ASSESSMENT OF THE STRUCTURE AND BIOMASS ACCUMULATION IN MANGROVE FOREST OF KILIFI CREEK, KENYA

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A Thesis submitted in partial fulfilment of the requirements for the Degree of Masters in Environmental Science of Pwani University

FEBRUARY, 2016

DECLARATION

I declare that this is my original work and not a duplication of any existing work and has never been submitted to this or any other University for the award of any certificate to the best of my knowledge.

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DEDICATION

I wish to express gratitude to my family, mom Roshanbai Hasham, brother Said & sister Fatma for their continuous support all through my study period.

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ABSTRACT

Mangroves are typical marine ecosystems in tropical and sub-tropical coasts and are one of the most productive systems in the world. In Kenya, mangroves have formed well developed forests in sheltered coastlines such as bays, creeks and estuaries as well as in deltas. This study assessed quantitatively the structure and biomass accumulation of the mangrove vegetation of Kilifi Creek. The study also estimated the above and below ground biomass accumulation in Kilifi mangrove forest. Forest structure was analyzed using the quadrat method where belt transects were laid perpendicular to the shoreline at Kibokoni and Maya covering different vegetation types. A total of 152 quadrants were laid along 10 transects at Kibokoni and 145 quadrants along 9 transects at Maya. The stand density varied between 1,488 trees ha^{-1} and 1,849 trees ha^{-1} between the two sites representing Kilifi creek. Six of the nine mangrove species found in Kenya were observed in Kilifi. These included; *Avicennia marina* (Forsk.) Vierh. (Acanthaceae), *Bruguiera gymnorrhiza* (L.) Lam., *Ceriops tagal (perr.)* C. B. Rob., *Rhizophora mucronata* Lam. (Rhizophoraceae), *Sonneratia alba* Sm. and *Xylocarpus granatum* J. Konig. Based on species importance value (I.V), the dominant mangrove species were *R. mucronata* and *A. marina* which is typical of mangrove forests in Kenya. The allometric equation which uses stem diameter and specific wood density as predictive variables with high coefficient of determination (r^2) of 0.979 and 0.954 respectively was used in estimating the above and below ground biomass accumulation. In comparison of the four dominant mangroves species, *R. mucronata* had the highest tree biomass accumulation of 85.7 ± 16.3 Mg ha^{-1}. This was followed by *A. marina* with 69.6 ± 12.1 Mg ha^{-1}. *Sonneratia alba* had 65.6 ± 12.3 Mg ha^{-1} while *C. tagal* reported a value of 53.5 ± 16.4 Mg ha^{-1}. There were significant differences in above ground and below ground biomass accumulation across the two sites with ($F_{(1, 4)} = 5.21$, $\rho < 0.05$) and ($F_{(1, 4)} = 7.25$, $\rho < 0.05$) respectively. Total biomass accumulation was similarly significantly different across the two sites ($F_{(1, 4)} = 5.12$, $\rho < 0.05$). A root: shoot biomass accumulation ratio of 1:2.7 was calculated for the whole of Kilifi creek mangrove forest. The findings of this study show the structural vegetation composition and estimates of tree mangrove biomass which can be utilized for conservation through negotiation of carbon credits in the carbon market and will aid in developing management strategies.

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ABBREVIATIONS

AAC:	Annual Allowable Cut
AGB:	Above Ground Biomass
AGC:	Above Ground Carbon
BGB:	Below Ground Biomass
BGC	Below Ground Carbon
$CO_{2:}$	Carbon dioxide
DBH:	Diameter at Breast Height
FAO:	Food and Agricultural Organization of the United Nations
GOK:	Government of Kenya
GPS:	Global Positioning System
ITCZ:	Inter-Tropical Convergence Zone
PES:	Payment for Ecosystem Service
RC:	Regeneration Class
REDD+:	Reducing emissions from avoided deforestation and forest degradation
TB	Total Biomass
TC	Tree Carbon
UNEP:	United Nation Environment Programme

DEFINITION OF TERMS

Annual allowable cut	A level of wood lot harvest permitted annually based on environmental, economic and social factors.
Carbon stock	This refers to the total amount of organic carbon stored in an ecosystem of a known size.
Climate change	The alteration in weather patterns due to natural variability or as a result of human activity.
DBH	Diameter at breast height, also known as D130.
Deforestation	Destruction and clearance of forests land to non-forest uses.
Disturbance	A temporary change in environmental conditions that results in a pronounced change in an ecosystem.
Forest management plan	A definite plan that applies best forestry practices and principles over space and time for sustainable forest conservation.
Forest sustainability	Exploitation of forestry resources without compromising the needs of the future generations.
Tree biomass	The quantity of organic matter in vegetation classified as trees including foliage, trunk, roots and branches.

CHAPTER ONE: BACKGROUND INFORMATION

1.0 Introduction

The term ‘mangrove’ has been broadly used to refer to both a type of plant and as an ecosystem. As ecosystems, mangroves are typical wetland ecosystems distributed worldwide on sheltered tropical and sub-tropical coastlines (Ellison *et al.,* 1999). Globally, there exist 50–75 species of mangrove in 20–26 genera found in about 16–20 families (Kathiresan and Bingham, 2001). Mangroves are globally valuable for both ecological and economic significances. They provide important habitats and feeding grounds for a range of benthic and pelagic marine animals and bird species (Nagelkerken *et al*., 2008). Mangroves are also important in climate regulation, nutrient cycling, shoreline protection and the provision of building materials and fuel wood (Alongi, 2008). They also play a key role in climate change mitigation and act as carbon sinks (Ong, 1993) capable of sequestrating on average more than 1,000 Mg C ha^{-1} (Bouillon *et al.*, 2008). However, it is estimated that the global range of mangrove forests has declined to less than 50% of the original total cover (FAO, 2005; Duke *et al*., 2007) augmenting enormous losses of forest biomass and consequent carbon sinks (Azyleah *et al.,* 2014). In Kenya, mangrove forests are threatened with degradation, with significant areas being lost over the past decade (Kairo *et al.,* 2002; Abuodha and Kairo, 2001), representing substantial carbon stock losses.

Mangroves are very dynamic and are subject to temporal changes in structure and composition. These changes may impact on the ecosystems structure, functions and human livelihoods (Walters *et al.*, 2008). Such changes might be as an immediate response of direct human influences due to over-exploitation (Rakotomavo and Fromard, 2010). Climate change has also been linked as a major threat to mangroves (Gilman *et al*., 2008) with adverse impacts such as rising of sea level which may pose great challenges to mangrove forests especially in low-lying areas (Nicholls and Lowe, 2004; Mimura *et al*., 2007) and cause possible ecosystem shifts characterized by changes in species composition and distribution (Kairo *et al*, 2002). The alarming trends in climate change impacts has led to interest in defining the role of mangroves in carbon sequestration in a bid to curb climate change impacts (Donato *et al.*, 2011). Reduced emissions from avoided deforestation and degradation (REDD+) represents international policies that aim at addressing issues of forest degradation, conservation and sustainable management. Under the REDD+ carbon credit mechanism, nations willing to reduce emissions from forest deforestation will be offered compensation. This will contribute to climate change mitigation as well as improving the livelihoods of communities dependent on the forests, thus relieving pressure on mangrove resources (Bosire *et al.*, 2013).

Mangroves in Kilifi Creek and Kenya at large are increasingly declining, accounting to an overall loss of 18% in the period between 1985 and 2000 (Kirui *et al*., 2013). Hence, there is a need to understand the mangrove vegetation structure with the purpose of predicting changes in future to aid forest management by providing site-specific quantitative vegetation data (Dahdouh-Guebas *et al*., 2000). Along the Kenyan Coast, comprehensive quantitative data on Kilifi mangroves is lacking (Bundotich, 2007) and this study aimed at bridging the gap. The study sought to establish the mangrove forest status through vegetation structure and biomass accumulation estimates, ultimately propose appropriate management measures for conservation of mangrove forests. The study also further sought to estimate the carbon stock as sequestered carbon can be traded as carbon credits thus support conservation and contribute to rural development.

1.1 Statement of the problem

Mangroves in Kenya are increasingly declining with Kilifi Creek accounting for the highest mangrove loss of 76% in the period between 1985 and 2000 (Kirui *et al*., 2013). This is mainly due to unsustainable utilization approaches, coupled by population pressure which increases the local demand for mangrove products. This negatively impacts on the ecosystem structure and its resilience to disturbances leading to loss of carbon sinks which mitigate against climate change impacts. Therefore, this necessitates the development of sustainable management strategies. However, inadequate site specific up-to-date quantitative data to effectively guide sustainable forest management plans is currently lacking for Kilifi mangroves.

1.2 Study rationale

Mangroves in Kenya are recognized as threatened by degradation. In Kilifi, the true status of the mangrove forest remains unknown and characterized with high degradation rates. Hence, there is an information gap which calls for bridging to help develop baseline inventory data for effective forest management and conservation. Ultimately, structural assessment will contribute to the development of sustainable mangrove forest management plan. In addition, knowledge on vegetation structure and regeneration potential is a pre-requisite to designing efficient forestry directives like AAC (annual allowable cuts) and designating periodic specific cutting areas for sustainable harvesting.

Accurately quantified carbon stock of Kilifi mangrove forest is lacking and this study sought to bridge the gap and aid to define their potential role in climate change mitigation as mangrove degradation will ultimately lead to subsequent carbon sink losses. Additionally, sequestered carbon can further be traded in the carbon market as carbon credits and thus support sustainable conservation and improving community livelihoods under the carbon financing scheme (REDD+). Accurately quantified carbon stocks of these forests will aid to define their potential role in climate change mitigation and form a platform to prompt further research in carbon sequestration in mangroves and curbing climate change.

1.3 Broad objective

The broad objective of the study was to determine the status of the vegetation structure and estimate the biomass accumulation of Kilifi mangrove forest so as to effectively guide sustainable forest conservation and management.

1.3.1 Specific objectives

1. To assess the forest structure of Kilifi mangrove forest.
2. To determine the variation between the above and below ground biomass accumulation in Kilifi mangrove forest.
3. To determine the variation in total biomass accumulation in Kilifi mangrove forest.
4. To model the future condition of Kilifi mangrove forest based on the current status of mangroves.

1.4 Research hypothesis

H_o: There is no significant difference in the structure of Kilifi mangrove forest.

H_o: There is no significant difference between the above and below ground biomass accumulation in Kilifi mangrove forest.

H_o: There is no significant difference in total biomass accumulation in Kilifi mangrove forest.

1.5 Conceptual framework of the study

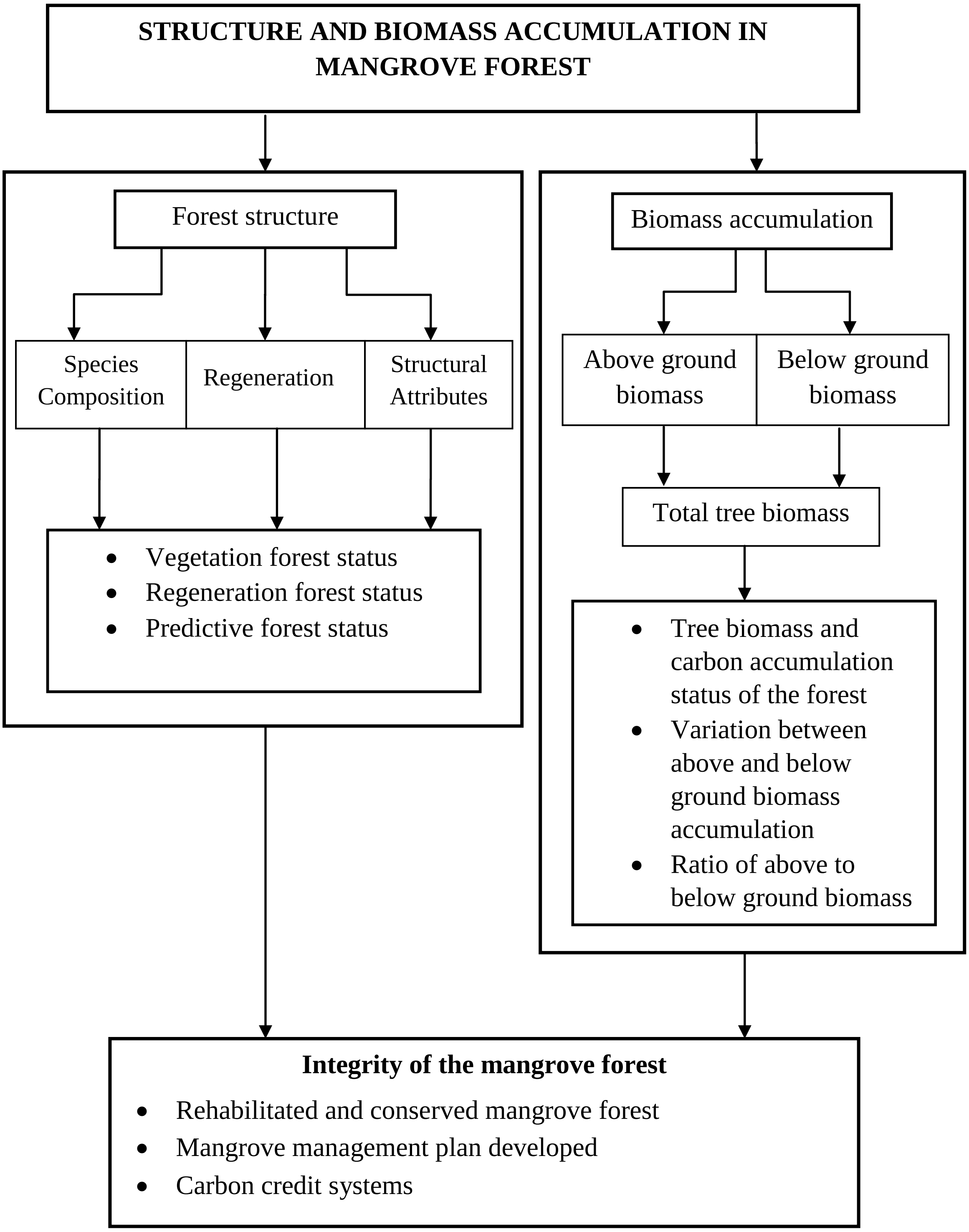

Fig.1**:** A flow chart outlining the conceptual framework of the thesis.

