CARBON STOCKS IN THE MANGROVE ECOSYSTEM OF RUFIJI RIVER DELTA, RUFIJI DISTRICT, TANZANIA

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A DISSERTATION SUBMITTED IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE IN ECOSYSTEMS SCIENCE AND MANAGEMENT OF SOKOINE UNIVERSITY OF AGRICULTURE. MOROGORO, TANZANIA.

ABSTRACT

One of the most important ecosystem services provided by mangrove ecosystems is to act as a carbon sink. Despite this role, most carbon storage studies in Tanzania have concentrated on terrestrial ecosystems. In this study, carbon and volume prediction models were developed for the mangrove ecosystem in Rufiji River Delta, Tanzania. The models developed were used to estimate carbon. Soil organic carbon as an important carbon reservoir was also assessed at different depths. Biomass and volume prediction models were developed using linear regression from a destructive sample of 50 trees spanning a wide range of DBH size classes. Soil organic carbon was analyzed by wet oxidation method. Biomass models were developed for stems, branches, roots, leaves and twigs and volume prediction models for total volume. All linear and power form models developed were significant at $P<0.05$ and $P<0.001$, respectively. The organic carbon was 39.61 t ha^{-1}, 28.04 t ha^{-1} and 32.85 t ha^{-1} at 0-15 cm, 15-30 cm and 30-60 cm, respectively. The Rufiji River Delta mangrove ecosystem was estimated to have 40.5 t ha^{-1} of aboveground carbon, 21.08 t ha^{-1} of belowground carbon (roots) and 98.57 t ha^{-1} of soil organic carbon. The soil organic carbon (39.61 t ha^{-1}) at surface layer (0-15 cm) was significantly higher than at 15-30 cm (28.04 t ha^{-1}) and 30-60 cm depth (32.85 t ha^{-1}) ($P<0.05$). *Rhizophora mucronata* contributed the highest (39.87%) biomass C, followed by *Avicennia marina* (28.06%). *Sonneratia alba* (2.58%) and *Lumnitzera racemosa* contributed the least (1.98%). Volume was estimated at 168.85 m^3 ha^{-1} with *Rhizophora mucronata* contributing 39.3% and *Avicennia marina* 27.1% of the total volume. Overall, soil organic C (61.6%) was almost twice that of vegetation carbon contributing 38.4% emphasizing the role of soil as an important carbon

reservoir in mangrove ecosystems. The Rufiji River Delta mangrove ecosystem has a high potential as an important carbon sink useful for climate change mitigation through sustainable management.

DECLARATION

I, **INNOCENT BERNARD LUPEMBE,** do hereby declare to the Senate of Sokoine University of Agriculture that this dissertation is my own original work done within the period of registration and that it has neither been submitted nor being concurrently submitted in any other institution.

..... 16.10.2014

Innocent Bernard Lupembe — Date

(MSc. Candidate)

The above declaration is confirmed by:

..... 16.10.2014

Prof. P.K.T. Munishi — Date

(Supervisor)

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To my wife; Mary Ndunguru and children; Anold Lupembe and Anna Lupembe. They missed me a lot while undertaking this endeavor.

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LIST OF ABBREVIATIONS AND SYMBOLS

AGB	Aboveground Biomass
ANOVA	Analysis of Variance
BA	Basal Area
BD	Bulk Density
BGB	Belowground Biomass
C	Carbon
DBH	Diameter at Breast Height
FAO	Food and Agriculture Organization of the UN
g	Basal area per tree
G	Basal area per hectare
GHG	Green house gases
Gt	Gigatonne
ha	Hectare
IPCC	International Panel on Climate Change
Mg	Megagram
N	Number of stems per hectare
OC	Organic Carbon
RCD	Root collar diameter
REDD+	Reduced Emissions from Deforestation and Forest Degradation
R/S	Root shoot ratio
SOC	Soil Organic Carbon
SPSS	Statistical Packages for Social Sciences

t	Tonne (metric)
TAGB	Total aboveground biomass
UNFCCC	United Nations Framework Convention on Climate Change

CHAPTER ONE

1.0 INTRODUCTION

1.1 Background Information

Reducing carbon emissions from Deforestation and forest Degradation in developing countries is of central importance in efforts to combat climate change (Gibbs *et al.,* 2007). Deforestation and land-use change accounts for about 20% of the total global anthropogenic carbon dioxide emissions (IPCC, 2007). The problems of C emissions are increasingly acute in tropical and subtropical forests where carbon stocks are decreasing at an alarming rate of 1-2 billion tonnes a year (Subedi *et al.*, 2010). For the world as a whole, carbon stocks in forest biomass decreased by an estimated 0.5 Gt annually during the period 2005–2010, mainly because of a reduction in the global forest area (FAO, 2010). One mechanism proposed to mitigate these emissions is through Reducing Emissions from Deforestation and forest Degradation (REDD+) that has potential to mitigate these emissions in developing countries (Burgess *et al.*, 2010). Also, the post-Kyoto implementing mechanism for the UNFCCC is now moving towards inclusion of reduced deforestation as an important mechanism for helping to reduce Green House Gases (GHG) emissions (Hannah and Lovejoy, 2011).

The world's forests store more than 650 billion tonnes of carbon, 44% in the biomass, 11% in dead wood and litter, and 45% in the soil (FAO, 2010). Forests sequester and store more carbon than any other terrestrial ecosystem and are an important natural 'brake' on climate change (Gibbs *et al.*, 2007). Including mangrove forests in various climate change mitigation strategies such as REDD+

initiatives can be a key strategy due to their large potential carbon sinks (Kauffman *et al.,* 2011, Kauffman and Donato, 2012). Mangroves are said to have a high potential for sedimentary carbon storage, and their carbon stock per unit area can be enormous (Twilley *et al.*, 1992). Worldwide, mangroves provide timber, fuel wood, and food for human sustainability and also are important habitats for birds, fish, crustaceans, shell-fish, reptiles and mammals, especially in developing countries (Alongi, 2002). In recognition of their national importance, all mangrove areas in Tanzania have been designated as forest reserves between 1928 and 1932 (Taylor *et al.*, 2003). This ecosystem is widely distributed along the coasts of tropical and subtropical areas (Alongi, 2002; Komiyama *et al.,* 2005; FAO, 2007). It is estimated that mangrove forests cover 15.6 million hectares globally (FAO, 2010).

Mangroves are among the most productive ecosystems on the earth with important roles in the global carbon cycle (Twilley *et al.*, 1992; Bouillon *et al.*, 2008; Tibor *et al.*, 2014). However, continued decline of mangrove ecosystems is caused by conversion to agriculture, aquaculture, tourism, urban development and overexploitation (Alongi, 2002). The rapid disappearance and degradation of mangroves could have negative consequences to the transfer of materials into the marine systems and influence the atmospheric composition and climate (Giri *et al.*, 2011).

1.2 Problem Statement and Justification

Biomass estimates are important for describing the current state of mangrove forests and for predicting the consequences of changes in age, size, structure and species

composition (Comley and McGuiness, 2005). It is also important for modeling the potential consequences of climate change and for carbon accounting (Snowdon *et al.*, 2002). Carbon stock data for different types of forests are needed for implementing REDD+ policy in Tanzania (Munishi *et al.*, 2010b). Worldwide, mangrove ecosystem deforestation accounts for 10% of the carbon released from deforestation each year; and yet mangroves amount to just 0.7% of the tropical forest areas (Donato *et al.*, 2011).

The mangrove ecosystem of Rufiji River Delta in Tanzania is likely to have high potential for carbon storage but there is little information on its quantification (Munishi *et al.*, 2010b). This ecosystem is experiencing rapid rates of deforestation and also threatened due to sea level rise hence emitting GHG to the atmosphere (Komiyama *et al.*, 2005; Kauffman *et al.*, 2011). Unlike other forest categories in Tanzania such as miombo woodlands and montane forests where allometric models for biomass estimation have commonly been developed and applied (Malimbwi *et al.*, 1994; Munishi and Shear, 2004; Shirima *et al.*, 2011; Swai *et al.*, 2014), none of such models exist for mangrove forests in Tanzania. Moreover there are few studies that quantify biomass and carbon stocks in the mangrove ecosystems in Tanzania (Taylor *et al.*, 2003). Most of the studies in Rufiji River Delta have focused on mangrove responses to sea level rise (Pethick and Spencer, 1990), structure of mangroves (Mattia and Malimbwi, 1999), the implications of physical processes on the mangrove, and mass mangrove mortality due to El Nino floods (Ochieng, 2002). The allometric models, carbon and volume estimates from this study will be useful in accurate quantification of the value of the ecosystem and in designing proper

management plans for the mangroves. This will ensure sustained potential of this ecosystem's contribution to carbon emission and climate change mitigation.

1.3 General Objective

The general objective of this study was to assess carbon storage of the mangrove ecosystem in Rufiji River Delta, Tanzania.

1.4 Specific Objectives

The specific objectives of this study were:

i. To develop and use allometric models for estimation of carbon stocks in the mangroves of Rufiji Delta.

ii. To develop and use volume prediction models for estimation of volume in the mangroves of Rufiji River Delta.

iii. To assess soil organic carbon (SOC) stocks in the mangrove ecosystem.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Distribution of Mangrove Forests

Mangrove forests are dominant ecosystems that form important coastal ecotones occupying the boundary between the land and the sea in many tropical and sub-tropical areas (Alongi, 2002; FAO, 2007). The term 'mangrove' is also used more generally to describe both the plant communities they form and the habitat itself (Clough, 2013). They grow in harsh environmental settings such as high salinity, high temperature, extreme tides, high sedimentation and muddy anaerobic soils (Giri *et al.*, 2011). The largest percentage of mangrove ecosystems is found between latitudes 5° N and 5° S (Giri *et al.*, 2011).

Although mangrove forests are distributed only in limited areas along coastlines, they may play an important role in carbon accumulation in tropical and subtropical regions in relation to the global carbon cycle (Twilley *et al.*, 1992). The total mangrove forest area of the world in 2000 was 137,760 km^2 in 118 countries and territories accounting for 0.7% of the total tropical forests of the world (Giri *et al.*, 2011). The most extensive mangrove area is found in Asia, followed by Africa and North and Central America. Five countries (Indonesia, Australia, Brazil, Nigeria and Mexico) together account for 48% of the total global area and 65% of the total mangrove area is found in just 10 countries (FAO, 2007). The remaining 35% is spread over 114 countries and areas, of which 60 have less than 10 000 ha of mangroves each (FAO, 2007).

