STRUCTURE AND BIOMASS ACCUMULATION OF NATURAL

MANGROVE FOREST AT GAZI BAY, KENYA

GITHAIGA, MICHAEL NJOROGE

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DECLARATION

This thesis is my original work and has not been presented for a degree in any other University or any other award

Githaiga, Michael Njoroge

Signed _____   Date _____

Supervisors:

We confirm that the work reported in this thesis was carried out by the candidate under our supervision.

Prof. Kiplagat Kotut

Department of Plant and Microbial Sciences

Kenyatta University

Signed _____   Date _____

Dr. Francis Kariuki

Department of Plant and Microbial Sciences

Kenyatta University

Signed _____   Date _____

Dr. James G. Kairo

Marine Ecology and Environmental Programme

Kenya Marine and Fisheries Research Institute

Signed _____   Date _____

DEDICATION

To my lovely wife Marion, my three daughters, Vanessa, Nelius and Diana, my son, Eric and to all who care for posterity.

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ACRONYMS AND ABBREVIATIONS

AGB   -   Above Ground Biomass

BGB   -   Below Ground Biomass

C   -   Carbon

CDM   -   Clean Development Mechanism

CI   -   Complexity Index

DBH   -   Diameter at Breast Height measured at 1.3 m above ground also expressed as D_{130}

FCPF   -   Forest Carbon Partnership Facility

HAD   -   Height Above Datum

IPCC   -   Intergovernmental Panel on Climate Change

IUCN   -   International Union of Conservation of Nature

IV   -   Importance Value Index

KMFRI   -   Kenya Marine and Fisheries Research Institute

LRS   -   Linear Regeneration Sampling

MEA   -   Millennium Ecosystem Assessment

PES   -   Payments for Ecosystem Services

RC   -   Regeneration Class

REDD+   -   Reducing Emissions from avoided Deforestation and Forest Degradation

UNEP   -   United Nations Environmental Program

UNFCCC   -   United Nations Framework Convention on Climate Change

WIO   -   Western Indian Ocean

ABSTRACT

Mangroves occupy only 0.4% of forested areas globally but are among the most productive ecosystems on earth. They account for about 11% of the total input of terrestrial carbon into the oceans. The above ground carbon stock in mangroves in some parts of the World has been estimated to be as high as 8 kg C m^{-2}; with a similar amount reported for below ground components. Although a lot of research has been done on estimates of mangrove biomass in Kenya, there is no information on biomass accumulation across the zones. The present study aimed at determining the forest structure and estimating above and below ground biomass accumulation in Gazi Bay mangrove forest. Forest structure was determined in the western, middle and eastern forest blocks of the Gazi Bay mangrove forest while biomass accumulation studies were done in the western forest block. In-growth cores of 80 cm long × 20 cm wide and 60 cm-depth were used to estimate below ground biomass accumulation. Data on tree height and stem diameter at breast height (DBH-$_{130}$) were used to estimate above ground biomass accumulation. Shoots were tagged for monitoring leaf phenology. Periodic measurements of environmental variables across four mangrove species zones were done at the beginning, thereafter every four months for a year. Composition and distribution pattern of natural regeneration was obtained using the method of linear regeneration sampling (LRS). Among the soil environment properties investigated, salinity had a significant negative correlation with above ground biomass accumulation. Comparing the four forest zones, *Sonneratia alba* had the highest biomass accumulation rate of 10.5 ± 1.9 t ha^{-1} yr^{-1}. This was followed by *Rhizophora mucronata* (8.5 ± 0.8 t ha^{-1} yr^{-1}), *Avicennia marina* (5.2 ± 1.8 t ha^{-1} yr^{-1}), and *Ceriops tagal* (2.6 ± 1.5 t ha^{-1} yr^{-1}). There were significant differences in above ground and below ground biomass accumulation across zones (F$_{(3, 8)}$ = 5.42, p = 0.025) and (F$_{(3, 8)}$ = 16.03, p = 0 001) respectively. Total biomass accumulation was significantly different across zones (F$_{(3, 8)}$ =15.56, p = 0.001). A root: shoot biomass accumulation ratio of 2:5 was computed for the whole forest. The finding of this study gives better estimates of mangrove carbon capture and storage which can be used in negotiations for carbon credits in the evolving carbon market.