The framework adopted for the study entails a broad outlook on the structural vegetation and biomass accumulation of Kilifi mangroves. The structural attributes of the vegetation and regeneration was assessed in chapters 4 and 5. Biomass accumulation estimates is also outlined in chapter 4. The chapter assessed the mangrove structural composition and estimated the above, below ground biomass and their ratios with the corresponding carbon accumulation estimates. A conceptual model for the structure of the thesis is shown in Fig. 1 above.

1.6 Scope and limitation of the Study

- The mangroves of Kilifi Creek are naturally separated into two main tidal creeks, Kibokoni and Maya respectively. In the framework of this study these two tidal creeks were sampled separately and compared. Kibokoni representing the eastern tidal creek while Maya constituting the western side.
- Difficulty in sampling some plots due to accessibility. This may affect the accuracy and precision of the results.

1.7 Ethical consideration in the study

- Some sampling sites were not sampled in the Kilifi mangrove forest due to the presence of socio-cultural sites locally known as “Kayas” by the Miji Kenda communities.

CHAPTER TWO: LITERATURE REVIEW

2.0 Introduction

This chapter reviews relevant literature on mangroves forest structure and biomass dynamics.

2.1 Importance of mangroves

Mangroves provide a wide range of ecosystem goods and services. They provide wood products for construction, firewood and other non-timber products such as fish, shrimps and crabs (Walters, 2005). Ecologically, mangroves are spawning grounds for fish, as well as feeding habitats for numerous migratory birds (Nagelkerken *et al*., 2008). In fisheries, mangrove ecosystems act as nursery and feeding grounds for commercial and artisanal fisheries. Mangroves also support other essential services including soil formation, photosynthesis, primary production, nutrient cycling and water cycling (Alongi, 2002). They also provide regulating benefits such as nutrient cycling, air quality regulation, and maintenance of biodiversity for ecosystem function. Mangrove ecosystems can sequester about five times more carbon than any forest terrestrial ecosystem (Donato *et al.,* 2012). They serve as carbon stores and sink (Ong, 1993). It has been estimated that mangroves store as much as 45 t C/ha (Bouillon *et al*., 2008) and sequester another 1.5 t C/ha/yr (Ong, 1993).

2.2 Mangrove environment and dynamics

Mangroves are vegetation types in the transitional zone from sea to land in extensive equatorial and (sub)tropical regions of the world and provide a habitat for many marine species (Nagelkerken *et al*., 2008). Mangroves mostly occur in deltas, creeks, protected bays, islands and river estuaries. They possess characteristics that make them structurally and functionally unique to adapt to these saline environments. They have various eco-physiological characteristics and adaptations such as aerial roots, viviparous embryos, tidal dispersal of propagules, rapid rates of canopy production, frequent absence of an under storey and the ability to cope with salt and to maintain water and carbon balance (Alongi, 2002). Mangrove forests are very dynamic over short time frames and display major structural differences in vegetation in less than 20 years (Giri *et al*., 2011) and must not be viewed as static entities. Vegetation dynamism is manifested by alteration in stand structure and composition over time (Alongi, 2008). Mangroves show apparent zonation of trees and other associated organisms across the intertidal seascape and many factors have been suggested to account for the phenomenon. These include salinity, soil type and chemistry, nutrient content, physiological tolerances, herbivory and competition (Smith, 1996). In light of individual trees, several factors operate in tandem to regulate plant growth, including temperature, nutrients, solar radiation, oxygen and water (Smith and Duke, 1987).

2.3 Mangrove structure

The magnitude and periodicities of forcing functions such as tides, nutrients, hydro-period and stresses such as cyclones, drought, salt accumulation and frost may significantly determine the community structure (Cintron and Schaefer-Novelli, 1984). As a result of the dynamic nature of mangroves, it is critical to assess the mangrove vegetation structure with the aim of predicting changes in the future for effective forest management and planning (Dahdouh-Guebas *et al.,* 2000). Hence, the de liocourt's exponential model has been utilized to infer the future forest status of Mangrove stands based on the current status in Tudor (Mohamed *et al.,* 2009), Tana delta (Bundotich, 2007) and Kiunga (Kairo *et al*., 2002). Its predictive nature makes it significant in the planning and sustainable management of the mangrove ecosystem (Githaiga, 2013).

The characterization of mangrove ecosystems and monitoring changes can also be done through the assessment of forest structure (Cintrón and Schaeffer-Novelli, 1984). Kairo *et al*., (2002) outlines some of the structural parameters used such as: tree height, stem diameter, basal area and diameter at breast height, from which other attributes like stand tables, regeneration rates, distribution patterns and complexity indices can be derived. A maximum stem diameter (D130) of over 80 cm and canopy heights of 35 m has been observed for mangrove forest in Kenya (Ferguson, 1993).

2.4 Human induced vegetation changes

Anthropogenic-induced changes on the structure of mangrove forests can be identified and monitored using natural change in stand succession and canopy structure (Alongi, 2002). Mangrove vegetation cover change is an indicator of degradation and can be used for ecological monitoring (Kairo *et al.,* 2001). The high presence of tree stumps in the forest can also portray the scale of human-induced degradation of mangrove stands (Kairo *et al*., 2002). However, the removal of mangroves can result in physical changes to a site, such as increased sediment salinity and reduced soil carbon (Lewis *et al*., 1995). This may inhibit natural regeneration, thus prompting restoration. The combination of forest's dynamism and its rejuvenation capacity provides an indication on the status of a forest and hence, guiding rehabilitation initiatives (Dahdouh-Guebas and Koedam, 2001). Similarly, anthropogenic influences may lead to alteration of mangrove forest structure resulting in species shifts due to selective harvesting (Kairo *et al*., 2002).

2.5 Natural regeneration

Mangroves have regenerative characteristics which make them adaptable, progressive and dynamic (Duke, 2001). This is mainly due to multitude stress factors linked with the tidal zone, and often impacted by terrestrial and river run-off (Bosire *et al.*, 2008). The linear regeneration sampling (LRS) technique provides an overview of the site regeneration potential in terms of seedling abundance, distribution and sizes (FAO, 1994). Seedlings above 40 cm in height are often referred to as "established regeneration", and those below are referred to as "potential regeneration" (FAO, 1994). Effective stocking is assessed by the relative presence, abundance and sizes of all regeneration classes. The most significant site conditions influencing natural regeneration include nature of the substrate, age of swamp, inundation class, salinity and sediments erosion and accretion (Duke, 2001). Gaps are common in mangroves. However, natural gaps in mangrove formations induce less severe physical and chemical changes than gaps formed by human disturbances (Clarke and Kerrigan, 2000), resulting in lowered regeneration (Allen *et al.*, 2001).

Mangrove regeneration is also negatively affected by propagule predation (Clarke and Kerrigan, 2002), incomplete removal of the over wood (detrimental to light demanding species) and scouring by drift wood (Duke, 2001). Silvi-cultural practices are adopted to enhance natural regeneration and diameter growth in mangroves through thinning to create openings (Devoe and Cole, 1998). Excessive physical damage during logging coupled with excess amount of debris from logging further threatens regeneration (Duke, 2001). Chong (1988) suggested that successful natural regeneration requires a minimum of 2,500 seedlings ha^{-1}. According to these figures, most of the previously studied mangrove forests in Kenya can be said to have successful natural regeneration (Bosire *et al.*, 2003).

2.6 Biomass accumulation

Mangroves are one of the most productive systems in the world with a mean global average of 218 $\pm$ 72 Tg C yr^{-1} (Bouillon *et al.*, 2008). They can sequester approximately 20 billion t C which exceeds the mean carbon stock (C-stock) in tropical upland, temperate, and boreal forests (Donato *et al.*, 2011). The overall productivity in mangroves is mainly dependent on the age of the forest, hydrodynamics, type of dominant species and topography in relation to geomorphology, latitude and climate

(Komiyama *et al.*, 2008). Most biomass work in mangroves has focused on above ground biomass with limited study on below-ground (Donato *et al*., 2011). There are very few allometric equations for below ground biomass of mangrove forests and that explains why they are among the least studied forests (Howard *et al*., 2014). Similarly, it is more difficult to collect and measure below ground biomass than above ground (Vogt *et al.*, 1998).

A large amount of biomass tends to be allocated below ground in mangroves compared to their terrestrial counterparts (Komiyama *et al*., 2000). Below-ground biomass may constitute less than 30% of the total biomass in terrestrial forests, while in mangroves root biomass makes up almost 40 – 60% of the total biomass (Saenger, 1982). On a global scale, mangrove forests in the tropics have much higher aboveground biomass than those in temperate areas (Duke *et al*., 2013). In terms of global estimates, Japan has an estimated above-ground biomass of 80.5 t ha^{-1} (Khan *et al*., 2009) and Sarawak Mangrove Forest in Malaysia with 116.8 t ha^{-1} (Chandra *et al*, 2011). In India, the estuarine complex along the Bay of Bengal reported a value of 60.0 - 117.7 t ha^{-1} (Kathiresan *et al*., 2013).

2.7 Threats to mangroves

Mangroves are prone to frequent threats caused by either natural or anthropogenic factors, which alters forest structure and characteristics (Ferwerda *et al*., 2007). Natural threats in mangroves may arise from events such as windstorms, lightning, frost damage, cyclones (Sherman *et al*., 2000). Climate change is manifested by increased temperatures, altered rainfall patterns, rising sea levels, and acidification of the ocean waters which may potentially pose great challenges to mangrove forests (Gilman *et al.*, 2008). Anthropogenic threats include population pressure, urban development, mining, aquaculture and overexploitation for timber, fish, and crustaceans (Alongi, 2002).

Diversion of freshwater and deteriorating water quality caused by pollutants and nutrients also pose a threat (Benfield *et al.*, 2005). Globally, mangrove cover is fast declining at 1 to 2% annually mostly due to conversion to agricultural fields, fishponds, saltpans and human settlement (Duke *et al.*, 2007). Increased demand of mangrove wood products, particularly for firewood and building poles, has led to degradation of forests in many areas along the Kenyan coast (Dahdouh-Guebas *et al.*, 2000; Bosire *et al.*, 2014), with an estimated loss of 10,310 ha either due to pollution or over-exploitation of resources (Abuodha and Kairo, 2001). Climate change has also been linked to the loss, particularly the 1997-98 ENSO which resulted in massive sedimentation causing vast destruction (Kitheka *et al.*, 2003).

2.8 Mangroves in Kenya

The Kenyan coastline extends from Kiunga (1° 39’’10.88” S) in the north to Vanga (4° 40‟35.36” S) in the south by 575 km. Mangroves are extensive on the northern Kenya coast around the Lamu archipelago (33,500 ha; ca. 67%) and permanent Tana/Sabaki river estuaries (3,045 ha) (Kairo, 2001). Smaller wetlands in the riverian regions of semi perennial and seasonal coastal rivers occur on the south coast, at Kwale (Shimoni-Vanga, Funzi Bay and Gazi Bay (8,375 ha), Mombasa (Port-Reitz, Tudor and Mtwapa Creeks, 2,490 ha) and Kilifi (Kilifi and Mida Creeks, 5,570 ha) (Mohamed *et al.,* 2009). There are two types of mangrove communities, as creek or fringe mangroves that occur along the Kenyan coast (Ruwa, 1993).The creek mangrove community is composed of mangrove trees that grow on low lying sedimentary shores in creeks and bays, and usually form well-developed forests that may show distinct species zonation. *R. mucronata* and *C. tagal* are dominant and occur in almost all mangrove formations. The rare species are *Heritiera littoralis* Dry and *Xylocarpus moluccensis* (Kairo, 2001).

A distinct zonation of species controlled by the tidal regime shows the following typical pattern from the sea to land *S. alba, R. mucronata, B. gymnorrhiza, C. tagal, A. marina, X. granatum, L. racemosa* and *H. littoralis* (Kairo, 2001). However, variability can be high leading to shifts in zonation patterns (Dahdouh-Guebas *et al.*, 2002). Quantitative assessments studies in Kenya have also been done in Kiunga (Kairo *et al.*, 2002), Tana River (Bundotich, 2007), Mida (Kairo *et al*., 2002), and Gazi bay (Bosire *et al.*, 2003). The current study aims at complementing the quantitative studies in the other coastal areas.

2.9 Mangrove management in Kenya

The Draft Forest Policy (Sessional Paper No. 1 of 2007), the Forests Act, 2005 and the KFS Strategic Plan (2009/2014) provides the legal framework for the management of forest resources in the Kenya. Mangroves were originally gazetted in Kenya as forests in 1932. The Forest Department, now re-established as the Kenya Forest Service (KFS) under the Forestry Act is particularly responsible for mangrove management in Kenya (GOK, 2007). However, coastal resource management in Kenya is governed by several legislations covering various sectors.