Mangroves are found in almost all countries along the west and east coasts of Africa, spreading from Mauritania to Angola on the west coast, and from Egypt to South Africa on the east coast, including Madagascar and several other islands. They are lacking in Namibia, probably due to the semi-arid, desert-like climate, with low and irregular rainfall, and lack of warming currents and favourable topographical features (FAO, 2007). In Tanzania, mangroves cover about 115 500 ha and stretch along coastal districts from the border with Kenya (North) to that with Mozambique (South) with high concentration of about 50 000 ha in the Rufiji River Delta which is the largest single mangrove forest in Eastern Africa (Taylor *et al.*, 2003). Mangroves are also well represented on coasts of Zanzibar (6 073 ha) and Mafia Islands (Mhamilawa, 2004).

2.2 Threats to Mangrove Ecosystems

Mangrove ecosystems are threatened by land use/land cover change as well as global climate change (Alongi, 2002; Giri *et al.,* 2011; Kauffman *et al.,* 2011). The global area of mangroves has decreased from around 16.1 million ha in 1990 to 15.6 million ha in 2010 (FAO, 2010). Urbanization of coastlines has led to the destruction of 3.6 million ha of mangroves worldwide from 1980 to 2005 (FAO, 2007). It is estimated that about 1 to 2% of mangrove forests are being deforested per year globally (Duke *et al.*, 2007; FAO, 2007), accounting for 10% of the carbon released from deforestation annually; and yet mangroves cover just 0.7% of the tropical forest areas (Donato *et al.*, 2011; Giri *et al.,* 2011).

Mangrove swamps are rapidly disappearing throughout Asia and Africa because of land reclamation, fish pond construction, mining and waste disposal (Turner and Jones, 1991). Human population growth has caused many mangrove forests like Jakarta Bay, Manila Bay and Singapore to disappear (FAO, 2010). The development of tourism industry along the coast has also been shown to be one of the threats to mangrove forests (Giri *et al.*, 2011). In some countries, browsing of mangroves by cattle and goats is the main threat (FAO, 2007).

2.3 Mangrove Ecosystem as Sinks and Sources of Carbon

A carbon sink is a natural or artificial reservoir that accumulates and stores some carbon containing chemical compounds for an indefinite period (Patil *et al.*, 2012). Coastal ecosystems like the mangroves have been traditionally overlooked for their contribution as carbon sinks in comparison to terrestrial forests (Kauffman *et al.*, 2011). Mangrove forests are characterized by high productivity and low rate of sediment respiration to net primary production. For this reason, mangrove sediments have a high potential for a long term organic C sequestration (Cerón-Bretón *et al.*, 2011). Inappropriate land uses in mangroves lead into a significant carbon loss (Pandey and Pandey, 2013). When mangroves are converted into agricultural land, organic carbon is brought to the surface and destroying plant root networks that physically trap carbon compounds. Cultivation also aerates soils, so facilitating oxidation of carbon compounds (Cowie, 2007). Therefore, high rates of land cover change in mangroves, coupled with large quantities of C susceptible to loss, underscore mangroves' exceptional relevance to strategies aimed at mitigating carbon emissions from land use activities (Kauffman *et al.*, 2011).

2.4 Carbon Pools in Mangrove Forests

Mangroves can roughly be divided into five carbon pools: aboveground biomass of live vegetation, belowground biomass of live vegetation, dead wood, forest floor (litter), and soil. Non-tree vegetation and litter are usually minor ecosystem components and can often be excluded from measurements without compromising the accuracy of the sample (Kauffman and Donato, 2012).

2.4.1 Aboveground carbon pool

In mangrove ecosystems, aboveground pool consists of trees >1.3 m height, palms, shrubs/dwarf mangroves, seedlings (herbs, litter, pneumatophores), downed wood (0.67 cm diameter, 0.67-2.54 cm, 2.54-7.6 cm, and >7.6 cm diameter) (Donato *et al.*, 2011; Kauffman *et al.*, 2011; Kauffman and Donato, 2012). Understorey vegetation (e.g. seedlings and herbs) is generally negligible in mangroves and its measurement for ecosystem carbon pools is usually unnecessary. Litter is also a small component of the total ecosystem carbon stock and therefore not usually sampled (Kauffman and Donato, 2012).

Brown (2002) reported that most of the hardwood forests had aboveground biomass in the range of 75–175 Mg ha^{-1} (or 38–90 Mg C ha^{-1}). In Nagura estuary on Ishigaki Island, Okinawa Prefecture, biomass in aboveground parts by Suzuki and Tagawa (1983) was 94.8 t ha^{-1} which is about 47.4 t C ha^{-1}. Ross *et al.* (2001) reported aboveground biomass in dwarf forests to be 22.28 ± 5.18 Mg ha^{-1} and in fringe forests was 56.02 ± 11.96 Mg ha^{-1} in USA. Aboveground biomass of 98.4 t ha^{-1} has been estimated (Faridah-Hanum *et al.*, 2012) where the highest biomass (50% of the TAGB)) was contributed by *Rhizophora mucronata.*

2.4.2 Belowground carbon pool of live vegetation

This carbon pool is made up of coarse and fine roots. Mangroves have a relatively larger amount of root biomass compared to upland forests, probably due to the need to support mangrove trees growing in the soft substrate (Komiyama *et al.*, 2008). This also helps to replenish nutrient losses (Alongi, 2008). While in terrestrial forests, belowground biomass (roots) accounts for about 20% of the total biomass (Cairns *et al.*, 1997), the belowground biomass in mangroves often represents 30–60% of the total biomass (Tamooh *et al.*, 2008). For example, Komiyama *et al.* (2008) reported a R/S biomass ratio of 12 mangrove stands ranging from 0.9-5. However, a low R/S biomass ratio of 0.22 has been reported by Abohassan *et al.* (2012) in the arid mangrove systems on the Red Sea Coast of Saudi Arabia.

Different methods have been used to estimate root biomass but generally excavation and coring methods in conjunction with allometric relationships are used (Snowdon *et al.*, 2002). Sampling belowground biomass in mangroves is logistically difficult (Tamooh *et al.*, 2008). Generally, the methods for determining root biomass stocks are not as well established as those for aboveground biomass (Cairns *et al.*, 1997). Therefore, the knowledge of biomass allocation to roots lags behind that of its aboveground counterpart (Cairns *et al.*, 1997). Root shoot ratios are used in reporting the belowground biomass stocks as a proportion of the aboveground biomass (Cairns *et al.*, 1977; Green *et al.*, 2007). Therefore, R/S biomass ratios are an indicator of relative belowground biomass to aboveground biomass (Green *et al.*, 2007).

Belowground biomass of roots down to 100 cm has been reported by Nguyen *et al.* (2009) increasing from 0.7 to 4 t C ha^{-1} in three and 10 years old plantations, respectively in *Kandelia candel* L. in Northern Vietnam. In Gazi bay, Kenya, live belowground C ranged from 3.8 ± 0.2 t ha^{-1} and 17.9 ± 0.6 t ha^{-1}, 24.2 ± 0.4 t ha^{-1} and 37.7 ± 1.0 t ha^{-1} and 19.5 ± 0.4 t ha^{-1} and 21.9 ± 0.9 t ha^{-1} for *Rhizophora mucronata*, *Sonneratia alba* and *Avicennia marina* stands, respectively, depending on the age of the stand (Tamooh *et al.*, 2008).

2.4.3 Soil carbon pool

Many mangroves have deep organic rich soils (peat) resulting in large carbon pools. This pool in mangroves is richer in carbon than above-ground carbon (Donato *et al.*, 2011; Kauffman *et al.*, 2011; Kauffman and Donato, 2012). Soil is the principle C pool in mangroves (Donato *et al.*, 2012). The large size of this below-ground pool and its poorly understood vulnerability to land use change makes its measurement relatively important (Kauffman and Donato, 2012). Despite the importance of soil carbon pools, they are the least studied pools in mangrove forests (Kauffman and Donato, 2012). This is likely due to the difficulty in obtaining accurate estimates (Donato *et al.*, 2011). Anaerobic conditions in the waterlogged mangrove soils slow down the decomposition of organic matter and accelerate carbon accumulation (Nguyen *et al.*, 2009).

In mangroves, carbon content generally changes much more slowly with depth than in upland forests (Donato *et al.*, 2011; Kauffman *et al.*, 2011). In Northern Vietnam, carbon accumulation to 100 cm depth has been reported to be 32 t ha^{-1} in bare land

and 52 to 93 t ha^{-1} in soil of 3 to 10 year old plantations (Nguyen *et al.*, 2009). Soil C of 315 and 818 Mg ha^{-1} have been reported elsewhere (Donato *et al.*, 2011). Pandey and Pandey (2013) estimated SOC as 87.83 t ha^{-1}, 36.99 t ha^{-1} and 44.08 t ha^{-1} for dense, moderate and sparse mangroves of Gujarat, respectively. Studies by Kauffman *et al.* (2011) in Micronesian mangrove forests in the western Pacific Ocean indicated that soils contained about 70% of the total ecosystem C stocks.

2.5 Allometric Models for Estimating Carbon for the Mangrove Ecosystems

Allometry is a powerful tool for estimating carbon from independent variables such as DBH and height that are easily quantifiable in the field (Komiyama *et al.,* 2005). Biomass studies of mangroves have been done in many places of the world for many species by using allometric relationships (Ong *et al.,* 2004, Gandaseca *et al.,* 2011). Measurement of tree biomass is important in order to understand the forest ecosystem characteristics (Gandaseca *et al.,* 2011). Common allometric relationship for estimating biomass from different organs of mangroves have been established by Komiyama *et al.* (2005) in South-East Asia; $Ws = 0.0696\rho\ (D^2H)^{0.931}$ for a trunk, $WL = 0.126\rho\ (D^2B)^{0.848}$ for leaf weight, $Wtop = 0.247\rho\ (D^2)^{1.23}$ for aboveground weight and $WR = 0.196\rho^{0.899}(D^2)^{1.11}$ for root weight where $D = D_{R0.3}$ for the species of Rhizophoraceae, D =DBH for the other species.

Ross *et al.* (2001) used both simple and multiple regression models for the estimation of aboveground biomass of *Avicennia germinans, Laguncularia racemosa* and *Rhizophora mangle*. They developed models for stem, branch, leaf, prop root and total biomass estimation, based on diameter at 30 cm above-ground,

height and crown volume. Fromard *et al.* (1998) also estimated the biomass of *A. germinans, Lumnitzera. Racemosa* and *Rhizophora sp.* through the use of DBH as independent variable. Allometric relationships being different for different tree species have been reported previously and mainly attributed to differences in the specific gravity (weight per volume) of the species' wood (Komiyama *et al.*, 2005). Since there is variability of basic density among individuals of a given species, among geographical locations and with age there is a need to develop allometric models of mangrove species in the Rufiji River Delta of Tanzania.

