and 37.7 1.0 C t ha^{-1}, 19.5 0.4 C t ha^{-1} and 21.9 0.9 C t ha^{-1} for *R. mucronata*, *S. alba*, and *A. marina* stands, respectively.

The amount of C in a mangrove forest is also determined by the type. Root C of 32.4 t ha^{-1}, 106.6-173.3 t ha^{-1}, and 187.0-272.9 t ha^{-1} have been reported in primary forests of *Sonneratia sp.*, *Bruguiera sp.*, and *Rhizophora sp.*, respectively (Komiyama et al. 1987). Because the mangroves in the Rufiji River Delta are secondary forests, they are unlikely to have the same high C stocks as primary forests. Abohassan et al. (2001) reported aboveground biomass of 14.77 t ha^{-1} and belowground biomass of 67.8 ha^{-1} in the Arid Mangrove Systems on the Red Sea Coast of Saudi Arabia, which corresponds to around 7 and 34 t C ha^{-1}, respectively. As can be observed, mangroves in arid places tend to have vast underground reservoirs.

Mangroves, particularly Rhizophora sp., have low R/S biomass ratios in tropical forests (Komiyama 2000). The current study employed an R/S biomass ratio of 0.49, which, if implemented, would result in a belowground C estimate of 19.85 t ha^{-1}, which is 1.23 t ha^{-1} less than that derived using the allometric model provided by this study. This R/S biomass ratio can be used to approximate the belowground biomass in mangrove habitats in the Rufiji River Delta, Tanzania because the difference is small.

Volume prediction models for the mangroves of the Rufiji River Delta

In this study, three-volume estimation equations were established (Table 3). The power model was very significant ($P<0.001$), and both linear models were significant ($P<0.05$). DBH was utilized as the single predictor variable in the first two equations, whereas DBH and height were employed in the third equation. The most common predictor variable in allometric models is the diameter (Malimbwi et al. 1994; Munishi et al. 2001; Munishi and Shear 2004; Munishi et al. 2010b). Compared to the other models, the power model explained 94% of the volume variance and had the smallest standard error. As a result, this model was employed to estimate tree volumes in this investigation.

Volume estimates for the mangroves of the Rufiji River Delta

This study's mean tree volume estimate of 168.85 ± 8.299 m^3 ha^{-1} (Table 5) was lower than Mattia and Malimbwi's (1999) estimate of 268 ± 6.08 m^3 ha^{-1}. They also calculated the basal area to be 28 ± 0.44 m^2 ha^{-1} and the average tree stocking to be 1,488 ± 2.50 trees per hectare. These were higher than the findings of the current research. The number of stems per hectare previously reported was higher because saplings (trees with less than 5 cm diameter and a height of more than 1 m) were included. Anthropogenic activities may have also contributed to the ecosystem's current decreased volume and basal area. Large portions of the Rufiji River Delta have been cleared for rice farming and selective logging, and this process is currently ongoing (Figure 9 and 10). Rice farming in Tanzania's Rufiji River Delta has resulted in the loss of approximately 1,700 hectares of mangroves. Rice is crucial for the survival of people in the area, and almost 75% of the population considers farming to be their top priority (Taylor et al., 2003).

Figure 9. Farmers weeding rice farms in Rufiji River Delta, Tanzania (Photo: Lupembe 2013)

Figure 10. Land preparation for planting rice in Rufiji River Delta, Tanzania (Photo: Lupembe, 2013)

Soil organic carbon in the mangroves of the Rufiji River Delta

The organic matter concentration of the surface layers in the Rufiji River Delta was higher, especially in undisturbed areas. On the other hand, SOC did not demonstrate a steady reduction in depth from 0-60 cm. The C content of the surface layers (0-15 cm) was higher, whereas the middle layer (15-30 cm) had a lower C content than the bottom layer (0-15 cm) (30-60 cm). These findings contradict those of Pandey and Pandey (2013), who found that there was more C in the lower layers (16 to 30 cm depth) than in the top levels (up to 15 cm depth). Organic C concentrations in the Rufiji River Delta ranged from 0.92 to 5.88%, with a mean of 2.54 ± 0.12%, significantly lower than those found in the Tropical Pacific by Donato et al. (2012). Among other anthropogenic activities, agriculture and selective logging may have contributed to the reduced C content in Tanzania's Rufiji River Delta.

The amount of carbon in soil varies widely amongst mangroves, and is primarily controlled by forest age, tidal exchange, and suspended matter sedimentation (Cerón-Bretón et al., 2011). Mangroves' upper soil layers contain more trash and dead (and living) roots than the lower layers, eventually raising the C content in the top layers (Nguyen et al., 2011). Long periods of tidal flooding combined with slow decomposition result in anoxic conditions and high organic matter content, explaining the

increased organic matter concentration in upper mangrove layers (Cerón-Bretón et al., 2011).

The SOC in this study is within the range of 71.8 to 154.8 t C ha^{-1} reported by Matsu et al. (2012). However, SOC in young Kandelia Kandel L. Blanco plantations was higher than that of Nguyen et al. (2009), ranging from 31 to 85 t ha^{-1}. Because this plantation was still young, it seemed likely that it had not yet gathered enough organic matter. In dense, intermediate, and sparse mangroves, Pandey and Pandey (2013) found 87.83 t C ha^{-1}, 36.99 t C ha^{-1}, and 44.08 t C ha^{-1}, respectively. These figures were lower than the ones found in the current research. In contrast, soil carbon estimations in the Rufiji River Delta were very low compared to greater C stocks in the Tropical Pacific reported by Donato et al. (2012), ranging from 631 to 754 Mg C ha^{-1}. Peat soils showed substantially greater organic carbon concentrations (13-15%) that lasted throughout the soil profile to depths below 1 m, resulting in higher carbon estimates.

In conclusion, the models created for estimating biomass and volume in the Rufiji River Delta mangrove environment should vastly improve the ability and reliability to estimate biomass and tree volume without harvesting trees. (ii) Higher carbon storage has been discovered in mangrove forests in the Rufiji River Delta, implying that conservation can greatly improve carbon stocks and attract large carbon-based funding for land restoration. (iii) Maintaining the health of mangrove forests and their vast carbon reserves is critical for climate change mitigation, which can be achieved by preventing deforestation in the Rufiji River Delta. (iv) Despite continuous deforestation, the large carbon stores in mangrove forests of the Rufiji River Delta, as demonstrated by this study, show that mangrove ecosystems are important conservation areas.

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