The Wildlife Conservation and Management Act, 2013 provides for the sustainable use and management of wildlife and their habitats. Hence, legal jurisdiction is also bestowed on Kenya Wildlife Service when mangroves occur within Marine Protected Areas (MPAs). These include the Watamu Marine National Park and Reserve (Mida Creek), the Kiunga Marine National Reserve and the Tana River Primate Reserve (Wells *et al.*, 2007).

The Fisheries Act (Cap 378 of 2012) provides for the development, management, exploitation, utilization and conservation of fisheries resources in Kenya. Article 50 (1) and 59 of the subsidiary regulations also has provisions for the protection of fish breeding areas including mangroves. The Environment Management and Coordination No. 8 of 1990 and No. 5 amended in 2005, led to the creation of the National Environmental Management Authority (NEMA), consolidates statutes on sustainable conservation and management of the environment, particularly the marine environment.

The Constitution of Kenya 2010 also offers guiding principles on the governance of the environment. Article 60 (1) (e) provides for sound conservation and protection of ecologically sensitive areas, including mangroves. Internationally, Kenya is a party to several conventions including the Convention on Biological diversity, Convention of the Law of the Sea, Ramsar Convention, 1971 and the United Nations Framework Convention on Climate Change.

CHAPTER THREE: MATERIALS AND METHODS

3.0 Introduction

This chapter provides information on the study area and defines the research design, sampling procedure and the data analysis.

3.1 Study area description

Kilifi Creek is located in Kilifi County, 55 km north of Mombasa city, Kenya and approximately 35 km South of Malindi town. The creek has an estimated area of 600ha with a narrow opening towards the ocean and occupies 22.4 km^2 (Sigana *et al.*, 2009). The deepest part of the creek is approximately 38 m wide at the entrance and a distance of about 4 km (500 m wide) separates the ocean from an open lagoon locally known as Bahari ya Wali. The Western side of the creek is extensively covered with mangrove trees of different species covering an area of approximately 360 ha. There are two main water channels Ndzovuni and Rare winding in between the mangrove forest to form the Konjora which leads into Bahari ya Wali. There is no clear zonation displayed by the dominant mangrove species in Kilifi Creek.

The Creek is home to six mangrove species and covers an estimated 600 hectares (Cohen *et al*., 2013). The mangroves of Kilifi creek are naturally separated into two main tidal creeks, Kibokoni and Maya respectively. In the framework of this study these two tidal creeks were sampled separately and compared. Kibokoni representing the eastern tidal creek while Maya constituting the western side. The creek is bordered by a steep cliff overlooking a tidal flat that extends to the mudflats occupied by the vast mangrove forest. It is also one of the largest creek systems along the Kenyan Coast, comprising various biotopes that include patches of coral reef, mudflats with and without seaweeds and estuarine ecosystems (Sigana *et al*., 2009).

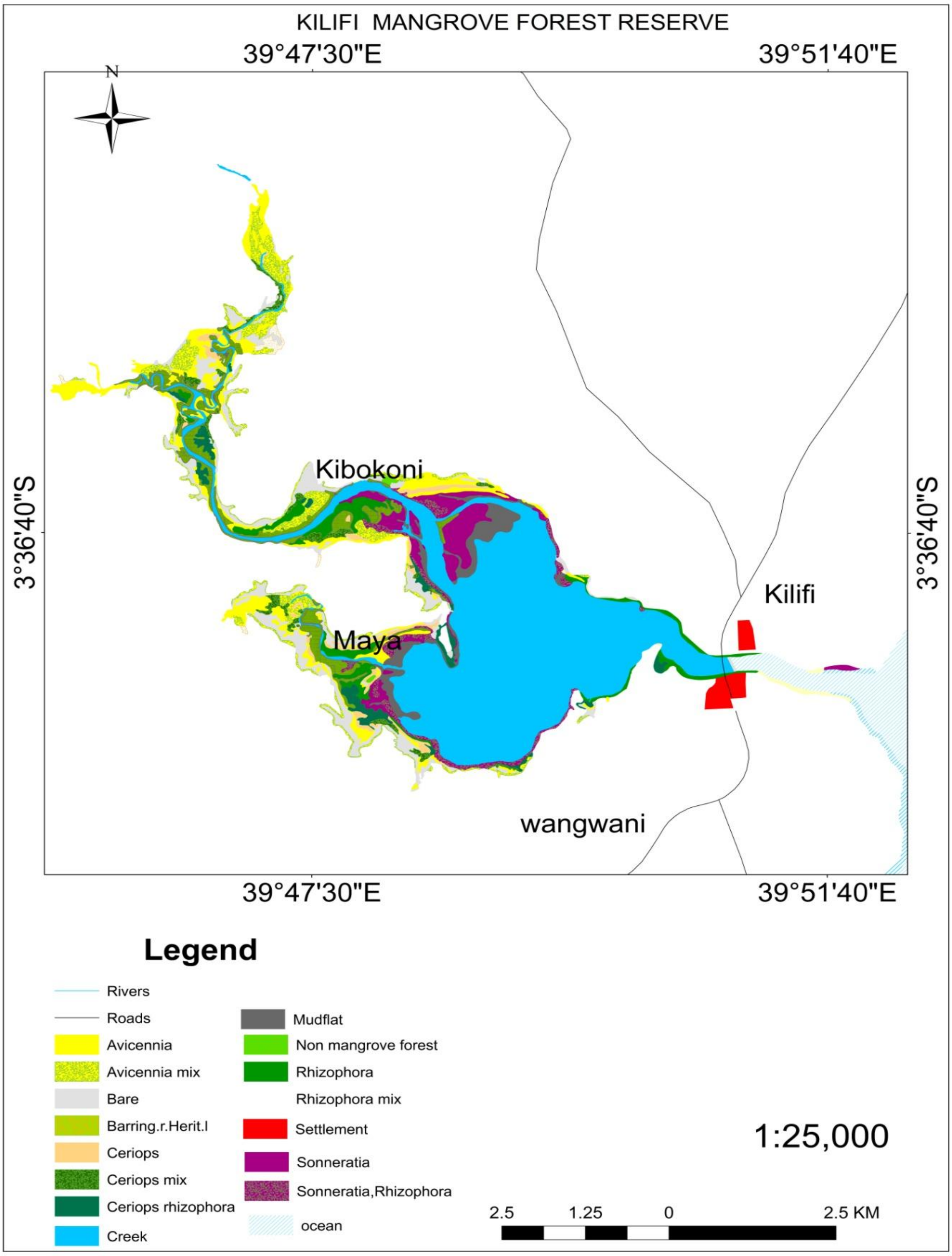

Fig.2: Map of Kilifi creek mangrove reserve

3.1.1 Climate

Kilifi is characteristic of the Kenyan coast exhibiting large-scale pressure systems dictated by the Inter-Tropical Convergence Zone (ITCZ) that creates 2 distinct seasons. The Southeast monsoon (SEM) runs from May to October while the Northeast monsoon (NEM) runs from December to March. The mean annual rainfall is about 1038 mm, with peaks in May and June; the mean annual temperatures are 23.9 C and 28.5 C, for the rainy and dry seasons respectively (Obura, 2001). Temperatures range between 24.0˚C in July when the coast is cool with highs of 32.0˚C in February. There are also two rainfall seasons, the long rains between April to July and short rains between October to December.

3.2 Study design

3.2.1 Forest structure and regeneration

A stratified systematic random study design was used to identify study sites and classify corresponding zones that are representative of the area across the topographic gradient based on vegetation type and stand conditions. An initial examination of medium-scale (1:25000) aerial photographs of the study area was used for forest stratification and to identify study sites. Belt line transects were then laid perpendicular to the shore line across the study sites and sampling done systematically from sea to land after every 50-100m interval based on the mangrove stand condition.

3.2.2 Biomass accumulation

Stratified random sampling technique was employed to identify study sites with zones stratified based on vegetation type and selected randomly representing the entire mangrove formation. An initial examination of medium-scale (1:25000) aerial photographs of the study area was used to stratify the forest and to identify study sites.

3.3 Sampling procedures

3.3.1 Forest structure and regeneration sampling

Along each belt line transects, quadrants of 10 m x 10 m for high density areas and 20 m x 20 m for low density areas were established. A total of 152 and 145 quadrants were sampled in Kibokoni and Maya respectively. Within each quadrant, individual mangrove trees with stem diameter greater than 2.5 cm were identified and counted. GPS coordinates were then taken in each plot. Vegetation parameters sampled included; diameter at breast height (DBH) was measured for each tree with a tape measure at 130 cm above ground (D_{130} sensu Brokaw and Thompson, 2000), Open canopy cover (%) and tree height (m) was estimated.

Composition and pattern of natural regeneration was obtained using linear regeneration sampling (Sukardjo, 1987). In 5 m x 5 m sub-plots (Within the main 10 m x 10 m plot), saplings densities of different species were recorded and grouped according to height classes in each plot. Saplings below 40 cm in height, termed as potential regeneration/Regeneration class 1 (RC I), while RC II (saplings between 40 and 150 cm height) and RC III (saplings or young trees over 1.5 m height but less than 3 m). The ratio of RCI: II: III was used to show the adequacy of natural regeneration (FAO, 1994).

3.3.2 Biomass and carbon stock accumulation estimates

Quadrants of 10 m x 10 m for high density areas and 20 m x 20 m for low density areas were established randomly based on the vegetation zone stratification. Within each Quadrant, individual mangrove trees with diameter greater than 2.5 cm were identified and counted. GPS coordinates were then obtained in each plot. In each tree, diameter at breast height (DBH) which was measured with a tape measure at 130 cm above ground (D_{130} sensu Brokaw and Thompson, 2000) and tree height (m) was estimated. All trees were selected within each plot, with a total of 104 plots sampled for aboveground and

26 plots for belowground across the entire mangrove formation according to Komiyama *et al* (2005).

3.4 Data analysis

3.4.1 Stand composition

All data analysis and graphical presentation were obtained with the STATISTICA 8.0 program. One-way ANOVA was performed on total stocking densities of different size classes, which was assumed as a measure of age. The relative density, dominance and frequency were estimated and the importance values established according to Dahdouh-Guebas and Koedam (2006).

Structural variables (parameters) including individual tree heights, stem diameters, mean stand densities, mean sapling densities, pole form types, mean regeneration density and the mean basal areas were subjected to a normality test and normalized where necessary. ANOVA test was then carried out to analyze the variation across each side of the creek.

Tree basal area, stand density and frequency were derived according to (Cintrón and Schaeffer-Novelli (1984). Stand densities were measured per species and the total in each plot as follows;

$$\text{Density of species (No. ha}^{-1}) = \text{Number of individual species} \times \frac{10{,}000\ \text{m}^2}{\text{Area of plot (m}^2)} \quad \text{............ Eq.i}$$

Total density of all species = sum of all species densities …...………………..... Eq. ii

Basal area was measured per species and total in each plot as follows:

$$\text{Basal area (m}^2) \text{ of each species} = 0.005 \times \text{DBH} \quad \text{………………………………… Eq.iii}$$

$$\text{Total basal area of (m}^2/\text{ha}) = \frac{\text{Sum of all species basal area}}{\text{Area of plot (m}^2)} \times 10{,}000 \quad \text{……….......Eq. iv}$$

$$\text{Relative density} = \frac{\text{No. of individuals of a species}}{\text{Total no. of individuals}} \times 100 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{Eq. v}$$

$$\text{Relative dominance} = \frac{\text{Total basal area of a species}}{\text{Basal area of all species}} \times 100 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{Eq.vi}$$

$$\text{Relative frequency} = \frac{\text{Frequency of a species}}{\text{Sum-frequency of all species}} \times 100 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{Eq. vii}$$

The Importance value of each species was derived by summing its relative density, relative frequency and relative dominance according to Dahdouh-Guebas and Koedam (2006a). The complexity index (I_c) of the forest was obtained as the product of number of species(s), basal area (m^2/ha) (b), maximum tree height (in meters) (h) and number of stems ha^{-1} (d) x 10^{-5} (Holdridge *et al*, 1971).

Stand densities were harmonized using De Liocourt's negative exponential model and the nature of future forest derived by fitting the model to the stand size class structures. The model was derived from a geometric series based on the number of trees in the largest size class of interest (a) and the ratio of the next largest class to the largest class (q). The number of classes was denoted as n to give:

$$aq^n, aq^{n-1}, aq^{n-2}, aq^{n-3}, \ldots\ldots aq^3, aq^2, aq^1, \quad \ldots\ldots\ldots\ldots\ldots\ldots \text{Eq. vii}$$

The model observes the ratio between the diameter classes of trees of uneven-aged stand in successive diameter classes was roughly constant for specific forests (Clutter *et al.,* 1983). This ratio was plotted against size classes and is represented as the exponential curve of the form:

$$y = ke^{-ax} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{Eq.viii}$$

where; y is the number of trees in diameter class x; e is the base of natural log (2.718) while k and a are constants that vary between sites and are calculated as:

$$k = N/e^{-ad_1} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{Eq. ix}$$

$$a = 1/d_2 - b \quad \text{……………………..……………..} \quad \text{Eq. x}$$

where N = theoretical number of trees in the first size class; d_1 = middle value for the first size class; b = stand diameter measurement threshold; and d_2 = mean stand diameter. "Constant k reflects the presence of seedling regeneration and tends to be large N in forests containing prolific seed-bearing tree species, while "a" determines the relative frequencies of successive diameter classes. A high "a" is associated with high mortality between classes and is likely to occur in stands comprising light demanding (shade intolerant) tree species" (Kairo *et al.*, 2002).