CHAPTER THREE

3.0 MATERIAL AND METHODS

3.1 Study Site Description

This study was conducted in the mangrove ecosystem in Rufiji River Delta, Tanzania. The delta covers 53 255 ha (Semesi, 1989 as cited by Mwalyosi, 2002) located between latitudes 7°50' and 8°03' S and longitudes 39°15' and 32°17'E7.47° E. It is about 178 km south of Dar es Salaam. Rufiji District is mainly covered with tropical forest and grassland vegetation types. The Rufiji River Delta forms part of the Rufiji River basin which covers an area of 177 000 km^2 (Mwalyosi, 2002; Taylor *et al.*, 2003). The Delta contains the largest area of estuarine mangroves in East Africa and provides nursery grounds for about 80% of Tanzania's prawn fishing industry (Pethick and Spencer, 1990). Common mangrove species in the Rufiji River Delta are *Rhizophora mucronata* Poir., *Sonneratia alba* J.E. Smith., *Ceriops tagal* (Perr.) C.B. Robinson., *Avicennia marina* (Forsk.) Vierh. and *Bruguiera gymnorrhiza* (L.) Savigny (Mwalyosi, 2002). Other species are *Lumnitzera racemosa* Wild., *Heritiera littoralis* Aiton and *Xylocarpus granatum* Koen. (See Appendix 3 for details).

Temperature in Rufiji District ranges from 13 to 41°C throughout the year and has two rainy seasons ranging from 750 to 1250 mm: short rains (October–December) and long rains (February–May). The population of the district is about 182 000 with the Ndengereko as the largest ethnic group (Mkindi and Meena, 2005). Agriculture is the main occupation (93% of the household) in the Rufiji floodplain and Delta. Different crops are grown with rice the staple food, being grown by 76% of the

households in the lower Rufiji River Valley. *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 largely grown for subsistence, but with a proportion being for cash income (Mkindi and Meena, 2005).

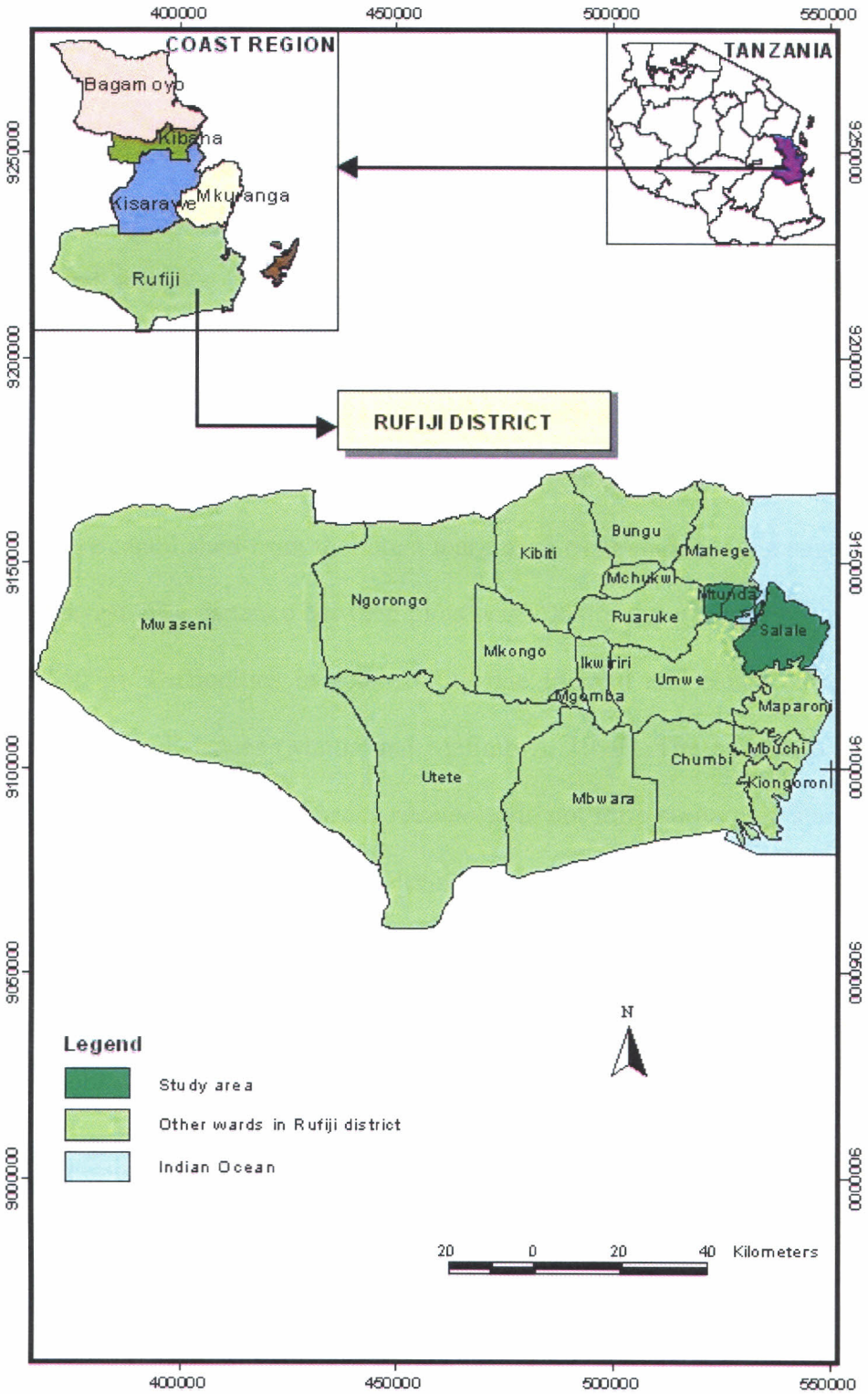

Figure 1: Location of the Study Site

3.2 Sampling Design

Stratified random sampling design as recommended by MacDicken, (1997) and Kauffman and Donato, (2012) was employed in this study for carbon inventory which is known to yield more precise estimates than other designs. The study area was stratified into six strata according to species distribution. Therefore, each stratum was defined by species type/dominant species. These strata were represented by *Heritiera littoralis*, *Avicennia marina*, *Rhizophora mucronata*, *Ceriops tagal*, *Sonneratia alba*, and *Bruguiera gymnorrhiza*. In each stratum, transects were established from the forest margins at right angles to the edges of the mangrove forest. The distance between plots was 100-150 m and between transects was 500-750 m. Difficulties in accessibility due to mud and canals necessitated such variations in distances (Mattia and Malimbwi, 1999). The other two species, *Xylocarpus granatum* and *Lumnitzera racemosa* do not form strata/pure stand in the study area. Thus they were included during inventory when encountered in other strata and were purposively selected during destructive sampling. Vegetation maps combined with ground truthing were used in allocating the strata. The sampling plots in each stratum were systematically laid with the starting point selected randomly.

3.3 Sample Size Determination

A pilot study was done prior to the actual field work to determine the DBH size classes and species distribution in the study area. The area of the forest and a pre-determined sampling intensity of 0.01% were used in determining the number of sampling plots which amounted to 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.

3.4 Data Collection for Aboveground Carbon Estimation

A total of 59 rectangular plots of size 20 m x 40 m (Munishi *et al.*, 2010b) were established systematically with a randomly selected starting point (Malimbwi *et al.*, 1994). Each plot was divided into eight sub-plots of 10 m x 10 m for easy parameter measurements. All trees with DBH $\geq$ 5 cm in each sub plot were measured (Appendix 1) for DBH using a diameter tape at 1.3 m from the ground and at 30 cm above the highest prop root for *R. mucronata* (Komiyama *et al.*, 2005). These trees were identified by their local and scientific names with the aid of a local botanist and management plan of the mangrove ecosystem. In each plot, three to five sample trees were measured for total height and then a height/diameter relationship was established and the equation was used to estimate the height of all other trees that were measured for DBH only.

3.5 Model Development

Destructive sampling approach was used for development of the allometric models. A total of 50 trees were randomly felled for biomass and volume model development. The selected trees ranged from 5 to 56 cm in diameter at breast height as identified during a pilot study. These trees were felled, separated into stems and branches and then cut into small billets of more or less the same top and bottom diameters (Plate 1). The billets were measured for mid diameters and length

individually for volume estimations (Plate 2). Thereafter, the billets were weighed for fresh weight using a hanging scale of 100 kg capacity and recorded (Appendix 2). Tree billets that could easily be lifted were fastened together with a sisal rope and weighed. Branches were treated in the same way as stems. Finally, small sample discs of about 2 cm thick were cut from the stems, roots and branches of each sample tree for determination of wet to dry weight conversion factors as recommended by Malimbwi *et al.* (1994); Munishi *et al.* (2010a); Ebuy *et al.* (2011); Ong and Gong, (2013). The volume of each section was estimated by using Huber's formula (equation 2). Twigs and leaves were collected and weighed fresh then small samples were taken for laboratory analysis. The total volume of the stems and branches was computed by summing the volumes of the individual billets.

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

where: V= volume (m^3)

d = diameter of the billet (cm)

L= length of the billet (m)

Plate 1: Cross cutting a tree of *Avicennia marina* into manageable billets in Rufiji River Delta, Tanzania (Photo: Lupembe, 2013)

Plate 2: Recording diameters of billets before weighing in Rufiji River Delta,Tanzania (Photo: Lupembe, 2013)

3.6 Estimation of Root Biomass

The surface soils from around the stump were excavated by using spades, shovels and hoes to expose all roots. All roots were measured for root collar diameter (RCD). For stumps that were easy to excavate, all roots were excavated and measured for fresh weights (Plate 3). For other stumps only three roots; small, medium and large, were measured for fresh weights. After being cut from the stump the roots were washed to remove mud then cut into small billets that were weighed fresh and recorded (Appendix 4). Small samples of about 2 cm thick were taken for laboratory analysis of wet to dry conversion factors (Snowdon *et al*., 2002; Ritson and Sochacki, 2003).

Plate 3: Pulling out a root stump of *Ceriops tagal* in Rufiji River Delta, Tanzania (Photo: Lupembe, 2013)

3.7 Collection and Handling of Soil Samples

To obtain accurate inventory of organic carbon stocks in the organic soil, three types of variables were measured: soil depth (cm), soil bulk density (gcm^{-3}), and concentrations of organic carbon (%C) within the sample as recommended by Pearson *et al.* (2007) and Murdyarso *et al.* (2010). Soil samples were collected from each plot centre at three different depths 0-15 cm, 15-30 cm and 30-60 cm by using a 98.125 cm^3 steel core sampler. Undisturbed soil cores as recommended by Munishi and Shear, (2004) were collected for determination of soil bulk density. The soil corer was pushed into the soil to the above depths and then removed. The soil samples were placed in plastic sealable tubes, labeled, weighed and then transported to the laboratory for analysis of soil organic carbon.