The nature of the future Kilifi mangrove forest was derived from the present forest by fitting exponential models to the size-class structures and comparing the results at a 0.05 significant level. Each class interval was considered to be independent and thus included as within-factor repeated measure variable during the analysis.

Regeneration densities and ratios (RC I: RC II: RC III) were calculated and analysed. Spatial pattern of distribution of adults and juveniles were analyzed using Morisita's index (I_δ) (Morista, 1959) with the application described in Greig-Smith (1983).

$$I_\delta = q\sum_{i=1}^{q} \frac{n(n-1)}{N(N-1)} \quad \text{……………………………………} \quad \text{Eq. xi}$$

Where; q is the number of quadrats, n_i is the number of individual species in the i^{th} plot and N is the total number of individuals in all q quadrats. If $I_\delta > 1$, the population is clustered, but when $I_\delta = 1$, the population is randomly dispersed. The population is evenly dispersed when $I_\delta < 1$.

Pole quality was assessed based on straightness of poles and assigned either form 1, 2 or 3. Form 1 stems denoted those with a straight lead stem and are considered ideal for construction but form 2 stems require slight modification before use. The straighter the pole, the more economically valuable it was, thus Form 3 were the least viable.

3.4.2 Biomass and carbon accumulation estimates

Data analysis was carried out using Microsoft Excel spreadsheet 2007 and Statistica 8. All data were tested for normality and normalized where necessary for parametric tests. Mean values of biomass and carbon data sets collected from the two representative sites of the creek were subjected to significance tests using one way ANOVA to compare the variation in total, above and below ground mean biomass and carbon accumulation across the two representative sites of Kilifi mangroves (Maya and Kibokoni).

The allometric equation which uses diameter and wood density as predictive variables with a high coefficient of determination (r^2) of 0.979 and 0.954 respectively was used. A general allometric equation ($W_{AGB} = 0.251\ \rho\ D^{2.46}$ $r^2 = 0.98$, n = 104, Dmax= 49 cm) by Komiyama *et al* (2005) was used to calculate above ground biomass. W_{AGB} represents the above-ground biomass and is given by; W_{AGG} is the above-ground biomass (kg), ρ = Species specific wood density of the species; D = diameter at breast height, Dmax = maximum diameter of 49 cm and n = number of plots sampled. The wood density for each species of mangrove was obtained from Bosire *et al* (2013) (Table 1) which has been developed for this region. The values of total above ground biomass (AGB) per plot was summed for all plots and averaged to get the mean stand above ground biomass.

A general allometric equation ($W_{BGB}= 0.199\ \rho^{0.899}\ D^{2.22}$ $r^2 = 0.95$, n = 26, Dmax = 45 cm) by Komiyama *et al* (2005) was used to estimate below ground biomass. W_{BGG} is the below-ground biomass (kg), ρ = species specific wood density of the species, D = diameter at breast height, Dmax = maximum diameter of 45 cm, n = total number of plots sampled. The estimated values of total below ground biomass per plot was summed for all plots and averaged to get the mean stand below ground biomass.

Table 1. Specific wood density of major mangrove species in West Indian Ocean.

Species	Density (g/cm^3)	Standard Error
C. tagal	1.1	0.0
B. gymnorrhiza	1.3	0.1
X. granatum	0.8	0.1
S. alba	0.8	0.0
A. marina	0.9	0.0
R. mucronata	1.1	0.1
H. littoralis	0.8	0.1

Source: Bosire *et al*. (2013).

Total biomass accumulation was calculated as the sum of above and belowground biomass accumulation. The ratio of AGB to BGB was calculated as the above ground biomass accumulation divided by the below ground biomass accumulation. A general equation; W_{BGC} = below ground biomass (kg C) * carbon conversion factor (0.39) by Bosire *et al* (2013) was used to calculate below ground carbon. A general equation; W_{AGC} = above ground biomass (kg C) * carbon conversion factor (0.39) by Bosire *et al* (2013) was used to calculate above ground carbon. The values of total biomass and carbon per plot were summed for all plots and averaged to determine the mean stand biomass and carbon stock.

CHAPTER FOUR: RESULTS

4.0 Introduction

This chapter discusses the mangrove structural composition including species composition, stand densities and structural attributes of each species. It defines the standing wood quality, regeneration status and the de liocourt’s predictive model. The biomass and carbon stock is also estimated for the mangrove formation.

4.1 Species composition

Six mangrove species were identified in Kilifi creek. In terms of the species’ importance values, *R. mucronata* and *A. marina* were the principal species in both Kibokoni and Maya. *S. alba* was observed to be pest infested.

Table 2: Structural attributes of the Kilifi mangrove forest

Site	**Species**	**Height**	**BA**	**Relative (100%)**			**Abso**	***IV**	**Rank**
		(m)	**(m²/ha^{-1})**	**Den**	**Dom**	**Freq.**	**Freq.**		
Kibokoni	*A. marina*	7.97±3.0	10.08	22.72	37.39	19.69	13	93	2
	B. gymnorrhiza	4.32±1.2	0.65	2.47	1.52	10.60	7	22	4
	C. tagal	3.00±0.5	1.56	21.33	3.63	19.69	13	58	3
	R. mucronata	5.90±1.1	10.09	37.40	37.46	34.85	23	133	1
	S. alba	5.92±2.9	2.35	15.77	19.76	13.64	9	58	3
	X. granatum	4.18±3.4	0.10	0.31	0.24	1.52	1	3	5
Total		***5.22**	**24.83**	**100**	**100**	**100**			
Maya	*A. marina*	6.37±2.8	11.35	18.00	35.27	21.42	15	90	2
	B. gymnorrhiza	5.7±2.5	0.86	4.07	2.69	7.14	5	19	5
	C. tagal	2.8±0.7	1.37	15.47	4.27	21.42	15	56	3
	R. mucronata	5.7±3.4	10.36	51.47	44.63	40	28	164	1
	S. alba	5.54±2.4	2.49	8.29	7.74	5.71	4	26	4
	X. granatum	4.8±0.75	1.73	2.67	2.37	4.28	3	15	6
Total		***5.15**	**27.16**	**100**	**100**	**100**			

* Values for the height (m) represent the stand mean ± standard deviation. Values for the Basal area (m² ha^{-1}) represent the sum of basal areas estimated per sampled plot.

*IV stands for species importance values and derived by summing its relative density, relative frequency and relative dominance.

* CI stands for complexity indices and is the product of number of species, basal area (m^2/ha), maximum tree height (m) and number of stems ha^{-1} x 10^{-5}. C.I values were Kibokoni (13.98) and Maya (13.68).

* Height totals show the mean height.

4.2 Stocking density and structural characteristics

The stand density in Kibokoni was 1,288 stems ha^{-1}. *R. mucronata* was the most abundant with 37.47%. *A. marina and C. tagal* constituted 22.70% and 21.36% respectively. The rest included *S. alba* (15.77%) and *B. gymnorrhiza* (2.42%) (Table 1). On the contrary, the stand density in Maya was higher with 1, 449 stems ha^{-1}.There were significant differences ($\rho < 0.05$) in the mean tree densities between the two sites. *R. mucronata* in Maya was dominant with 51.49%. Others species included *C. tagal* (15.52%), *S. alba* (8.27%) and *B. gymnorrhiza* (4.06%).

The average mean height was 5.22 m and 5.15 m for Kibokoni and Maya respectively.There were variations in heights of the species across the two sites with *A. Marina* reporting the highest with 7.97 ± 3.0 m and 6.37 ± 2.8 m in Kibokoni and Maya respectively. On the contrary, *C. tagal* had the least values with 3.00 ± 0.5 m and 2.8 ± 0.7 m respectively. There were also significant differences in tree heights ($F_{(1,\ 2234)} = 18.64$; $\rho < 0.05$) and stem diameters ($F_{(1,\ 2234)} = 53.52$; $\rho < 0.05$) between Kibokoni and Maya. However, a positive correlation was observed between height and stem diameter between the two sites. Stem diameter of trees generally increased with height (Fig. 2).

Kibokoni and Maya had basal areas of 24.83 m^2 ha^{-1}and 27.16 m^2 ha^{-1} respectively. The mean basal areas across the two sites showed significant differences ($\rho < 0.05$). Maya had slightly higher complexity index (13.98) than Kibokoni (13.68) and it indicates more structural complexity of the former than the latter. In terms of the species Importance Value, *R. mucronata* was the most important species in both Kibokoni and Maya with I.V values of 133 and 164 respectively. Similarly, the species had the highest relative density, dominance and frequency in both sites with the highest values reported in Maya with 51.47, 44.63 and 40 respectively.

Table 3**:** Stand table for Mangrove forest of Kilifi

Area	Species	*< 4	4.0-7.5	7.5-11.5	11.5-14.0	14.0-20.5	20.6-34.9	>35.0	Density Stems/ha
Kibokoni	*A. marina*	5	28	25	21	64	154	41	338
		(1.36)	(8.16)	(7.48)	(6.12)	(19.05)	(45.58)	(12.4)	(22.70)
	B.gymnorrhiza	0	7	9	7	5	9	0	37
		(0)	(18.5)	(25)	(18.75)	(12.5)	(25)	(0)	(2.42)
	C. tagal	41	170	157	21	14	3	0	317
		(13)	(53.62)	(16.62)	(6.5)	(4.34)	(0.72)	(0)	(21.36)
	R. mucronata	14	147	127	28	30	191	0	556
		(2.48)	(26.45)	(15.7)	(4.95)	(5.37)	(34.29)	(0)	(37.47)
	S. alba	3	28	0	28	58	60	21	235
		(0.09)	(11.7)	(0)	(11.7)	(24.5)	(25.5)	(8.8)	(15.77)
	X. granatum	0	0	0	0	5	0	0	5
		(0)	(0)	(0)	(0)	(100)	(0)	(0)	(0.27)
	Total ha^{-1}	**62**	**379**	**234**	**105**	**175**	**416**	**62**	**1,288**
	Percentage (%)	**(4.3)**	**(26.4)**	**(16.4)**	**(7.3)**	**(12.3)**	**(29.0)**	**(0.3)**	
Maya	*A. marina*	3	52	34	26	91	109	124	333
		(0.78)	(15.62)	(10.16)	(7.81)	(27.34)	(32.81)	(51.77)	(18)
	B.gymnorrhiza	0	23	34	8	5	5	100	75
		(0)	(31.3)	(44.83)	(10.34)	(6.89)	(6.89)	(45.38)	(4.06)
	C. tagal	18	203	0	8	21	3	71	287
		(6.36)	(70.9)	(0)	(2.72)	(7.27)	(0.9)	(6.83)	(15.52)
	R. mucronata	60	408	192	52	81	143	151	952
		(6.28)	(42.89)	(20.21)	(5.46)	(8.42)	(55.02)	(27.69)	(51.49)
	S. alba	8	47	16	18	21	44	0	153
		(5.08)	(30.5)	(10.12)	(11.86)	(13.56)	(28.81)	(0)	(8.27)
	X. granatum	0	0	18	13	2	13	5	49
		(0)	(0)	(37)	(26)	(5)	(26)	(14.28)	(2.65)
	Total ha^{-1}	**89**	**733**	**294**	**125**	**221**	**317**	**451**	**1,449**
	Percentage (%)	**(4)**	**(32.9)**	**(13.2)**	**(5.6)**	**(9.9)**	**(14.2)**	**(20.2)**	

* Values in parentheses indicate percentage of the total stem density in each area per size class (cm) per species.

* The stem diameter classes are grouped according to utilization classes, fito, pau, mazio, boriti, nguzo, vigingi and mbao, from smallest to the highest respectively in that order.

A. marina was dominated with stem diameter size class 20.6 – 34.9 cm with stem density of 45.58% and 32.81% in Kibokoni and Maya respectively. A distinctive numerical dominance of young *C. tagal* trees was evident in both Kibokoni and Maya respectively. However, Kibokoni showed younger but taller *R. mucronata* than Maya attaining an average height of 5.9 m, although the individuals encountered were fewer (n =225). The most abundant pole sizes were of larger diameter classes 20.6 - 34.9 cm in Kibokoni (416 stems ha^{-1}) and >35.0 cm in Maya (451 stem ha$^{\mathbf{-1}}$) (Table 3). These are considered the least economically viable and usually left back in the natural forest. On the contrary those of 11.5 - 14.0 cm diameter which are the most preferred in the Kenyan market, were the least abundant in Kibokoni (105 stems ha^{-1}) and Maya (125 stems ha^{-1}). *R. mucronata* had the least value in Kibokoni (28 stem ha^{-1}) and Maya (52 stem ha^{-1}) in the same size class due to being the most market-preferred mangrove species in Kenya for local utilization, including building poles and source of wood fuel.

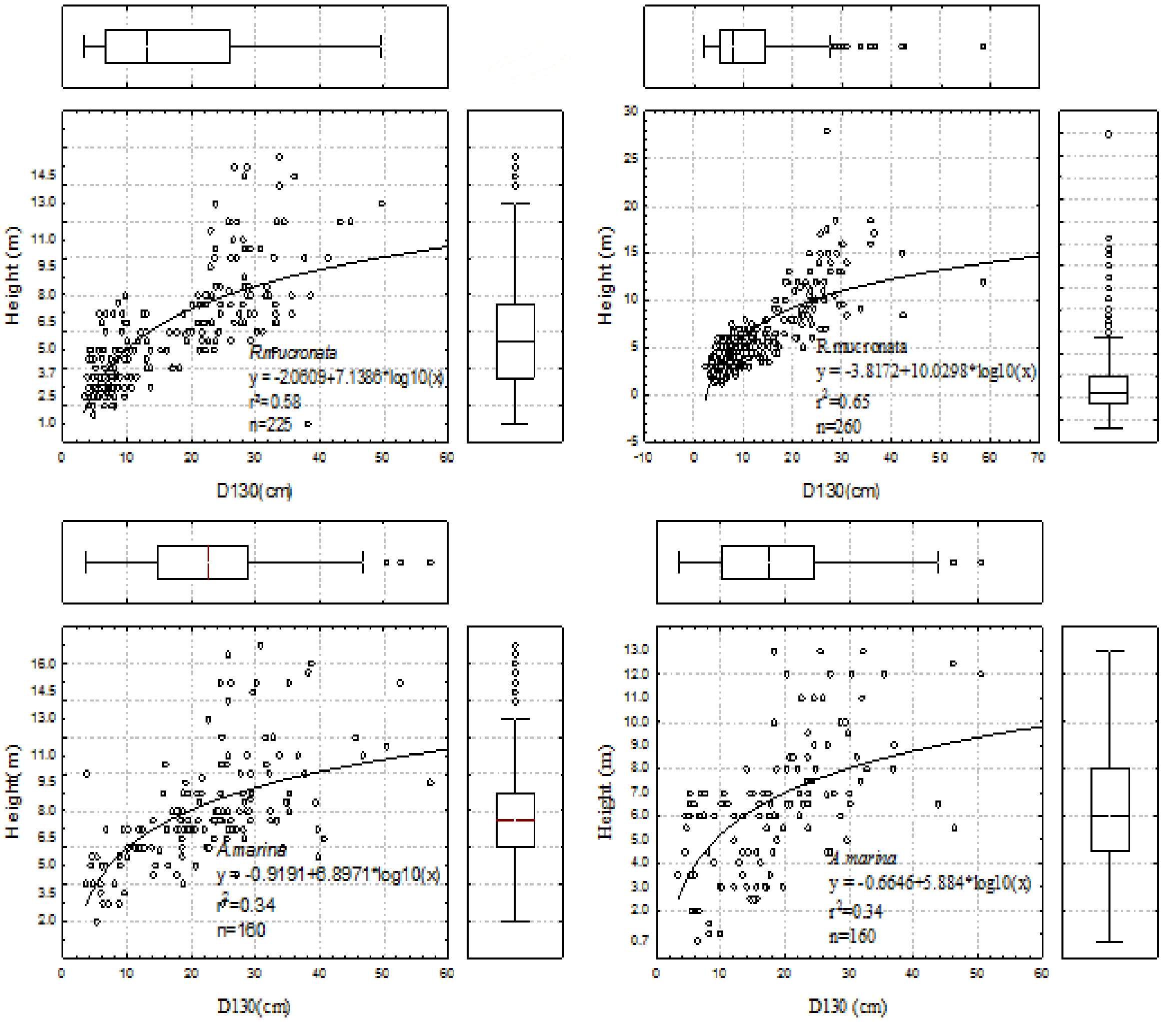

Fig. 3: Scattergrams of heights against stem diameter D_{130} distribution for the principle species *R. mucronata* and *A. Marina.*

The equation, correlation coefficients (r^2), ($P < 0.05$) are given in each case. The box-plots display percentile distributions with the ends of the boxes positioned at the 25% and 75% percentiles of the data set. The extremities of the plot correspond to the maximum and minimum observed values in the data set.

4.3 Wood quality

Table 4: Tree form distributions per mangrove species in Kilifi

Area	Species	Form Class			Density
		1	2	3	(stems ha^{-1})
Kibokoni	*A. marina*	8(6.15)	65(50)	57(43.85)	130
	B. gymnorrhiza	1(16.67)	8(50)	7(43.75)	16
	C. tagal	19(13.9)	57(41.91)	60(41.12)	136
	R. mucronata	43(19.0)	102(45.13)	81(35.84)	226
	S. alba	2(11.11)	5(33.33)	8(55.56)	15
	X. granatum	1(9.09)	2(36.36)	5(54.55)	8
	Total ha^{-1}	**74**	**239**	**218**	**531**
	Percentage (%)	**(13.93)**	**(45.01)**	**(41.06)**	
Maya	*A. marina*	9(7.09)	61(48.03)	57(44.88)	127
	B. gymnorrhiza	1(3.45)	13(44.83)	15(51.72)	29
	C. tagal	20(17.5)	37(32.46)	57(50)	114
	R. mucronata	58(23.1)	164(38.99)	144(37.8)	366
	S. alba	1(25)	1(25)	2(50)	4
	X. granatum	1(5.26)	3(26.32)	8(68.42)	12
	Total ha^{-1}	**90**	**279**	**283**	**652**
	Percentage (%)	**(13.80)**	**(42.79)**	**(43.40)**	

* The values in the table show the densities per ha and percentages (in brackets).

Maya had a higher number of straight poles (90 stems ha^{-1}) compared to Kibokoni (74 stem ha^{-1}). This was due to a higher overall density in Maya (652 stems ha^{-1}) than Kibokoni (531 stem ha^{-1}). The mangrove stand was also characterized with high tree stump densities with Kibokoni (1,280 ha^{-1}) having slightly higher than Maya (916 ha^{-1}), indicating a higher scale of exploitation pressure in the former than in the latter.

However, the general quality of standing wood did not show significant differences ($\rho > 0.05$) between the two sites. *R. mucronata* had the highest number of straight poles in Kibokoni (43 stems ha^{-1}) and Maya (58 stems ha^{-1}). On the contrary, it also showed the highest number of crooked poles in both Kibokoni (81 stems ha^{-1}) and Maya (114 stems ha^{-1}). *C. tagal* also produced the second highest number of straight poles in Kilifi (39 stems ha^{-1}).

The general quality of the standing wood in Kilifi was dominated by classes 2 and 3 which constituted 86.14% (Table. 4). On the contrary, the straight poles only made up 13.86% of the wood stand. Approximately 41.92% of the mangrove stand in Kilifi Creek had the crooked poles of form 3 which has a low market value and represents the general quality of the standing wood quantity in the Kilifi Creek (Table. 4). This clearly shows selective harvesting with preference for straight poles.

4.4 De Liocourt's Model

The observed (bars) and predicted (curve) stem size composition is depicted in Fig. 4. There are significant differences between the observed and predicted size distribution in both sites [Kibokoni (χ^2 = 210.8585 df = 5 $\rho< 0.05$); Maya (χ^2 = 215.6598 df = 5 $\rho< 0.05$)].

The tree densities in Kilifi creek mangrove forests were observed to generally decline with increase in diameter classes (Fig. 4). The higher '*a*' value in Kibokoni (0.62) denotes higher tree mortality between diameter classes than in Maya (0.38) (Fig. 4). The Larger '*k*' value in Kibokoni (1,531) reflects presence of more prolific seed bearing tree species than in Maya (607).

The observed stem size distributions in both sites display selective harvesting, with over-harvesting of tree stems sizes 7.5 – 11.4 cm and 11.5 - 14.0 cm respectively in both sides of the creeks (Fig. 4). On the contrary, the large stem sizes 20.5 - 35.0 cm of low local commercial value were left in the forest.

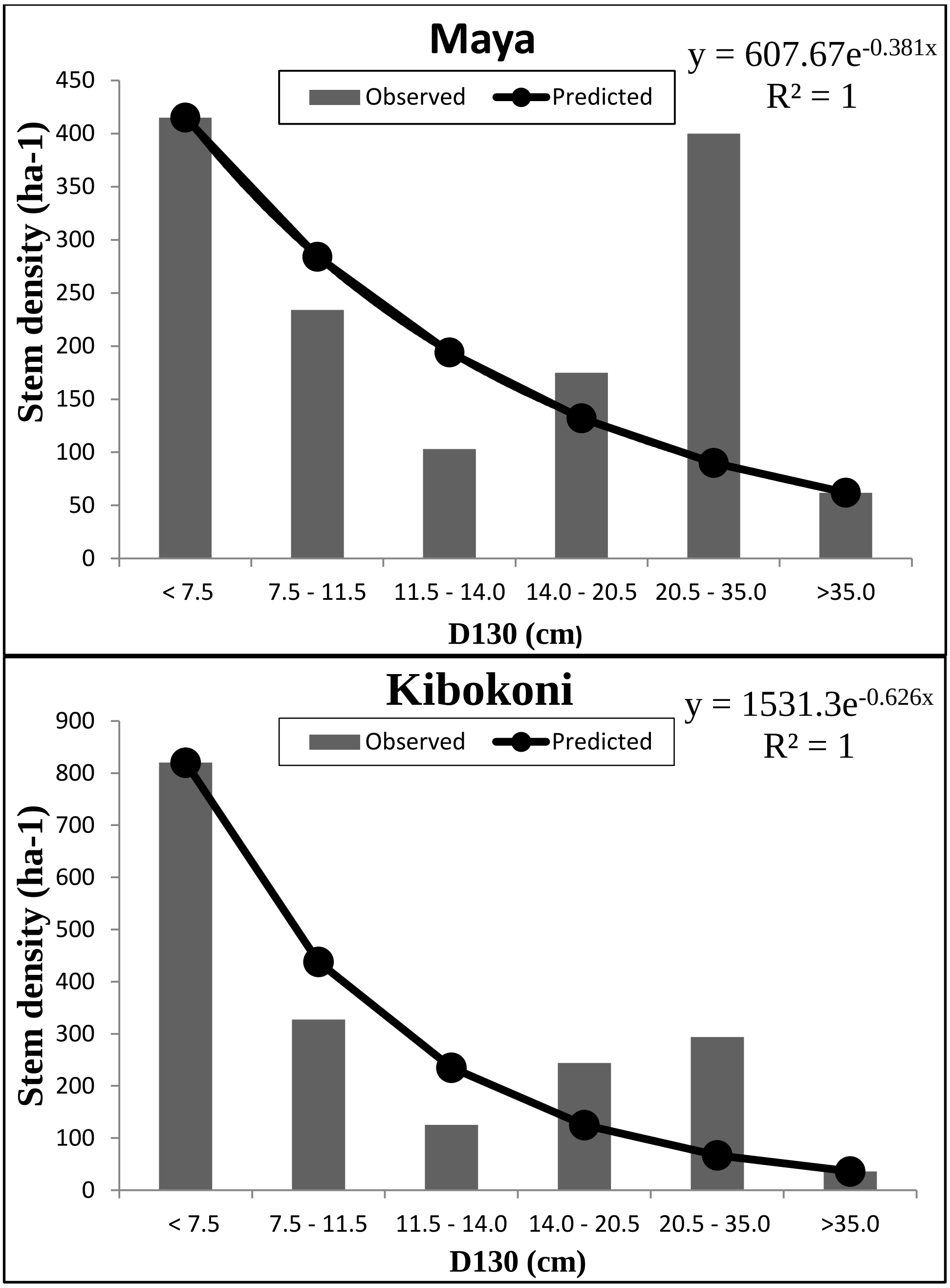

Fig. 4: De Liocourt’s exponential negative model showing the Observed (bars) and predicted (curve) size class distribution of the mangrove stands of Kilifi

The high *‘k’* value in the stand curve $y = ke^{-ax}$ reflects the occurrence of sporadic natural regeneration in the forest. The ‘*a*’ value demonstrates tree mortality between diameter classes.

4.5 Forest Regeneration

Table 5: Juvenile density (Saplings ha^{-1}) in Kilifi mangroves

Area	Species	Regeneration			Density
		(0-40cm)	(40-150cm)	(150-300cm)	(stems ha^{-1})
Kibokoni	*A. marina*	1,310(82.6)	124(7.82)	152 (9.58)	1,586 (9.21)
	C. tagal	680(25.72)	1,021(38.62)	943(35.66)	2,644(15.36)
	R. mucronata	6,421(49.45)	3,885(29.91)	2,680(20.64)	12,986(75.42)
	S. alba	0(0)	1(50)	1(50)	2(100)
	Total ha^{-1} **Proportion (%)**	**8,412** **(48.86%)**	**5,030** **(29.22%)**	**3,775** **(21.92%)**	**17,217**
Maya	*A. marina*	429(49.53)	312(36.02)	125(14.43)	866(5.03)
	B. gymnorrhiza	652(87.28)	51(6.71)	53(7.01)	756(4.39)
	C. tagal	2,148(29.23)	2,322(31.6)	2,878(39.17)	7,348(42.75)
	R. mucronata	4,005(42.81)	2,792(29.84)	2,558(27.34)	9,355(54)
	S. alba	0(0)	0(0)	1(100)	1(0.00)
	X. granatum	29(50)	26(44.83)	3(5.17)	58(0.34)
	Total ha^{-1} **Proportion (%)**	**6,611** **(38.45%)**	**5,140** **(29.90%)**	**5,439** **(31.64%)**	**17,190**

* Values in parenthesis indicate percentages.