3.8 Determination of Soil Organic Carbon (SOC)

In the laboratory, the soil cores were removed from the tubes and wet mass was recorded. The samples were then oven dried at 103 ± 2°C to a constant weight (Cerón-Bretón *et al.*, 2011). Soil BD was computed as a ratio of oven dry weight to soil core volume (98.125 cm^3) for each sample. Soil samples for C concentration determination were air dried and then ground. The samples were then carefully sieved through a 2-mm mesh to remove gravels, roots, and other debris. A Wet Oxidation method (via Walkley-Black method) was used for determining SOC content. Soil organic carbon content was multiplied by soil bulk density and soil depth to obtain total soil carbon storage per unit area (equation 3).

Total C (t C ha^{-1}) = (soil B.D (g cm^{-3}) x soil depth (cm) x % C)..... (3)

3.9 Data Analysis

3.9.1 Development of allometric models

In the laboratory, the stem, branch and root discs from the field were soaked in water for eight days and weighed for green weight. Thereafter, all samples were oven dried at 105°C to a constant dry weight. The basic density of the samples was calculated as a ratio of mass (g) to volume (cm^3). The volume of the samples was determined by water displacement method. The biomass ratio for the stem and branch samples was calculated as the ratio of the oven dry weight to the green weight of the wood samples (Malimbwi *et al.*, 1994; Munishi and Shear, 2004, Munishi *et al.,* 2010a) and then averaged by component and by species. The samples for leaves and twigs w ere oven dried at 70 °C to a constant weight. Biomass for stems, branches, and leaves and twigs were obtained as a product of their green weights and the biomass ratio (equation 4) (Snowdon *et al.*, 2002).

Biomass (Kg) = Green Weight (Kg) x Biomass Ratio..... (4)

3.9.2 Estimation of root biomass

In the laboratory, root samples were oven dried at 80 ^{0}C to a constant weight. Since only few roots were measured for fresh weight in the field, an RCD-biomass relationship was developed to estimate the biomass of the other roots (equation 5). The biomass estimated was then regressed against DBH to get biomass prediction models.

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

where: B = biomass (kg), RCD = root collar diameter (cm).

3.9.3 Fitting and selection criteria for the best fit models

Biomass and volume data were processed using Microsoft Excel spreadsheet Windows 7 and a Statistical Packages for Social Sciences (SPSS Version 16 software). The biomass and volume were regressed against DBH, a combination of DBH and height, and DBH, height and wood density to develop biomass/carbon and volume prediction models (Malimbwi *et al.*, 1994; Munishi *et al.*, 2001; Munishi *et al.*, 2010b). Least squares regression analysis was used to determine the best fit models for the biomass and volume components. The best fit models were selected in accordance with the following criteria: smallest standard error of estimate (SEE), highest coefficient of determination (R^2), and optimal performance in a graphical analysis of residuals.

In developing the biomass and volume models, the following general forms of biomass/volume equations were fitted and tested:

Models 1: $Ln(Y) = b_o + b_1 Ln(DBH)$ ..... (6)

2: $Ln(Y) = b_o + b_1 Ln(DBH) + b_2 Ln(H)$ ..... (7)

3: $Y = b_o + b_1(DBH^2 H)$ ..... (8)

4: $Ln(Y) = b_o + b_1 Ln(dDBH^2H)$ ..... (9)

5: $Y = aX^b$ ..... (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.

3.9.4 Computation of biomass and volume

The allometric models developed with DBH as a predictor variable were used in predicting the biomass/ carbon storage and volume from the plot tree diameter data (Malimbwi *et al.*, 1994; Munishi *et al.,* 2010a). The amount of carbon was computed by multiplying the plot biomass by 0.50 as it is assumed that about a half of biomass is carbon (Malimbwi *et al.,* 1994; Munishi *et al.*, 2001; Munishi and Shear, 2004; Basuki *et al.,* 2009).

3.9.5 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);

$G = (1/n)\ (g_i)/a$..... (12)

where: G = Basal area per hectare

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

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

CHAPTER FOUR

4.0 RESULTS

4.1 Allometric Models for Carbon Prediction

The allometric equations for the dry weight of stems and roots are presented in Table 1 and they generally fitted the data well, and their coefficients of determination were more than 80%. All models were significant ($p<0.05$). Although significant, the biomass/carbon prediction models for branches, leaves and twigs were not as strong as for the stems and roots. Munishi *et al.* (2010a) observed the same with Miombo woodlands that the biomass/carbon prediction models developed for branches and twigs were not strong though significant.

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 & twigs	B=Exp{-4.081+1.881ln(DBH)}	0.38	1.0670	<0.05

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

4.2 Wood Basic Density

Wood basic density for stems ranged from 0.33 to 0.69 g cm^{-3} with a mean of 0.59 ± 0.042 g cm^{-3} (Table 2). For branches, wood basic density ranged from 0.32 to 0.65 g cm^{-3} with a mean of 0.57 ± 0.038 g cm^{-3} while for roots, basic density ranged

from 0.18 ± 0.021to 0.72 ± 0.037 g cm^{-3} with a mean of 0.47 ± 0.055 g cm^{-3}. The general trend was that roots had lower basic density than branches (Table 2). However, the roots of *R. mucronata* had higher basic density of 0.72 0.72 ± 0.037 g cm^{-3} than some stems and branches. *L. racemosa* had the lowest root basic density of 0.18 ± 0.021 g cm^{-3}.

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**

4.3 Biomass Characteristics of the Mangrove Species in Rufiji River Delta

Most of the biomass of the mangrove species was in trunks (55.63%) than in branches (9.62%), and leaves and twigs (2.80%). The BGB (31.95%) was about half of the AGB (Appendix 5). Stilt roots in *R. mucronata* also had higher biomass than some branches and leaves. *R. mucronata* and *A. marina* showed the strongest regressions compared to other mangrove species. Stems and BGB had strongest

associations with DBH (R=0.9, P<0.01). Branches and, leaves and twigs biomass showed a weak positive relationship with DBH (R=0.6, P<0.01).

4.4 Carbon Contents of the Mangrove Ecosystem in Rufiji River Delta

The total C stock in Rufiji River Delta was estimated to be 160.15 t ha^{-1}. The highest contribution of C to the total C stock was from the soil which was 98.57 t ha^{-1}. Soil C alone contributed about 62% of the total C estimates of the ecosystem. Total aboveground C was estimated to be 40.5 t ha^{-1} (25.29%). Stems contributed the highest (55.34%) followed by branches (8.22%). Leaves and twigs contributed the least (2.21%) to the total aboveground C stocks. Belowground C pool (roots) was estimated to be 21.08 t ha^{-1} which was 13.16% of the total C stock in the Rufiji River Delta (Fig. 2). Overall, belowground C (roots and soils) was estimated to be 74.71% of the total C stock in Rufiji River Delta, Tanzania.

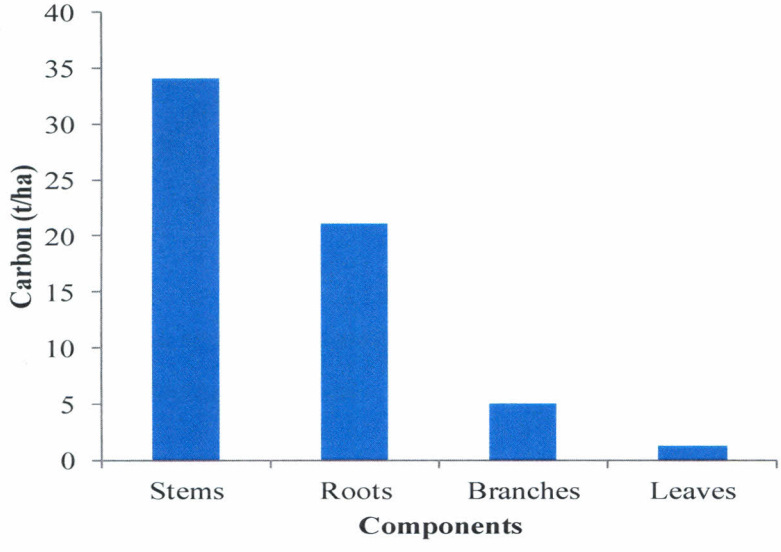

Figure 2: Carbon stocks as contributed by different tree components in the mangrove ecosystem of Rufiji River Delta, Tanzania

4.5 Proportional Contribution to C Stocks by Different Species

Tree species contributions to the total carbon stocks on hectare basis were as follows: *R. mucronata* stored the highest amount of carbon per unit area (39.87%) 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* contributed the least (1.98%) to the total carbon stocks (Fig. 3).

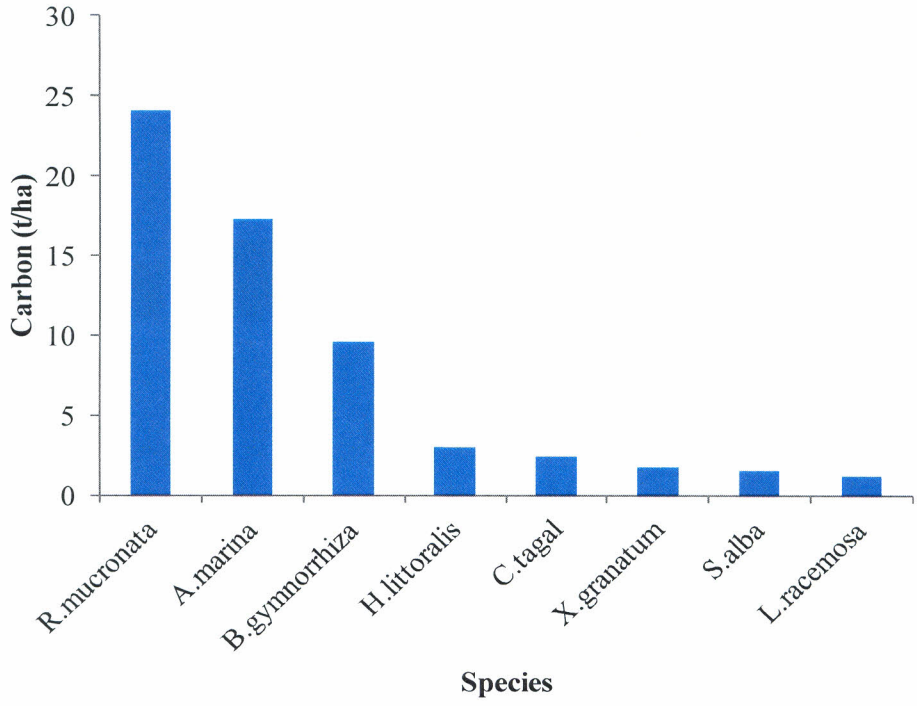

Figure 3: Carbon stocks as contributed by different mangrove species in Rufiji River Delta, Tanzania

4.6 Carbon Storage at Different DBH Size Classes

The mangrove species had different carbon storage capacities in different DBH classes (Fig. 3). The highest amount of carbon was from DBH class 25-29.9 cm which contributed 30.85% of the total carbon stocks followed by DBH class >34.9

cm that had 23.25% contribution to the total carbon stocks. The lowest carbon contribution was from DBH class 5-9.9 cm (4.08%) followed by DBH class 10-14.9 cm (5.76%). This implies that small sized trees may not contribute much carbon in the ecosystem though they are important in ensuring future carbon stocks are maintained in the ecosystem.

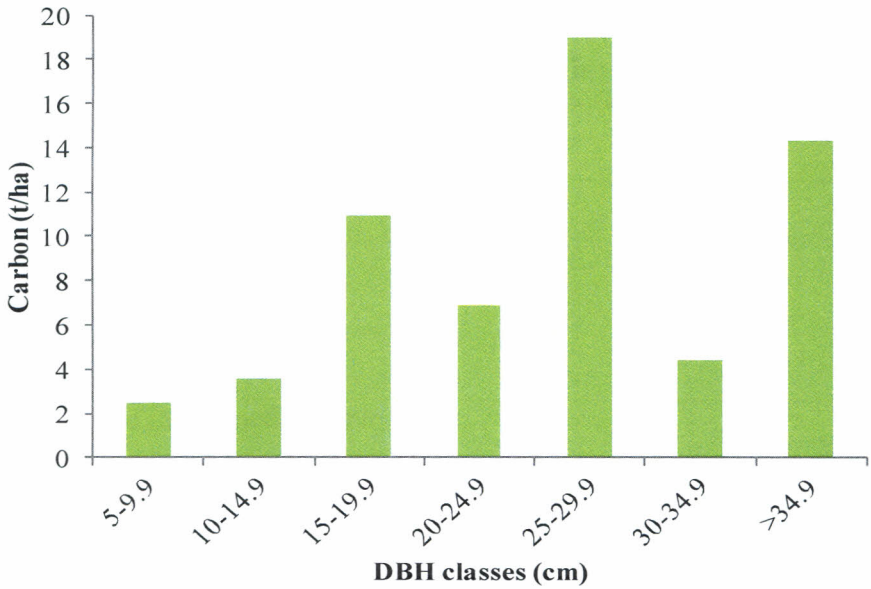

Figure 4: Mangrove tree carbon storage at different DBH classes in Rufiji River Delta, Tanzania

4.7 Wood Volume, Stocking Rate and Basal Area Estimation for the Mangroves of Rufiji River Delta

All volume equations obtained were significant ($P<0.05$) for linear models and ($P<0.001$) for a power model (Table 3). The first two equations used DBH only as a predictor variable while the third equation used DBH and height as predictor variables. Stocking was highest in DBH class 5-9.9 cm (37.45%) followed by DBH class 15-19.9 cm (21.33%). There were numerous trees of DBH less than 5 cm

especially for *C. tagal*. The lowest stocking was contributed by DBH class 30-34.9 cm (2.12%) indicating the presence of large trees. Basal area was higher in DBH class 25-29.9 cm (30.12%) and the lowest basal area was shown by DBH class 5-9.9 cm (5.46%).

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

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 (m^2 ha^{-1})	V (m^3 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**

The estimated volume from the current study was 168.85 ± 8.299 m^3 ha^{-1}. *R. mucronata* had the highest volume (39.26%) followed by *A. marina* (27.10%). *L. racemosa* and *S. alba* contributed the lowest, 2.24% and 2.47%, respectively (Table 5). Trees in DBH class 25-29.9 cm accounted for 30.13% of the total tree volume. DBH classes 5-9.9 cm and 10-14.9 cm contributed the lowest wood volume, 5.43% and 6.75% respectively (Table 4). Smaller diameter trees had lower volume per unit area and larger trees had higher volumes per unit area.

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

Species	Volume (m^3 ha^{-1})	%
Rhizophora mucronata	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 racemosa	3.78 ± 0.126	2.24
Total	**168.85 ± 8.299**	**100.00**

4.8 Soil Organic Carbon

Soil bulky density (BD) ranged from 0.53 to 1.17 g cm^{-3} with a mean of 0.89 ± 0.17 g cm^{-3}. There were no significant differences in soil BD between sampling points ($P>0.05$). Carbon concentration ranged from 0.72 to 5.88% with a mean of 2.52 ±

0.272. There was no significant difference in carbon concentration between 15-30 and 30-60 cm layers ($P>0.05$). However, the top (0-15 cm) layer had significantly higher % C than other layers ($P<0.05$). Soil pH ranged from 2.34 to 7.46 with a mean of 5.78 ± 0.214 (Fig. 5). This indicates that the soils were very strongly acidic to moderately alkaline and the dominant soil texture was clay.

The mean soil organic C storage in the mangrove ecosystem per depth was 33.5 ± 3.356 t ha^{-1} (Fig. 5). Overall, the average soil organic C of the mangrove ecosystem of Rufiji River Delta for all depths was 98.57 t ha^{-1}. The surface layer (0-15 cm) had higher amount of soil organic C of 39.61 ± 2.979 t ha^{-1} than the lower layers. The middle layer (15-30 cm) had a mean soil organic C of 28.04 ± 1.817 t ha^{-1} which was lower than that of the bottom layer (30-60 cm) with a mean soil organic C of 32.85 ± 2.579 t ha^{-1}. This discrepancy is partly due to the nature of mangrove soils which are very unstable and soft unlike soils of terrestrial ecosystems. There is frequent mixing of soils of different layers in the mangrove ecosystems. Soil organic C in the surface layer differed significantly from the middle and the bottom layers ($P<0.05$). The soil organic C in the middle layer did not differ significantly from the bottom layer ($P>0.05$).

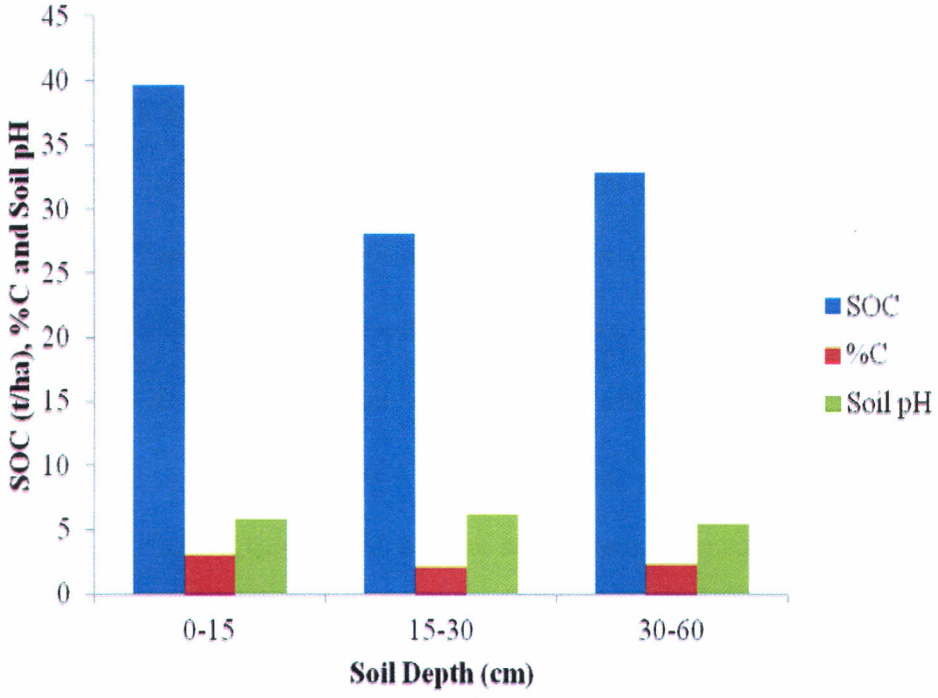

Figure 5: Soil organic carbon, carbon concentration and soil pH at different depths in the mangrove ecosystem of Rufiji River Delta, Tanzania

CHAPTER FIVE

5.0 DISCUSSION

In this study carbon stocks were assessed in the mangrove ecosystem of Rufiji River Delta, Tanzania. Carbon/biomass in mangroves has been studied for the past 20 years by using allometric models (Komiyama, 2005). In this study, allometric models were developed through regression of the biomass/volume against DBH and/height as predictor variables. The models developed were used in predicting aboveground, belowground, and volume of the mangrove ecosystem in Rufiji River Delta. Soil organic carbon as an important reservoir of C was also assessed.

5.1 Biomass/Carbon Prediction Models for the Mangroves of Rufiji River Delta

This study adopted the use of DBH only in estimating biomass in the mangrove ecosystem of Rufiji Delta owing to the difficulties associated with height measurements in this particular ecosystem. Several studies that have used regression to investigate biomass in mangroves have adopted the DBH as the only independent variable (Ong *et al.*, 2004; Soares *et al.*, 2005). However, some studies used equations based on height and DBH for the estimation of aboveground biomass of mangrove species (Suzuki and Tagawa, 1983; Ross *et al.*, 2001; Abohassan, 2012). Other studies even included crown diameter as a predictor variable (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 (Chave *et al.*, 2005).

Most studies have recommended the use of models where tree biomass is determined from DBH only, which has a practical advantage because most of the inventories include DBH measurements. Moreover, DBH is easy to measure accurately in the field (Segura and Kanninen, 2005).

The biomass of branches and, leaves and twigs was less predictable compared to stem and root biomass. This has also been reported by Munishi *et al.* (2010a); Sawadogo *et al.* (2010) and Wang *et al.* (2011). Hence the ability to predict the biomass of large woody components such as stems and total aboveground biomass is more accurate than that of smaller components such as branches and twigs. This is because the branches and leaves are very sensitive to light, water, nutrients and soil conditions i.e micro climate and competition with neighbors (Sawadogo *et al.*, 2010).

5.2 Biomass Carbon in the Mangrove Ecosystem of Rufiji River Delta

Brown (2002) reported that most of the hardwood forests had aboveground biomass in the range of 75–175 Mg ha^{-1} (or 38–90 Mg C ha^{-1}). The C estimates by the current study are within this range. The estimated aboveground C storage in Rufiji River Delta (40.5 t C ha^{-1}) is comparable to that reported by Faridah-Hanum *et al.* (2012) in Marudu Bay forest of 98.4 t ha^{-1} with about 49 t C ha^{-1}. *Rhizophora mucronata* had the highest biomass which was about 50% of the TAGB. According to Suzuki and Tagawa (1983), total aboveground biomass is greatly affected by stocking (density), basal area, and height. *Rhizophora mucronata* in Rufiji River Delta had the highest basal area (39.25%) and moderate stand density.