Sapling density ranged between 17, 190 ha^{-1} and 17, 217 ha^{-1} in Kilifi. *R. mucronata* dominated both Kibokoni (75.42%) and Maya (54%). However, there was no significant difference ($F_{(1,183)} = 2.05$; $\rho > 0.05$) in the mean densities of juveniles size classes between Kibokoni and Maya. Only one sapling of *S. alba* was recorded in Maya. Similarly, Juveniles of *B. gymnorrhiza* and *X. granatum* were entirely absent in Kibokoni. This raises concern over the future status of the two species under the current ongoing exploitation regime.

The regeneration ratios for saplings RCI: RCII: RCIII was 2:1:1 and 1:1:1 for Kibokoni and Maya respectively. The regeneration ratios are not within the range of effective stocking rate of 6:3:1 for saplings described by Chong (1988). Therefore, this poses a threat to the future forest re-stocking and sustainability. However, Chong (1988) also highlighted that 2,500 seedlings ha^{-1} is sufficient for natural regeneration.

Hence, Kilifi mangroves still possess good regeneration potential and with regulated harvesting it can restock itself sufficiently.

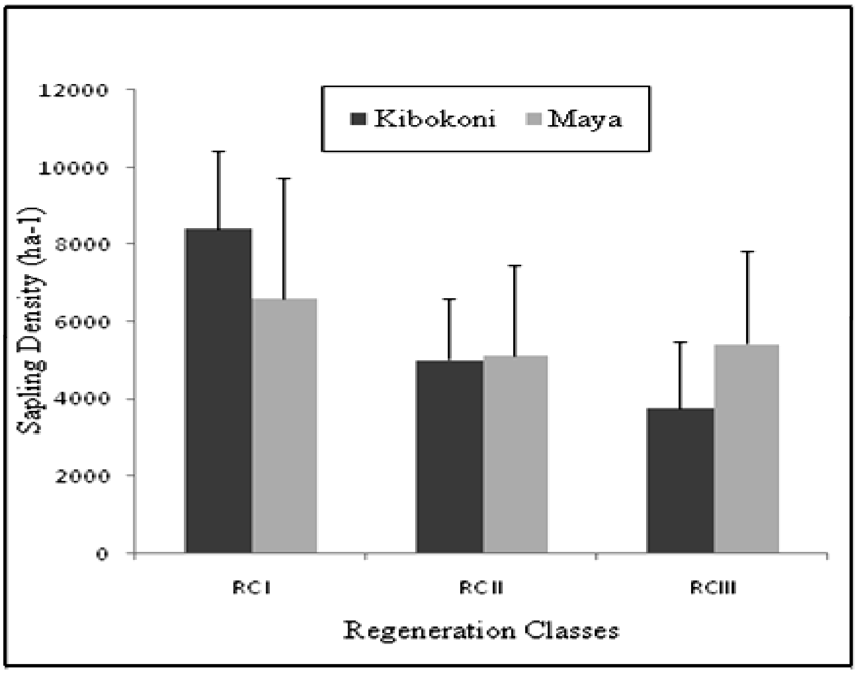

Fig. 5: Box plot of mangrove sapling densities across regeneration classes

The ends of the box are positioned at the 75% percentiles of the data set. Established saplings of RCII and RCIII constituted for Kibokoni (29.22%) and Maya (27.31%) respectively. Most saplings were in RCI in Kibokoni (48.86%) and Maya (38.45%). The number of saplings in RCIII was relatively higher in Maya than in Kibokoni Area (n = 5,600). This indicates higher survival of seedling in Maya which may imply more favorable conditions existing in Maya. This is also reflected by the lower tree mortality ‘a’ value (0.39) in Maya than in Kibokoni (0.62) (Fig. 4).

In both sites, higher abundance of saplings in smaller gaps and under canopies than in larger gaps were observed (Fig. 6). The highest density was found under intermediate open canopy cover of 20% - 50%. Above 60% open canopy cover, with large gaps (>60%) very few saplings were present (Fig. 6).

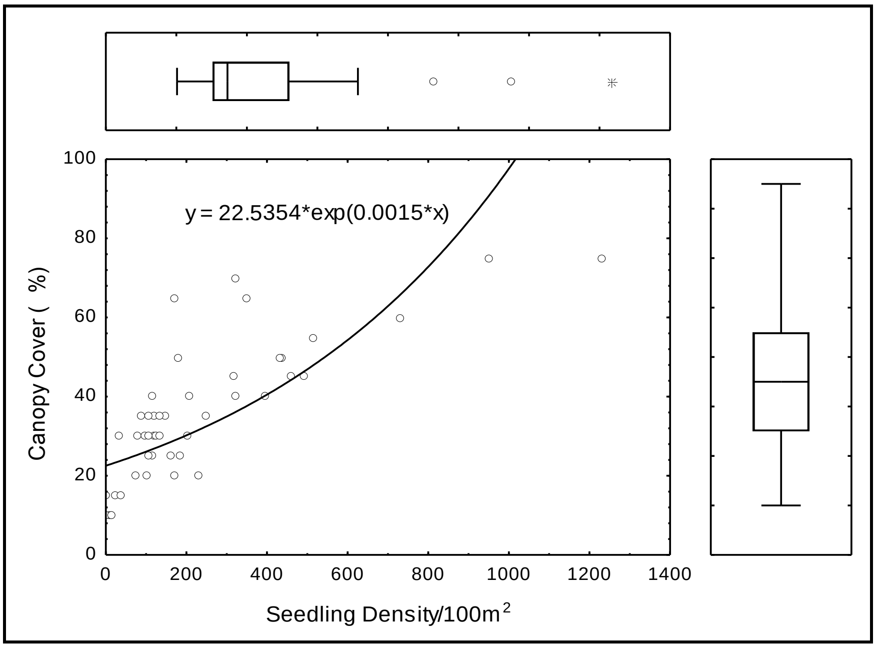

Fig. 6: Scattergram of open canopy vs. seedling densities.

The box plots display percentage distribution in each case. The ends of the box are positioned at the 25th and 75th percentiles of the data set.

Examination of adult and saplings dispersion patterns for the principal mangrove species showed adults displaying a tendency towards random distribution $I_\delta << 1$. However, a clustered distribution for saplings ($I_\delta >> 1$) was observed (Table 6).

Table 6: Morista Index for principal adults and saplings species in Kilifi Mangroves

Site	Species	Distance from the creek (m) 20	100	150	200	300	400
Kibokoni	*A. marina*	—	0.90 (1.54)	0.42 (1.74)	1.46 (1.51)	1.15 (0.52)	—
	R. mucronata	1.24 (1.03)	0.71 (0.34)	1.17 (1.35)	0.93 (1.33)	1.02 (2.02)	0.67 (1.20)
Maya	*A. marina*	—	1.07 (0.80)	1.18 (1.21)	0.51 (1.33)	1.21 (0.72)	—
	R.. mucronata	1.36 (1.12)	0.47 (0.8)	0.92 (1.13)	0.98 (1.32)	1.10 (1.98)	1.04 (1.23)

* Values in parenthesis indicate Morista index for saplings.

4.6 Comparative Analysis

Table 7: Structural characteristics of Kilifi mangrove forest compared to others along the coastal area

	Kilifi	[1]Kiunga	[2]Mida	[3]Ngomeni	[4]Gazi	[5]Tudor
Basal area (m^2/ha)	25.99	46.97	23.62	33.14	3.19	13.02
Stand density (Stems ha^{-1})	1,368	2,142	1,192	1,251	678	1,283
Average canopy ht (m)	5.18	12.50	12.10	9.54	8.3	4.37
Complexity Index (C.I)	13.82	60.81	6.97	25.22	0.35	3.49

* [1]Kiunga (Kairo *et al.*, 2002), [2]Mida (Kairo *et al.*, 2002), [3]Ngomeni (Bundotich, 2007), [4]Gazi (Bosire *et al.*, 2003), [5]Tudor (Mohamed *et al.*, 2009).

Table. 7 displays the structural characteristics of several studied mangrove forests along the Kenyan coast against Kilifi mangroves. Kiunga, Mida and Ngomeni all lie in the north of the Kenyan coast. On the contrary, Gazi lies in the South. Kiunga mangroves had the highest basal area, stand density, average canopy heights and complexity index of 46.97 m^2 ha^{-1}, 2,142 stems ha^{-1}, 12.5 m and 60.81 respectively. This was followed by Ngomeni with basal area (33.14 m^2 ha^{-1}), stand density (1,251 stems ha^{-1}), average canopy height (9.54 m) and complexity index (25.22).

On the contrary, Gazi bay mangroves reported the least values with basal area (3.19 m^2 ha^{-1}), stand density (678 stems ha^{-1}), average canopy heights (8.3 m) and complexity index (0.35). This clearly shows that mangrove forests to the north coast are structurally more complex than those on the southern part of Kenya.

4.7 Biomass accumulation estimates

4.7.1 Above ground biomass accumulation

Above ground biomass accumulation in Kilifi mangrove forest was highest in *R. mucronata* with a mean of 61.4 ± 5.5 Mg ha^{-1}(range: 55.2 – 64.9 Mg ha^{-1}) (Table. 8). This was followed by *A. marina* with 48.7± 6.8 Mg ha^{-1}(range: 41.4 – 53.9 Mg ha^{-1}). *B.*

gymnorrhiza and *X. granatum* had the least values with 26.4 ± 9.4 Mg ha^{-1} (range: 11.4 – 38.4 Mg ha^{-1}) and 24.7 ± 11.4 Mg ha^{-1} (range: 10.8 – 32.4 Mg ha^{-1}) respectively.

Table 8: Above ground biomass accumulation (AGB) for Kilifi mangroves

Area	Species	AGB (Mg ha^{-1})	Range (Min - Max)
Kilifi	*R. mucronata*	61.4 ± 5.5	55.2 – 64.9
	A. Marina	48.7 ± 6.8	41.4 – 53.9
	S. alba	34.5 ± 9.7	28.4 – 44.9
	C. tagal	36.9 ± 16.4	18.4 – 46.9
	B. gymnorrhiza	26.4 ± 9.4	11.4 – 38.4
	X. granatum	24.7 ± 11.4	10.8 – 32.4

* Values for AGB indicate average mean ± standard deviation.

Comparatively, Kibokoni had higher above ground biomass (104.6 ± 22.4 Mg ha^{-1}) (range: 75.4 – 129.9 Mg ha^{-1}) than Maya (96.0 ± 15.8 Mg ha^{-1}) (range: 78.4 – 112.9 Mg ha^{-1}). Using a one way ANOVA test, the difference in mean above ground biomass accumulation across the two sites was found to be significant ($F_{(1, 4)} = 5.21$, $\rho < 0.05$).

4.7.2 Below ground biomass accumulation

The below ground biomass accumulation was found to be highest in the *S. alba* with a mean below ground biomass accumulation of 30.5 ± 8.5 Mg ha^{-1} (range: 18.2 – 42.4 Mg ha^{-1}) followed by *R. mucronata* with a mean of 24.2 ± 9.7 Mg ha^{-1} (range: 15.2 – 32.4 Mg ha^{-1}) (Table 9). Similarly, *B. gymnorrhiza* and *X. granatum* had the least values with 11.01 ± 4.6 Mg ha^{-1} (range: 6.2 – 18.5 Mg ha^{-1}) and 10.6 ± 3.5 Mg ha^{-1} (range: 6.8 – 14.2 Mg ha^{-1}) respectively.

Table 9: Below ground biomass accumulation (BGB) for Kilifi mangroves

Area	Species	BGB (Mg ha^{-1})	Range (Min - Max)
Kilifi	*R. mucronata*	24.2 ± 9.7	15.2 – 32.4
	A. Marina	21.6 ± 5.0	17.3 – 24.6
	S. alba	30.5 ± 8.5	18.2 – 42.4
	C. tagal	16.2 ± 6.4	10.5 – 21.3
	B. gymnorrhiza	11.0 ± 4.6	6.2 – 15.5
	X. granatum	10.6 ± 3.5	6.8 – 14.2

* Values for BGB show average mean ± standard deviation.

Comparatively, Kibokoni had slightly higher below ground biomass with a value of 38.6 ± 16.5 Mg ha^{-1} (range: 20.8 – 42.2 Mg ha^{-1}) compared to Maya with Maya 37.2 ± 11.4 Mg ha^{-1} (range: 21.8 – 44.8 Mg ha^{-1}). Using ANOVA test, the mean below ground biomass accumulation across the two sites was found to differ significantly ($F_{(1, 4)} = 7.25$, $\rho < 0.05$).

4.7.3 Total biomass accumulation

The total biomass accumulation was obtained by pooling above and below ground biomass accumulation. The total overall biomass for Kilifi Mangrove forest was 138.3 ± 18.6 Mg ha^{-1} (range: 108.8 – 152.8 Mg ha^{-1}) with above ground and below ground constituting (72%) and (28%) respectively (Table. 10). The overall biomass in Kibokoni was 143.2 ± 27.9 Mg ha^{-1} (range: 109.2 – 163.4 Mg ha^{-1}) composed of (73%) above ground biomass (AGB) and (27%) below ground biomass (BGB).

Maya had comparatively less biomass with a total value of 133.2 ± 17.3 Mg ha^{-1} (range: 108.4 – 152.4 Mg ha^{-1}) with (72%) and (28%) above ground biomass (AGB) and below ground biomass (BGB) respectively. Kibokoni had comparatively taller stands (Table 2) accounting for the higher amounts of biomass as taller stands generally have greater biomass (Duke *et al*., 2013). There were significant differences in the mean total biomass across the two sites ($F_{(1, 4)} = 5.12$, $\rho < 0.05$). This may be as a result of the large variations within each site.