Ross *et al.* (2001) reported aboveground biomass in Dwarf forests to be 22.28 ± 5.18 t ha^{-1} and in Fringe forests 56.02 ± 11.96 t ha^{-1} that was equivalent to about 11 t C ha^{-1} and 28 t C ha^{-1}, respectively. The current study reported relatively higher aboveground C stocks. However, the aboveground C reported in the current study could even be more if dead woods and trees of less than 5 cm were also included.

Belowground C stocks (roots) in Rufiji River Delta fall within a range reported by Tamooh *et al.* (2008) in Gazi Bay, Kenya, that ranged 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} and 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 also depends on the type of the mangrove forest. For example, in primary forests of *Sonneratia sp*, *Bruguiera sp*, and *Rhizophora sp*, root C of 32.4 t ha^{-1}, 106.6-173.3 t ha^{-1}, 187.0-272.9 t ha^{-1} respectively has been reported (Komiyama *et al.*, 1987). Mangroves in Rufiji River Delta are secondary forests so they are unlikely to show higher C stocks as shown by primary forests. In the Arid Mangrove Systems on the Red Sea Coast of Saudi Arabia, Abohassan *et al.* (2001) reported aboveground biomass of 14.77 t ha^{-1} and belowground biomass of 67.8 ha^{-1} equal to about 7 and 34 t C ha^{-1} respectively. Thus it can be seen that mangroves in arid areas tend to have large reservoirs belowground.

In the tropical forests, the mangroves, especially *Rhizophora sp*, tend to have low R/S biomass ratios (Komiyama, 2000). In the current study, a R/S biomass ratio was 0.49 which if used, the belowground C is estimated to be 19.85 t ha^{-1} less by 1.23 tC ha^{-1} from that obtained by the use of allometric model developed by this study.

Since the difference is small, this R/S biomass ratio can be used as an approximation of the belowground biomass in mangrove ecosystems in Rufiji River Delta, Tanzania.

5.3 Volume Prediction Models for the Mangroves of Rufiji River Delta

Three equations for estimating volume were developed in this study (Table 3). Both linear models were significant ($P<0.05$) and the power model was strongly significant ($P<0.001$). The first two equations used DBH as the only predictor variable, while the third equation used DBH and height as predictor variables. Diameter is the most common predictor variable in allometric models (Malimbwi *et al.*, 1994; Munishi *et al.*, 2001; Munishi and Shear, 2004; Munishi *et al.*, 2010b). The power model was the best choice as it explained 94% of the volume variance and had the smallest standard error compared to the others. Therefore, this model was used in estimating tree volumes in this study. The developed equations from the current study may allow rapid estimates of available volume, and thus aid in planning for sustainable management of this ecosystem.

5.4 Volume Estimates for the Mangroves of Rufiji River Delta

The mean tree volume estimate of 168.85 ± 8.299 m^3 ha^{-1} from this study (Table 5) was lower than earlier volume estimates by Mattia and Malimbwi (1999) whose mean volume was 268 ± 6.08 m^3 ha^{-1}. They also estimated basal area as 28 ± 0.44 m^2 ha^{-1} and mean stocking of 1488 ± 2.50 trees per hectare. These were higher than results obtained in the current study. The number of stems per hectare reported earlier was higher as saplings (trees of diameter less than 5 cm and more than 1 m

in height) were also included. Anthropogenic activities may have also partly contributed to the current lower volume and basal area in this ecosystem. Large areas in Rufiji River Delta have been and are still being cleared for rice cultivation and selective logging (Plate 4 and 5). Rice cultivation in northern areas of the Rufiji River Delta in Tanzania has led to losses of around 1 700 ha of mangroves. About 75 % of the population considers farming their first priority and rice is important for the survival of people in the area (Taylor *et al.*, 2003).

Plate 4: Farmers weeding rice farms in Rufiji River Delta, Tanzania (Photo: Lupembe, 2013)

Plate 5: Land preparation for planting rice in Rufiji River Delta, Tanzania (Photo: Lupembe, 2013)

5.5 Soil Organic Carbon in the Mangroves of Rufiji River Delta

The surface layers in Rufiji River Delta had higher organic matter content especially in undisturbed areas. However, SOC did not show a consistent decrease with depth from 0-60 cm. Surface layers (0-15 cm) had higher C content; the middle layer (15-30 cm) had lower C content than the bottom layer (30-60 cm). These results are in contrast to that of Pandey and Pandey (2013) that reported more C in the lower layers (16 to 30 cm depth) as compared to the upper layers (up to 15 cm depth). Organic C concentrations 0.92-5.88% with a mean of 2.54 ± 0.12% in Rufiji River Delta were very low than that reported by Donato *et al.* (2012) in the Tropical Pacific. Anthropogenic activities especially agriculture and selective logging may have partly contributed to the lower C concentration in Rufiji River Delta, Tanzania.

The amount of C in soil differs greatly in different mangroves, which is mainly influenced by forest age, the degree of tidal exchange and sedimentation of suspended matter (Cerón-Bretón *et al.*, 2011). The upper soil layers of mangroves hold more litter and dead (and living) roots than the lower layers, gradually increasing the C content in the top layers (Nguyen *et al.*, 2011). Long periods of tidal flooding and low decomposition rates result in sustained anoxic conditions and high content of organic matter, which also explain the higher values in organic matter content at the upper layers in mangroves (Cerón-Bretón *et al.*, 2011).

The SOC in this study falls within the range reported by Matsu *et al.* (2012) of 71.8 to 154.8 t C ha^{-1}. However, SOC was relatively higher than those of Nguyen *et al.* (2009) of 31 to 85 t ha^{-1} in young *Kandelia kandel* L. Blanco plantations. It is probably that this plantation had not yet accumulated enough organic matter as it was still young. Pandey and Pandey (2013) reported 87.83 t C ha^{-1}, 36.99 t C ha^{-1} and 44.08 t C ha^{-1} in dense, moderate, and sparse mangroves respectively. These values were relatively lower than those reported in the current study. On the other hand, soil carbon estimates in Rufiji River Delta were very low compared to higher C stocks of 631 to 754 Mg C ha^{-1} reported by Donato *et al.* (2012) in Tropical Pacific. Such higher carbon estimates were due to peat soils that had much higher organic carbon concentration (13-15%) that remained throughout the soil profile to depths below 1 m.

CHAPTER SIX

6.0 CONLUSIONS AND RECOMMENDATIONS

6.1 CONCLUSIONS

(i) The models developed for estimating biomass and volume in the mangrove ecosystem in Rufiji River Delta should significantly improve capacity to accurately estimate biomass and tree volume without harvesting trees.

(ii) Higher C storage in mangrove forest in Rufiji River Delta has been revealed and this suggests that conservation can significantly enhance carbon stocks, and could attract significant carbon based funding for land restoration.

(iii) Sustainable management of mangrove forests and their large C stocks is of high importance and climate change mitigation on which REDD+ can be based through avoiding deforestation of mangroves in Rufiji River Delta.

(iv) In the face of continued deforestation, the high carbon stocks in mangrove forests of Rufiji River Delta as shown by this study provide evidence that mangrove ecosystems are priority areas for conservation.

6.2 RECOMMENDATIONS

(i) Given differences in root extraction methods, more C studies especially belowground biomass in Rufiji River Delta in Tanzania is still needed.

(ii) Inclusion of dead wood in assessing C in the mangrove ecosystems in Rufiji River Delta is important in determining the full potential of this ecosystem to act as a carbon sink.

REFERENCES

Abohassan, R. A. A.; Okia, C. A.; Agea, J. G.; Kimondo, J. M. and McDonald, M. M. (2012). Perennial Biomass Production in Arid Mangrove Systems on the Red Sea Coast of Saudi Arabia. *Environmental Research Journal*, **6** (1): 22-31.

Alongi, D. M. (2008). Mangrove forests: Resilience, protection from tsunamis, and responses to global climate change. *Estuarine, Coastal and Shelf Science*, **76**: 1-13.

Alongi, D. M. (2002). Present state and future of the world's mangrove forests. *Environmental Conservation,* **29** (3): 331-349.

Basuki, T. M.; van Laake, P. E.; Skidmore, A. K. and Hussin, Y. A. (2009). Allometric equations for estimating the above-ground biomass in tropical lowland Dipterocarp forests. *Forest Ecology and Management,* **257**: 1684–1694.

Bouillon, S.; Borges, A. V.; Castaneda-Moya, E.; Diele, K.; Dittmar, T.; Duke, N. C.; Kristensen, E.; Lee, S. Y.; Marchand, C.; Middelburg, J. J.; Rivera-Monroy, V. H.; Smith, T. J III. and Twilley, R. R. (2008). Mangrove production and carbon sinks: a revision of global budget estimates. *Global Biogeochemical Cycling,* **22**: 1–12.

Brown, S. (2002). Measuring carbon in forests: current status and future challenges. *Environmental Pollution,* **116**: 363-372.

Burgess, N. D.; Bahane, B.; Clairs, T.; Danielsen, F.; Dalsgaard, S.; Funder, M.; Hagelberg, N.; Harrison, P.; Haule, C.; Kabalimu, K.; Kilahama, F.; Kilawe, E.; Lewis, S. L.; Lovert, J. C.; Lyatuu, G.; Marshall, A. R.; Meshack, C.; Miles, L.; Milledge, S. A. H.; Munishi, P. K. T.; Nashanda, E.; Shirima, D.; Swetnam, R. D.; Willcock, S.; Williams, A. and Zahabu, E. (2010). Getting ready for REDD+ in Tanzania: a case study of progress and challenges. *Fauna and Flora International, Oryx,* **44** (3): 339-351.

Cairns, M. A.; Brown, S.; Eileen, H.; Helmer, E. H. and Baumgardner, G. A. (1997). Root biomass allocation in the world's upland forests. *Oecologia*, **111**: 1-11.

Cerón-Bretón, J. G.; Ceron-Cerón-Bretón, R. M.; Rangel-Marron, M.; Muriel-Garcia, M.; Cordova-Quiroz, A. V. and Estrella-Cahuich, A. (2011). Determination of carbon sequestration rate in soil of a mangrove forest in Campeche, Mexico. *International Journal of Energy and Environment,* **3** (5): 328-336.

Chave, J.; Andalo, C.; Brown, S.; Cairns, M. A.; Chambers, J. Q.; Eamus, D.; Fo¨ lster, H.; Fromard, F.; Higuchi, N.; Kira, T.; Lescure, J.-P.; Nelson, B. W.; Ogawa, H.; Puig, H.; Rie´ra, B. and Yamakura, T. (2005). Tree allometry and improved estimation of carbon stocks and balance in tropical forests. *Oecologia,* **145**: 87-99.

Clough, B. (2013). *Continuing the Journey Amongst Mangroves*. ISME Mangrove Educational Book Series No. 1. International Society for Mangrove Ecosystems (ISME), Okinawa, Japan, and International Tropical Timber Organization (ITTO), Yokohama, Japan. 86 pp.