Table 10: Overall biomass accumulation for Kilifi mangroves

Area		Biomass (Mg ha^{-1})	Range (Min - Max)
Kilifi	TB	138.3 ± 18.6	108.8 – 152.8
	AGB	103.4 ± 11.2 (72)	88.8 – 122.8
	BGB	37.9 ± 9.4 (28)	26.2 – 43.1
Kibokoni	TB	143.2 ± 27.9	109.2 – 163.4
	AGB	104.7 ± 12.5 (73)	88.3 – 126.4
	BGB	38.6 ± 6.5 (27)	29.3 – 42.4
Maya	TB	133.2 ± 17.3	108.4 – 152.4
	AGB	96 ± 5.9 (72)	88.2 – 99.1
	BGB	37.2 ± 8.4 (28)	28.2 – 43.1

* Values for biomass indicate average mean ± deviation.

* Values in parenthesis show percentages.

Total biomass accumulation of each species was obtained by pooling its above and below ground biomass accumulation. *R. mucronata* had the highest total biomass accumulation with 85.7 ± 16.3 Mg ha^{-1} (range: 58.3 – 98.1 Mg ha^{-1}) (Table 11). *S. alba* had a total biomass accumulation of 65.7 ± 12.3 Mg ha^{-1} (range: 56.3 – 80.1 Mg ha^{-1}). *B. gymnorrhiza* and *X. granatum* had the least values with 37.5 ± 11.7 Mg ha^{-1} (range: 24.6 – 46.4 Mg ha^{-1}) and 35.3 ± 14.8 Mg ha^{-1} (range: 18.6 – 49.8 Mg ha^{-1}) of total biomass accumulation respectively. A BGB: AGB biomass accumulation ratio of 1:2.7 was calculated for the whole of Kilifi mangrove forest.

Table 11: Total biomass accumulation per species for Kilifi mangroves

Area	Species	(TB) (Mg ha^{-1})	Range (Min - Max)
Kilifi	*R. mucronata*	85.7 ± 16.3	58.3 – 98.1
	A. Marina	69.7 ± 12.1	55.8 – 79.7
	S. alba	65.7 ± 12.3	56.3 – 80.1
	C. tagal	53.5 ± 10.4	39.3 – 69.4
	B. gymnorrhiza	37.5 ± 11.7	24.6 – 46.4
	X. granatum	35.3 ± 14.8	18.6 – 49.8

* Values for Total biomass indicate average mean ± deviation.

4.7.4 Ratio of above ground to below ground (AGB: BGB)

In the overall Kilifi mangrove forest, *S. alba* had the highest ratio of below ground biomass and above ground biomass accumulation BGB: AGB with almost 1:1.3 with the below ground biomass accumulation accounting for about 46% of the total biomass. *A. marina* had a high BGB: AGB ratio of about 1:2.24 with the below ground biomass accumulation representing 30% of the total biomass. *R. mucronata* reported the lowest ratio of 1:2.53 with the least below ground biomass accumulation representing only 28% of the total tree biomass. *C. tagal, B. gymnorrhiza* and *X. granatum* all had high below to above ground ratios of 1:2.3, 1:2.4 and 1:2.3 with the below ground biomass accumulation representing 31%, 29% and 30% of the total biomass respectively. On the overall, the mean BGB: AGB ratio of the whole Kilifi mangrove forest was 1:2.7, with the below ground biomass accumulation accounting for 27% of the total biomass.

4.8 Tree carbon stock

The total corresponding tree carbon stock was estimated by pooling the above ground C-stock and below ground C-stock. The total carbon stored and sequestrated for Kilifi creek mangroves was estimated at 69.2 ± 9.3 Mg C ha^{-1} (range: 54.0 – 76.4 Mg C ha^{-1}) constituting (72%) and (28%) in the above ground carbon and below ground carbon respectively (Table. 12). This shows that the above ground carbon accounted for about 82% of the total carbon pool while below ground carbon constituted only 18%. The total carbon densities were significantly different ($F_{(1, 4)} = 6.45$, $\rho < 0.05$) across the two sites.

Kibokoni reported higher total carbon accumulation (71.6 ± 13.9 Mg ha^{-1}) (range: 54.6 – 81.7 Mg C ha^{-1}) than Maya (66.6 ± 8.6 Mg C ha^{-1}) (range: 54.2 – 76.2 Mg C ha^{-1}). Similarly, the former had higher above ground carbon accounting for (73%) of the tree Carbon and below ground carbon amounting to 19.28 ± 7.7 Mg C ha^{-1} (range: 10.2 – 23.7 Mg C ha^{-1}) (27%). The latter reported an above ground Carbon of 48 ± 2.9 Mg C ha^{-1} (range: 44.1 – 49.5 Mg C ha^{-1}) (72%) and below ground carbon with a value of 18.6 ± 4.2 Mg C ha^{-1} (range: 14.1 – 21.5 Mg C ha^{-1}) (28%).

Table 12: Overall tree carbon for Kilifi mangroves

Area		Tree Carbon (Mg C ha^{-1})	Range (Min - Max)
Kilifi	TC	69.2 ± 9.3	54.0 – 76.4
	AGC	51.7 ± 5.6 (72)	44.4 – 61.4
	BGC	18.9 ± 4.8 (28)	13.1 – 21.5
Kibokoni	TC	71.6 ± 13.9	54.6 – 81.7
	AGC	52.3 ± 6.3 (73)	44.1 – 63.2
	BGC	19.28 ± 7.7 (27)	10.2 – 23.7
Maya	TC	66.6 ± 8.6	54.2 – 76.2
	AGC	48 ± 2.9 (72)	44.1 – 49.5
	BGC	18.6 ± 4.2 (28)	14.1 – 21.5

* Values for tree carbon indicate average mean ± deviation.

* Values in parenthesis show percentages.

CHAPTER FIVE: DISCUSSION

5.0 Introduction

This chapter discusses the mangrove stand structural composition of the study area, the regeneration status, wood stand quality and the de liocourt's predictive model. It also shades light on the biomass accumulation estimates and carbon stocks within the mangrove formation.

5.1 Mangrove stand composition

The stand densities for Kilifi mangrove forest (1,288 - 1,449 stems ha^{-1}) are within the range for similar forests reported globally (322 - 2,470 stems ha^{-1}) (Jimenez *et al.*, 1985). The mangrove formation generally possesses attributes typical of other locally reported mangrove forests. The basal area and stem densities of Kilifi mangroves (25.99 m^2 ha^{-1}, 1,368 stems ha^{-1}) were within the range of other *R. mucronata* dominated forests along the Kenyan coastline with Mida (23.62 m^2 ha^{-1}, 1,192 stems ha^{-1}) (Kairo *et al.*, 2002); Kiunga (46.97 m^2 ha^{-1}, 2,142 stems ha^{-1}) (Kairo *et al.*, 2002); Ngomeni (33.14 m^2 ha^{-1}, 1,251 stems ha^{-1}) (Bundotich, 2007); Tudor Creek (13.02 m^2 ha^{-1}, 1,145 stems ha^{-1}) (Mohamed *et al.*, 2009).

The complexity index (C.I) for Kilifi mangroves (13.82), an indicator of the overall structural development of a forest stand, was lower than values reported for mangroves of the Kenyan North coast with Kiunga having a C.I value of 60.81 (Kairo *et al.*, 2001) and the Tana Delta with 25.22 (Bundotich, 2007). However, Kilifi creek mangroves had higher values than Mida, Tudor and Gazi creek with C.I of 6.97 (Kairo *et al.*, 2002), 3.20 (Mohamed *et al.*, 2009) and 0.35 (Bosire *et al.*, 2003) respectively, all occurring in the South of the Kenyan Coast.

The relatively low complexity index values for Kilifi mangroves may be attributed to a higher scale of exploitation pressure as a result of easier accessibility. This has caused over-exploitation resulting in a forest stand characterized with relatively high density of old or stunted vegetation (Table 3). This is characteristic of unmanaged mangrove forests experiencing unregulated harvesting (Kairo *et al*., 2002; Mohamed *et al*., 2009). The influence of environmental factors such as edaphic conditions, local inundation regime and the inflow of fresh water may also account for the difference in the status of the forest though the anthropogenic element may have an immediate profound effect on the structure of the forest.

Kilifi mangroves contains some of the largest mangrove trees in Kenya, with trees reporting more than 80 cm DBH and 28 m height compared to 35 m height reported for Kiunga (Kairo *et al*., 2001). The average canopy cover in Kibokoni was higher than Maya partly explaining the lower stem densities in the former compared to the latter. The 'shading effect' by tall trees potentially inhibits regeneration, promotes seedlings and juvenile mortalities. This is mainly a result of limited supply of light to the under-storey.

5.2 De liocourt's model

The de liocourt's negative exponential model confirms the selective forest disturbance regime based on the needs of the people, devoid of a consistent harvesting plan, contributing to a selective spatial distribution of different size classes. Assuming that tree size express age, a density curve was obtained in this study (Fig. 3) to predict the nature of the future forest. The observed low stem density of market-preferred pole sizes (11.5 – 14.0 cm) and abundance of the larger poles (20.5 – 35 cm) indicates selective harvesting. The smaller pole sizes have high market value thus face higher scale of exploitation pressure characterized by the dominance of young tree stumps in the vegetation stand, while the larger sizes are considered of low local commercial value and characteristically left back in the forest. This concurs with earlier observations made in most Kenyan mangroves (Kairo *et al*., 2002; Aboudha and Kairo, 2001).

Harmonizing the irregularities in the stem size distribution can be achieved by harvesting excess trees in those size-classes where observed densities are higher than expected. In this case, larger stem diameter classes of 14.0 – 20.5 cm and 20.5 – 35.0 cm.

The introduction of multiple uses of mangrove wood will reduce stem density per size class, hence minimize the ‘shading effect’ induced by large trees which will have detrimental impacts on the future forest re-stocking and species composition dynamics. Therefore, harvesting should be regulated through forest zoning for multiple uses, coupled with a harvesting regime that incorporates replanting and closed periods, ensuring adequate regeneration and forest growth in the long run.

5.3 Wood quality characteristics

Anthropogenic influences such as unregulated harvesting have cumulative effects on the structure and regeneration of a forest (Berger *et al*., 2006). These effects are manifested by low stem densities, high density of tree stumps, enlarged canopy gaps and often, a dominant crooked tree form depending on the harvesting regime. Similarly, our observations indicate that Kilifi mangroves are dominated by a crooked tree form (Table. 4), indicating over exploitation and harvesting patterns that are unregulated. This has led to selective removal of higher quality poles due to market preference. *R. mucronata* is reported to produce most of the straight poles in Kenya and is often the most preferred species in the market (Kairo *et al*., 2001). Similarly in Kilifi mangroves, *R. mucronata* had the highest number of straight poles (101 stems ha^{-1}) (Table. 4).

In comparison, Kilifi mangroves and generally the South of the Kenyan Coast had higher percentage composition of a crooked tree form with Kilifi, Mida and Tudor creek reporting 41.92%, 37.79% (Kairo *et al*., 2002) and 59.66% (Mohamed *et al*., 2009) respectively. On the contrary, the North of the Kenyan Coast had lower values with 24.18% in Kiunga (Kairo *et al.* 2001) and 33% in Ngomeni (Bundotich, 2007). This further confirms observation by Kairo *et al.* (2002) that mangroves in the South coast including Kilifi are facing higher scale of anthropogenic pressure. Kiunga and Mida mangrove forests occur within a National marine reserve and thus have a management regime explaining the low percentage of the crooked tree form.

On the contrary, Kilifi mangroves are unmanaged characterized with unregulated harvesting causing overexploitation and degradation indicated by the high percentage of crooked tree form (Table. 4). Mangrove degradation in Kenya manifests itself in terms of lowered quality of poles (Kairo *et al*., 2002), resulting in loss in the national economic value of mangrove forests in Kenya. The population pressure coupled by the increasing demand for mangrove wood products in Kilifi, the future quality of Kilifi mangrove products remains threatened.

5.4 Forest rejuvenation

The overall juvenile density varied greatly between localities but was on average high, ranging between 17,190 - 17,217 seedlings ha^{-1}. This is higher than the recommended 2,500 seedlings ha^{-1} by FAO (1994). Hence the mangrove forest of Kilifi Creek has a good potential for successful forest re-stocking and natural recovery. The relatively high regeneration in Kilifi creek (Table. 5) further indicates the inherent capacity of the mangrove forest to recover under the current disturbances regime.

The juvenile species diversity was comparatively lower in Kibokoni than Maya. This may be linked to less favorable site conditions leading to high juvenile mortality. The high ‘a’ value in the de liocourt’s exponential model equation also suggested higher mortality rates in Kibokoni (0.62) than Maya (0.38).

Observations indicate regeneration based on the “direct replacement” model, with species replaced by members of the same species as reflected by stand composition. Similarly, observation of juvenile distribution in most cases corresponded to those of their parent trees which concur with earlier observations along the Kenyan coast (Van Speybroeck, 1992). However, there was periodic occurrence of juveniles in zones occupied by adults of different species which can be linked to re-colonization by a more competitive species.