Comley, B. W. T. and McGuinnes, K. A. (2005). Above-and below-ground biomass, and allometry of four common northern Australian mangroves. *Australian Journal of Botany*, **53**: 431-436.

Cowie, J. (2007). *Climate Change. Biological and Human Aspects*. Cambridge University Press. Cambridge, UK. 487pp.

Donato, D. C.; Kauffman, J. B.; Murdiyarso, D.; Kurnianto, S.; Stidham, M. and Kanninen, M. (2011). Mangroves among the most carbon-rich forests in the tropics. *Nature Geoscience*, **4**: 293-297.

Donato, D. C.; Kauffman, J. B.; Mackenzie, R. A.; Ainsworth, A. and Pfleeger, A. C. (2012). Whole-island carbon stocks in the tropical Pacific: Implications for mangrove conservation and upland restoration. *Journal of Environmental Mangement*, **97**: 89-96.

Duke, N. C.; Meynecke, J. O.; Dittmann, S.; Ellison, A. M.; Anger, K.; Berger, U.; Cannicci, S.; Diele, K.; Ewel, K. C.; Field, C. D.; Koedam, N.; Lee, S.Y.; Marchand, C.; Nordhaus, I. and Dahdouh-Guebas, F. (2007). A world without mangroves? *Science*, **317**: 41-43.

Ebuy, J.; Lokombe, J. P.; Ponette, Q.; Sonwa, D. and Picard, N. (2011). Allometric equation for predicting aboveground biomass of three tree species. *Journal of Tropical Forest Science,* **23** (2): 125-132.

FAO. (2007). The World's Mangroves 1980-2005. A Thematic Study prepared in the framework of the Global Forest Resources Assessment 2005. FAO Forest Paper No. 153. [ftp://ftp.fao.org/docrep/fao/010/a1427e/a1427e00.pdf] Site accessed on 9/1/2012.

FAO. (2010). Global Forest Resources Assessment 2010. Main report. Food and Agriculture Organization. Forest Paper No. 163. Rome, Italy. [http://www.ipex.org/files/global_forest_resources.pdf] Site accessed on 9/1/2012.

Faridah-Hanum, I.; Kudus, K. A. and Saari, N. S. (2012). Plant diversity and biomass of Marudu Bay Mangroves in Malaysia. *Pakistan Journal of Botany*, **44**: 151-156.

Fromard, F.; Puig, H.; Mougin, E.; Marty, G.; Betoulle, J. L. and Cadamuro, L. (1998). Structure, above-ground biomass and dynamics of mangrove ecosystems: new data from French Guiana. *Oecologia,* **115**: 39–53.

Gandaseca, G.; Chandra, I. A. and Abu Hena, M. K. (2011). Aboveground Biomass Production of *Rhizophora apiculata* Blume in Sarawak Mangrove Forest. *American Journal of Agricultural and Biological Sciences*, **6** (4): 469-474.

Gibbs, H. K.; Brown, S.; Niles, J. O. and Foley, J. A. (2007). Monitoring and estimating tropical forest carbon stocks: making REDD a reality. *Environmental Resources Letter*, **2**: 1-13.

Giri, C.; Ochieng, E.; Tieszen, L. L.; Zhu, Z.; Singh, A.; Loveland, T.; Masek, J. and Duke, N. (2011). Status and distribution of mangrove forests of the world using earth observation satellite data. *Global Ecology and Biogeography,* **20**: 154–159.

Green, C.; Brian, T.; O'Shea, M.; Edward P. F. and Kenneth A. B. (2007). Above- and belowground biomass measurements in an unthinned stand of Sitka spruce (Picea sitchensis (Bong) Carr.). *European Journal of Forest Resources*, **126**: 179–188.

Hannah, L. and Lovejoy, T. (2011). Conservation, Climate Change, and Tropical Forests. In: Bush, M. B., Flenley, J. R. and Gosling, W. D. (Editors). *Tropical Rainforest Responses to Climatic Change* (Second Edition). Springer-Verlag Berlin Heidelberg. pp 431- 443.

IPCC. (2007). *Climate change* 2007. *The physical science basis: Contribution of Working Group I to the Fourth Assessment Report of the IPCC.* Cambridge University Press: Cambridge, UK.

Kauffman, J. B. and Donato, D. C. (2012). Protocols for the measurement, monitoring and reporting of structure, biomass and carbon stocks in mangrove forests. Working Paper No. 86. Center for International Forestry Research, Bogor, Indonesia. [http://www.cifor.org/publications/ pdf_files/WPapers/ WP86 CIFOR.pdf] Site accessed on 20/03/2012.

Kauffman, J. B.; Heider, C.; Cole, T. G.; Dwire, K. A. and Donato, D. C. (2011). Ecosystem Carbon Stocks of Micronesian Mangrove Forests. *Wetlands,* **31**: 343-352.

Komiyama, A.; Ong, J. E. and Poungparn, S. (2008). Allometry, biomass, and productivity of mangrove forests: A review. *Aquatic Botany*, **89**: 128-137.

Komiyama, A.; Paungparn, S. and Kato, S. (2005). Common allometric equations for estimating the tree weight of mangroves. *Journal of Tropical Ecology*, **21**: 471-477.

Komiyama, A.; Havanond, S.; Srisawatt, W.; Mochida, Y.; Fujimoto, K.; Ohnishi, T.; Ishihara, S. and Miyagi, T. (2000). Top/root biomass ratio of a secondary mangrove (*Ceriops tagal* (Perr.) C.B. Rob.) forest. *Forest Ecology Management*, **139**: 127-134.

Komiyama, A.; Ongino, K.; Aksornkoae, S. and Sabhasri, S. (1987). Root biomass of a forest in Southern Thailand.1. Estimation by trench method and zonal structure of root biomass. *Journal of Tropical Ecology*, **3**: 97-108.

MacDicken, G. K. (1997). A Guide to Monitoring Carbon Storage in Forestry and Agroforestry Projects. Winrock International Institute for Agricultural Development. 87pp.

Malimbwi, R. E.; Solberg, B. and Luoga, E. (1994). Estimation of biomass and volume in miombo woodlands at Kitulang'alo forest reserve, Tanzania. *Journal of Tropical Forest Science,* **7** (2): 230-242.

Matsui, N.; Morimune, K.; Meepol, W. and Chukwamdee, J. (2012). Ten Year Evaluation of Carbon Stock in Mangrove Plantation Reforested from an Abandoned Shrimp Pond. *Forests*, **3**: 431-444.

Mattia, S. B. and Malimbwi, R. E. (1999). Structure of Natural Mangrove Forests at Rufiji Delta, Tanzania. In: *Proceedings of SUA/AUN Workshop on Tanzania Forestry Sector: Problems and Possible Solutions*. (Edited by Malimbwi, R. E. and Nsolomo, V. R.), 23-26 March 1998, Olmotonyi, Arusha, Tanzania. 202-210pp.

Mhamilawa, M. E. (2004). State of Mangroves in Tanzania Coast: European Joint Master in Water and Coastal Management. Universidade do Algarve. 2004-2005.[http://www.freewebs.com/arbmwcnetwork/Tanzania.pdf] Site visited on 20/01/2012.

Mkindi, A. R. and Meena, H. E. (2005). Rufiji District Residents and Adaptation to Environmental Changes over Time. Envirocare. CEEST Foundation. 14pp.

Munishi, P. K. T.; Mringi, S.; Shirima, D. D. and Linda, S. K. (2010a). The Role of the Miombo Woodlands of the Southern Highlands of Tanzania as carbon sinks. *Journal of Ecology and the Natural Environment,* **2** (12): 261-269.

Munishi, P. K. T.; Temu, R. P. C.; Shirima, D. D.; Lulandala, L. L.; Mbilinyi, B.; Mtengeti, E.; Moe, S. R.; Totland, O.; Mwakalila.; S. and Mpeta, A. (2010b). Quantification and Mapping of Carbon Stocks and Plant Diversity in Different Land Cover Types in Tanzania. A Research Proposal Submitted to Climate Change Impacts, Adaptation and Mitigation Programme. Sokoine University of Agriculture. 59pp.

Munishi, P. K. T. and Shear, T. H. (2004). Carbon Storage in Afromontane Rainforests in the Eastern Arc Mountains of Tanzania: their net contribution to atmospheric carbon. *Journal of Tropical Forest Science,* **16** (1): 78-93.

Munishi, P. K. T.; Mhagama, M.; Muheto, R. and Andrew, S. M. (2001). The role of Urban Forestry in Mitigating Climate Change and Performing Environmental Services in Tanzania. *Tanzania Journal of Forestry and Nature Conservation,* **77**: 25-34.

Murdyaso, D.; Donato, D.; Kauffman, J. B.; Kurnianto, S.; Stidham, M. and Kanninen, M. (2010). Carbon storage in mangrove and peatland ecosystems. A preliminary account from plots in Indonesia. Working paper 48. Center for International Forestry Research, Bogor, Indonesia. 35pp [www.nrs.fs.fed.us/pubs/jrnl/2009/nrs_2009_murdiyarso_001.pdf] Site accessed on 20/02/2012.

Mwalyosi, R. B. B. (2002). Management of the Rufiji - Delta as a wetland. Institute of Resource Assessment. University of Dar es Salaam. Tanzania [http://www.oceandocs.org/bitstream/1834/532/1/Wetlands114124.pdf] Site accessed on 8/7/2012.

Nguyen,T. C.; Ninomiya, I.; Long, N. T.; Tri, N. H.; Tuan, M. S. and Hong, P. N. (2009). Belowground carbon accumulation in young *Kandelia candel* (L.) Blanco plantations in Thai Binh River Mouth, Northern Vietnam. *International Journal of Ecological Development*, **12**: 107-117.

Ochieng, C. A. (2002). Research Master Plan for the Rufiji Flood Plain and Delta 2003-2013. Technical Report No. 28. Rufiji Environmental Management Project. 79 pp.

Ong, J. E. and Gong, W. K. (2013). *Structure, Function and Management of Mangrove Ecosystems*. ISME Mangrove Educational Book Series No. 2. International Society for Mangrove Ecosystems (ISME), Okinawa, Japan, and International Tropical Timber Organization (ITTO), Yokohama, Japan. 71pp.

Ong, J. E.; Gong, W. K. and Wong, C. H. (2004). Allometry and partitioning of the mangrove, *Rhizophora apiculata. Forest Ecology and Management,* **188**: 395–408.

Pandey, C. N. and Pandey, R. (2013). Carbon sequestration by Mangroves of Gujarat, India. *International Journal of Botany and Research*, **3** (2): 57-70.

Patil, V.; Singh, A.; Naik, N.; Seema, U. and Sawant, B. (2012). Carbon sequestration in mangroves ecosystems. *Journal of Environmental Resources Development*, **7**: 576-583.

Pearson, T. R. H.; Brown, S. L. and Birdsey, R. A. (2007). Measurement Guidelines for the Sequestration of Forest Carbon. General Technical Report, NRS-18. Newtown Square, PA: USDA, Forest Service, Northern Research Station. 42 pp [http://www.nrs.fs.fed.us/] Site accessed on 19/01/2012.

Pethick, J. and Spencer, T. (1990). Mangrove response to sea level rise. The Rufiji Delta, Tanzania. Frontier Tanzania. Interim Report. 7pp.

Ritson, P. and Sochacki, S. (2003). Measurement and prediction of biomass and carbon content of *Pinus pinaster* trees in farm forestry plantations, south-western Australia. *Forest Ecology and Management*, **175**: 103-117.

Ross, M. S.; Ruiz, P. L.; Telesnicki, G. J. and Meeder, J. F. (2001). Estimating above-ground biomass and production in mangrove. *Wetlands Ecology and Management,* **9**: 27–37.

Sawadogo, L.; Savadogo, P.; Tiveau, D.; Zida, S. D. D. D.; Nouvellet, Y.; Oden, P. C. and Guinko, S. (2010). Allometric prediction of above-ground biomass of eleven woody tree species in the Sudanian savanna-woodland of West Africa. *Journal of Forestry Research*, **21** (4): 475-481.

Segura, M. and Kanninen, M. (2005). Allometric Models for Tree Volume and Total Aboveground Biomass in a Tropical Humid Forest in Costa Rica. *Biotropica,* **37** (1): 2–8.

Shirima, D. D.; Munishi, P. K. T.; Lewis, S.; Burgess, N.; Marshall, A.R.; Balmford, A.; Swetnam, R. D. and Zahabu, E. M. (2011). Carbon storage, structure and composition of Miombo woodlands in Tanzania's Eastern Arc Mountains. *African Journal of Ecology,* **49** (3): 332-342.

Snowdon, P.; Raison, J.; Grierson, P.; Adams, M.; Montagu, K.; Bi, H.; Burrows, W. and Eamus, D. (2002). Protocol for sampling tree and stand biomass. National Carbon accounting system technical report No. 31. Australian Greenhouse Office, Canberra. [citeseerx.ist.psu.edu/ viewdoc/ download? doi=10.1.1.116.263] Site accessed on 14 June 2013.

Soares, M. L. G and Schaeffer-Novelli, Y. (2005). Above-ground biomass of mangrove species.I. Analysis of models *Estuarine, Coastal and Shelf Science,* **65**: 1-18.

Subedi, B. P.; Pandey, S. S.; Pandey, A.; Rana. E. B.; Bhattarai, S.; Banskota,T. R. S.; Tamrakar, C. R. (2010). Forest Carbon Stock Measurement: Guidelines for measuring carbon stocks in community-managed forests. Asia Network for Sustainable Agriculture and Bioresources (ANSAB), Kathmandu, Nepal 69pp.

Suzuki, E. and Tagawa, H. (1983). Biomass of a mangrove forest and a sedge marsh on Ishigaki Island, Southern Japan. *Japanese Journal of Ecology*, **33**: 231-234.

Swai, G.; Ndangalasi, H.J.; Munishi, P.K.T. and Shirima, D.D. (2014). Carbon stocks of Hanang forest, Tanzania: An implication for climate mitigation. *Journal of Ecology and the Natural Environment*, **6** (3): 90-98.

Tamooh, F.; Huxham, M.; Karachi, M.; Mencuccini, M.; Kairo, J. G. and Kirui, B. (2008). Below-ground root yield and distribution in natural and replanted mangrove forests at Gazi bay, Kenya. *Forest Ecology and Management*, **256**: 1290-1297.

Taylor, M.; Ravilious, C. and Green, E. P. (2003). *Mangroves of East Africa*. UNEP World Conservation Monitoring Centre. Cambridge, United Kingdom. 26 pp.

Tibor, V.; Megan, J.; Linwood, P. and Brian, M. (2014). *Mangrove Ecosystem Services Valuation: State of the Literature.* NI WP 14-06. Durham, NC: Duke University.

Turner, K. and Jones, T. (1991). (Editors). *Wetlands: Market and Intervention Failures*. Earthscan Publications Ltd. London. 202pp.

Twilley, R. R.; Chen, R. H. and Hargis, T. (1992). Carbon Sinks in Mangroves and their Implications to the Carbon Budget of Tropical Coastal Ecosystems. *Water, Air and Soil Pollution*, **64**: 265-288.

Wang, J.; Zhang, C.; Xia, F.; Zhao, X.; Wu, L. and Gadow, K. v. (2011). Biomass Structure and Allometry of *Abies nephrolepis* (Maxim) in Northeast China. *Silva Fennica*, **45** (2): 211–226.

APPENDICES

Appendix 1: Data sheet for tree stem measurements in plots

Location..... Date.....

Stratum No	PSP No	Sub-plot	Stem No	Latin Name	Local Name	DBH	POM	Height	Notes

Appendix 2: Data sheet for aboveground destructive sampling

Billet No.	**Stems**				**Branches**			
	Length (cm)	Mid Diameter (cm)	GW (Kg)	DW (Kg)	Length (cm)	Mid Diameter (cm)	GW (Kg)	DW (Kg)

Appendix 3: Mangrove species of Rufiji River Delta, Tanzania

S/N	Species	Family	Vernacular name
1	*Avicennia marina*	Aviceniaceae	Mchu
2	*Bruguiera gymnorrhiza*	Rhizophoraceae	Msinzi
3	*Ceriops tagal*	Rhizophoraceae	Mkandaa
4	*Heritiera littoralis*	Steculiaceae	Msikundazi
5	*Lumnitzera racemosa*	Combretaceae	Mtong'oto
6	*Rhizophora mucronata*	Rhizophoraceae	Mkaka/Mkoko
7	*Sonneratia alba*	Sonneratiaceae	Mpira
8	*Xylocarpus granatum*	Meliaceae	Mkomafi

Appendix 4: Data sheet for belowground biomass (roots)

Tree No	Name	Diameter (cm)	Root No	RCD (cm)	GW (Kg)	DW (Kg)

Appendix 5: Biomass (kg) allocation in different mangrove tree components

S/N	Species	DBH (cm)	Stems	Branches	Leaves & twigs	BGB
1	*Heritiera littoralis*	37.7	606.90	58.57	40.53	287.22
2	*Heritiera littoralis*	19.3	123.13	9.68	7.14	41.92
3	*Heritiera littoralis*	15.4	55.83	16.12	10.37	35.63
4	*Heritiera littoralis*	10.6	24.30	1.36	1.13	9.46
5	*Heritiera littoralis*	45.8	658.26	53.41	23.15	452.13
6	*Rhizophora mucronata*	25	215.90	86.99	12.32	114.99
7	*Ceriops tagal*	14.1	42.26	11.72	5.59	73.86
8	*Rhizophora mucronata*	32.4	341.31	261.56	39.86	201.76
9	*Xylocarpus granatum*	10.1	31.33	13.92	1.07	9.65
10	*Avicennia marina*	23.2	234.99	18.82	12.35	75.50
11	*Sonneratia alba*	20.1	187.12	11.36	0.16	34.34
12	*Avicennia marina*	55.6	624.01	118.25	35.35	710.51
13	*Avicennia marina*	21.7	256.48	29.99	11.25	96.0567
14	*Avicennia marina*	42.8	484.46	87.95	24.59	386.08
15	*Avicennia marina*	32.5	581.53	72.07	18.10	203.22
16	*Sonneratia alba*	23.7	201.32	67.60	6.60	97.33
17	*Sonneratia alba*	18.9	96.33	4.12	0.82	57.43
18	*Sonneratia alba*	16.6	127.50	6.65	0.89	89.62
19	*Sonneratia alba*	22.2	156.76	41.98	7.89	83.57
20	*Xylocarpus granatum*	13.7	50.69	13.38	0.89	25.75
21	*Xylocarpus granatum*	10.9	31.55	9.29	1.80	15.92

22	*Xylocarpus granatum*	26.4	239.05	57.04	13.13	125.17
23	*Xylocarpus granatum*	18.7	85.88	20.61	5.41	56.02
24	*Rhizophora mucronata*	20.7	152.79	28.80	5.13	71.00
25	*Rhizophora mucronata*	31.6	634.09	36.44	16.98	190.34
26	*Rhizophora mucronata*	13.8	63.63	6.02	1.75	27.59
27	*Rhizophora mucronata*	21.3	166.88	19.18	8.38	107.64
28	*Avicennia marina*	13.4	67.95	6.76	0.68	25.8
29	*Bruguiera gymnorrhiza*	22	189.06	32.93	0.16	81.8
30	*Ceriops tagal*	18.6	101.73	6.78	1.45	98.45
31	*Ceriops tagal*	14.3	47.48	4.44	1.31	29.98
32	*Ceriops tagal*	14.8	57.13	12.23	4.12	32.48
33	*Ceriops tagal*	22.1	124.13	23.10	8.12	82.70
34	*Ceriops tagal*	13.3	50.17	7.33	1.34	25.31
35	*Bruguiera gymnorrhiza*	22.5	240.93	41.24	6.06	117.14
36	*Bruguiera gymnorrhiza*	15.8	98.65	14.19	1.17	83.92
37	*Bruguiera gymnorrhiza*	14.4	57.24	27.95	2.83	30.47
38	*Bruguiera gymnorrhiza*	34	291.14	56.26	8.61	84.35
39	*Lumnitzera racemosa*	19.3	31.89	9.12	4.76	93.00
40	*Lumnitzera racemosa*	10	27.28	1.53	2.67	5.28
41	*Lumnitzera racemosa*	20.6	31.80	5.21	3.54	70.20
42	*Lumnitzera racemosa*	8.1	9.74	1.32	6.62	7.97
43	*Lumnitzera racemosa*	36.3	229.94	5.59	4.46	102.00
44	*Lumnitzera racemosa*	17.2	21.37	4.82	3.62	46.10

45	*Lumnitzera racemosa*	23.4	103.34	24.27	10.68	94.49
46	*Heritiera littoralis*	14.9	40.73	10.29	14.46	32.99
47	*Heritiera littoralis*	19.6	81.15	14.17	5.57	62.51
48	*Bruguiera gymnorrhiza*	25.6	364.11	27.66	29.32	116.50
49	*Xylocarpus granatum*	18.7	65.32	26.53	9.69	56.02
50	*Sonneratia alba*	9	19.70	0.00	0.00	10.19
	Total		**8826.30**	**1526.61**	**443.85**	**5069.34**
	% contribution		**55.63**	**9.62**	**2.80**	**31.95**