The principal species in Kilifi Creek has conferred advantage over the other species under the current disturbance regime. The enlarged canopy gap as a result of unregulated harvesting has favored the salinity tolerant *A. marina* and the shade intolerant *R. mucronata* over the other species (Table. 5). On the contrary, *B. gymnorrhiza* (756 saplings ha^{-1}), *X. granatum* (58 saplings ha^{-1}) and *S. alba* (3 saplings ha^{-1}) had comparatively very low regeneration. This was also expected of *X. granatum* because it is characterized as a rare species in Kenya and not extensive in distribution. Low regeneration of *S. alba* may be due to the hydrological tidal regime with relatively strong mechanical effects of tides and wave currents in the low tidal zones. Similar observations were made in Tudor creek (Bosire *et al*., 2014)

Unregulated harvesting has enlarged gaps resulting in the abundance of juveniles in smaller gaps/open canopy and under inter-mediary canopies (20 - 40%) than in larger gaps (>60%) (Fig. 5). Forest canopy gaps are as a result of anthropogenic disturbances such as selective harvesting (Duke, 2001). This harvesting pattern is evident in Kilifi Creek (Fig. 3), driven by the local market demands and preference. Large canopy openings are characterized by increased light, higher soil salinities and temperature.

This will consequently induce lowered regeneration and altered forest growth due to limiting site conditions within large gaps (Clarke and Kerrigan, 2000). Thus, constraining the successful future forest re-stocking. Therefore, this calls for the mangrove management regime to develop specific management strategies for the harvesting of different species to ensure maintenance of forest diversity and gap recovery is fast enough to minimize human-induced canopy gap sizes within Kilifi mangrove forest.

5.5 Biomass accumulation estimates

5.5.1 Above ground biomass accumulation

This study indicated that Kilifi mangrove forest has high biomass accumulation potential with variations across the different vegetation zones. Variations in above ground biomass accumulation could be linked to differences in the structural mangrove composition including the stand densities. The prevailing environmental site conditions including salinity and fresh water input also account for the differences. In addition, age of the stand, species individual plant attributes, management systems and degree of anthropogenic pressure including harvesting pressure also play a key role.

In terms of species attributes, *Rhizophora* has prop roots which could be considered as part of the above ground biomass. This accounts for the high above ground biomass accumulation for this particular species. The comparatively lower above ground biomass accumulation in the landward species; *C. tagal* may be due to the high salinity stress conditions within their zones due to lack of daily tidal inflows that limits their growth. Globally, the mean above ground biomass in this study (103.4 Mg ha^{-1}) was higher than the reported value of 80.5 Mg ha^{-1} (Khan *et al.*, 2009) for mangroves in Okinawa, Japan. However, it was less than values reported for the Bahile mangrove forest in the Philippines with 356.1 Mg ha^{-1} (Azyleah *et al.*, 2014) and Sarawak Mangrove Forest in Malaysia with 116.8 Mg ha^{-1} (Chandra *et al.*, 2011).

5.5.2 Below ground biomass accumulation

The high variation in the below ground biomass accumulation between the species could be linked to both the inherent characteristics of the species and prevailing site conditions such as salinity. The high value observed in the seaward species; *S. alba* is for the provision of strong anchorage support against high velocity wave action and also to increase the surface area for gaseous exchange. High variation in salinity conditions in the both the Landward species; *A. marina* and *C. tagal* could have resulted in better roots development as an adaptation for nutrients and oxygen uptake in the hyper saline and anoxic substrate conditions as represented by the high root:shoot ratio.

R. mucronata had a low below ground biomass accumulation as most of its roots constitute the above ground biomass in the form of prop roots. All the other species had high below ground biomass with *B. gymnorrhiza* and *X. granatum* constituting 30% each. This further highlights the challenge of growing in a hypoxic, nutrient-deficient and hyper-saline mangrove environment.

The overall percentage for below ground biomass in Kilifi (27%) was significantly higher than the value of 8.5% reported for the *Rhizophora* species in Malaysia (Ong *et al.*, 1995) and 20% for a 12 year old replanted *R. mucronata* plantation in Kenya (Kairo *et al.*, 2008). The variation is mainly due to differences in the management regimes. Globally, the mean below ground biomass in this study (37.9 Mg ha^{-1}) was lower than the reported value of 134.9 Mg ha^{-1} (Bosire *et al.*, 2013) in Zambezi delta, Mozambique.

5.5.3 Total biomass and carbon accumulation

This study indicates that Kilifi mangrove forest has high biomass and corresponding carbon storage potential with variations across the different species and vegetation zones. Comparatively, the high biomass in Kibokoni can be linked to the higher tree height stand compared to Maya (Table. 2) as mangrove biomass generally increases with height (Duke *et al*., 2013). *R. mucronata* had the highest biomass estimate due to being the most dominant species in Kilifi mangrove forest with the highest density.

However, variation in total biomass and carbon accumulation estimates could also be linked to the differences in salinity conditions within different mangrove localities. *S. alba* and *R. mucronata* are seaward species in zones with smaller ranges of salinity fluctuations due to daily tidal inflows. On the contrary, *A. marina* and *C. tagal* are landward species within zones that are subject to wide variations in salinity conditions.

Consequently, this inhibits growth due to hyper-saline conditions because mangrove trees attain optimum growth at low to moderate salinity levels (Ball, 2002), thus resulting in reduction in biomass and consequent Carbon stock. However, other variables such as forest age, species type, anthropogenic pressure, management regime and local climatic variation could potentially affect biomass allocation patterns resulting in observed variations in different forests settings (Tamooh *et al.*, 2008).

The differences in biomass accumulation between the seaward *S. alba and R. mucronata* zones against the landward *A. marina* and *C. tagal* zones further highlights the spatial differences in environmental conditions across the forest setting.

The overall tree biomass of Kilifi forest (138.3 Mg ha^{-1}) was lower than the global estimated value of 460 Mg ha^{-1} (Komiyama *et al*., 2008) and 757 t ha^{-1} (Azyleah *et al*., 2014).

5.5.4 Ratio of above ground to below ground biomass (AGB:BGB)

The ratio of above ground to below ground for *R. mucronata*in this study (1:2.5) was lower than in a 12 year old replanted *R. mucronata* plantation in Kenya where a ratio of 1:4 was obtained (Kairo *et al*., 2008). This variation could be also be attributed to differences in management regimes. The present study was carried out in a natural forest, whereas the previous related study was done in a *R. mucronata* plantation where management activities such as the spacing which aid to minimize competition which could have influenced tree growth and development.

The overall forest ratio of 1:2.7 reported in this study was within the range reported for mangroves by Kauffman *et al.* (2011) and Azyleah *et al.* (2014) with 1:2.6 and 1:2.8 respectively. This further illustrates that the carbon content of roots are generally lower than the above ground tree components (Howard *et al*., 2014). Comparatively, the above ground and below ground biomass ratio for Kilifi was lower than the reported ratio of 1:4 recorded by Ong *et al.* (1995) in a 20 year plantation of *Rhizophora* species in the Matang mangrove forest in Malaysia.

The ratio for this study was also lower than the 1:4 recorded for terrestrial forests (Cairns *et al.*, 1997) which further confirms that mangroves accumulate larger amounts of biomass in their below ground roots compared to terrestrial forests due to the prevailing nutrient limited, oxygen devoid, hyper-saline conditions and loose substrate condition in mangroves (Komiyama *et al*., 2000).

5.6 Tree carbon stock

This study presents a high carbon storage potential for Kilifi mangroves with variations across the two study sites. Global estimates indicate that the Bahile forest in Indonesia had significantly higher mean carbon stock of 356 t C ha^{-1} (Azyleah *et al.*, 2014) than the 69.2 t C ha^{-1} reported in Kilifi mangrove forest.

The above ground carbon estimates also showed that Bahile forest mangrove in Indonesia (263.8 t C ha^{-1}; Azyleah *et al*., 2014) and Thailand (220.5 t C ha^{-1}; Kridiborworn *et al.,* 2012) had higher above ground C-stock mean than the reported value of 51.7 t C ha^{-1} in Kilifi. However, in Southern China the value of 55.0 t C ha^{-1} (Chen *et al*., 2012) was within range of the present study.

The below ground mean C-stock of the micronesean forest in Asia; 110 t C ha^{-1} (Kauffman *et al*., 2011) was also higher than the value of 18.9 t C ha^{-1} reported in Kilifi mangroves. However, the present study had higher values than the mangrove plantations in Northern Vietnam; 10.7 t C ha^{-1} (Nguyen *et al*., 2009) and Tamil Nadu, India; 15.5 t C ha^{-1} (Kathiresan *et al*., 2013).

The variation in carbon stock could be linked to the factors affecting stand biomass including; age of stand, individual species structural characteristics and management systems. The overall below carbon content of roots was only 18% of the total carbon accumulation and this is expected of mangrove ecosystems as the below carbon is usually lower than the above ground tree components (Howard *et al.,* 2014).

CHAPTER SIX: CONCLUSION AND RECOMMENDATIONS

6.0 Conclusion

The mangroves of Kilifi creek are disturbed and are recipient of significant anthropogenic pressure, such as over-exploitation coupled by unregulated and selective harvesting which has had an accumulated effect on the structure and regeneration of the forest through loss of mangrove stands and subsequent carbon stock losses. Therefore, this poses a principal threat to the future sustainability of the mangrove forest. This is typical of unmanaged forests devoid of a management plan.

However, despite the disturbance regime Kilifi mangroves showed inherent resilience which implies with improved management, the forest can naturally re-stock itself. The high potential of carbon stocks reported in Kilifi mangroves further presents the opportunity of exploring the mangrove carbon credit systems to promote local socio-economic development and concurrently conserve the Kilifi mangroves carbon sinks.

6.1 Implications

This study presents a good example of anthropogenic impacts in a mangrove forest setting. The Primary focus is paid more to the goods the ecosystem provides but less to the ecological services resulting in unsustainable exploitation. This leads to forest degradation adversely affecting the structure and regeneration of mangroves which threatens the future forest sustainability. Substantial carbon stock losses compromises the climate change mitigation potential of mangroves increasing local vulnerability to climate change impacts.

The current mangrove harvesting pattern is alarming in Kenya unless timely management interventions are introduced, the integrity of the natural ecosystem will remain threatened manifested by particular species under critical threat e.g. *X. granatum*.

The information from this study should be relevant to the mangrove management regime, particularly KFS (Kenya Forest Service) in developing appropriate strategies in sustainably managing and conserving this fragile ecosystem. Quantitative data on Kilifi mangroves in this study will provide appropriate guidelines in designing cutting plans. Similarly, knowledge on the quantity of poles per size-class and their relevant species will be essential in the issuance of harvesting licenses. Biomass accumulation estimates results will also have direct application in market based Payments for Ecosystem Services (PES) such as Reduced Emissions from Deforestation and Degradation (REDD+) and will aid in both community development and conservation of mangroves for sustainability.

6.2 Recommendations

This study recommends the following;

i. Mangrove rehabilitation should be established to curb forest degradation and stand losses to curb the ongoing over-exploitation and selective harvesting pressure.

ii. A management plan should be designed and effectively implemented to guide the sustainable utilization of Kilifi mangrove forest. The diminishing stands of *Xylocarpus granatum* should also be of key mangrove management interest to avoid further degradation and eventual extinction of the rare species in Kenya.

iii. Harvesting should also be regulated through zoning of the forest that includes replanting and closed periods, allowing for optimal forest regeneration and growth. Introduction of multiple uses of mangrove wood will also reduce stem density per size class, hence minimize the ‘shading effect’ induced by large trees inhibiting regeneration.

iv. Mapping of Kilifi Mangroves based on biomass accumulation to quantify losses and identify areas for priority rehabilitation. In addition, allocation of high biomass areas for carbon offset projects (REDD+ Candidates) with low carbon accumulation areas utilized for activities such as ecotourism and aqua culture.

v. Future studies need to quantify the amount of soil biomass and carbon in the deep sediment and in peat and hence, there remains a gap. Research also needs to model the ecosystem carbon balance for the entire Kilifi mangrove forest and determine the Net Ecosystem Productivity. Site-Specific and species specific biomass equations should also be developed for a more precise quantification of mangrove tree biomass.

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APPENDICES

Appendix 1: Data sheet for forest assessment

Observer……………………
Photo no……………….........   Site………………..   Plot size…………................
Inundation Class (1-5)………   Forest type………   Total cover………….........
Distance from Creek………..

Species	DBH (cm)	Ht (m)	Form (1-3)	Regeneration Species	Regeneration Density	Reg. class	Quadrat size

Other observations (e.g. over-harvesting, regeneration status, influence of fresh water,(etc)……………………………………………………………………

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Appendix 2: Structural variables results

Tree density versus site

Source	DF	SS	MS	F	ρ
Site	1	716.24	407.57	26.07	0.0005
Error	1234	3208.10	1.53		
Total	1235	3924.34			

Basal area versus sites

Source	DF	SS	MS	F	ρ
Site	1	0.28659	0.18634	15.60	0.0001
Error	1434	2.32246	0.00122		
Total	1435	2.60903			

Height versus sites

Source	DF	SS	MS	F	ρ
Site	1	12108.7	6553.2	41.02	0.00012
Error	2234	28367.4	14.2		
Total	2238	40476.1			

Wood quality versus sites

Source	DF	SS	MS	F	ρ
Site	1	119.63	58.61	14.32	0.13
Error	872	1116.80	3.43		
Total	872	1236.43			

Appendix 3: Biomass results

ANOVA Biomass

Variable		DF	MS	F	ρ
AGB	Zone	1	10.325	5.21	0.001
Error		4	2.152		
BGB	Zone	1	6.325	7.25	0.002
Error		4	0.421		
TB	Zone	1	16.165	5.12	0.025
Error		4	3.164		