CHAPTER ONE

1.0   INTRODUCTION

1.1   Background information

Mangroves are salt-tolerant trees and shrubs that fringe intertidal areas of tropical and sub–tropical coastlines. They are keystone coastal ecosystems that are of economic, ecological and environmental importance to millions of people in the tropics. Mangroves provide important habitats and feeding grounds for a range of benthic and pelagic marine animals and bird species (Saenger, 2002; FAO, 2007a; FAO, 2007b), providing commercial fisheries resources and nursery grounds for coastal fisheries (Costanza *et al.*, 1997). As much as 75% of commercial fish species in the tropics spend part of their life cycle in mangroves environment (Mumby *et al.*, 2008). Mangroves are also important in climate regulation, nutrient cycling, habitat provisioning, shoreline protection and the provision of building materials and fuel wood. The value of mangrove goods and services worldwide has been estimated at US $ 1.6 billion each year (FAO, 2007b).

The area of mangroves in the world is estimated at 1.5 million km^2 (Giri *et al.*, 2011). This is about 0.4% of tropical forests or ~12% of the world's total land area (Komiyama *et al.*, 2002)**.** Despite this relatively small area, they have a significant role in the carbon cycling (Bouillon *et al.*, 2008). Mangroves are among the most productive ecosystem on earth and store on average more than 1,000 Mg C ha^{-1}. The carbon is stored in living and dead wood, although the predominant store is in the sediment (Donato *et al.*, 2011).

Observed trends in global warming and need for climate change mitigation has interested scientists on the need to understand the potential role of mangroves in carbon capture and

storage. A set of international policies called reduced emissions from deforestation and degradation (or REDD+) concerns both reducing emissions and enhancing carbon stocks through actions that address deforestation, forest degradation, forest conservation and sustainable forest management. Under REDD+ mechanism, countries willing and able to reduce emissions from deforestation and forest degradation will be compensated for doing so. Kenya has submitted a REDD Readiness Preparation Proposal (R – RPP) to the World Bank's Forest Carbon Partnership Facility (FCPF). This proposal spells out a roadmap of preparation activities indicating how REDD preparation work will be organized and managed and the financial resources needed. With approval, Kenya hopes to raise its forest cover to 10% which will contribute to climate change mitigation as well as improving the livelihoods of communities dependent on the forests through the multiple benefits such as carbon credits.

1.2   Statement of the problem

Until recently, REDD+ initiatives have concentrated on terrestrial forests with less focus on other ecosystems such as mangrove which have now been identified as key in carbon capture and storage. Past studies on vegetation productivity in mangroves have tended to rely on above ground components particularly diameter increment and litter collection (Clough, 1992; Ong, 1993). Failure to include below ground components, which in some mangrove forests may account for about 50% of total production, Komiyama *et al*. (2008), has led to underestimation of ecosystem productivity. Further, without reliable data on below ground productivity it will be difficult to accurately quantify the rates of carbon sequestration in mangrove forests.

Few studies have correlated mangrove productivity with environmental gradients such as salinity, redox, pH, temperature and tidal range. In the absence of environmental information, no

significant progress has been made in the interpretation of functional attributes of these forests. This study aimed at determining the structure and productivity of mangrove forest across environmental gradients.

1.3   Justification

The concept of Payments for Ecosystem Services (PES) is becoming one of the most important new tools for environmental management. International concern in the conservation of critical habitats and improvement of community's livelihoods within and adjacent to natural ecosystems has elicited a lot of work through major organizations. Conservation focus has been directed to threatened areas where local communities extract goods and services for their livelihood. Such intervention measures aim at reducing the threats to these ecosystems occasioned by among others, over-exploitation of resources and transformation to other uses. Since mangrove forests have been identified as significant sinks of carbon, accurate quantification of carbon capture and storage of these forests will help us establish their potential role in climate change mitigation. Sequestered carbon can then be traded as carbon credits thus supporting conservation and contributing to rural development. However lack of globally accepted methodologies curtails our estimation of the carbon capture and storage in the pools. Results of this work will be used to model carbon sequestration in mangroves forests. Such results have wide application in market based Payments for Ecosystem Services (PES) such as Reduced Emissions from Deforestation and Degradation (REDD+). Results obtained from this study will form a basis for further research in carbon accounting in mangroves and climate change mitigation.

1.4   Objectives

1.4.1   General objective

The overall objective of the study was to determine the structure and biomass accumulation in the mangrove forest of Gazi Bay.

1.4.2   Specific objectives

i.   To assess the forest structure across the three blocks of Gazi Bay mangrove forest.

ii   Determine the relationship between selected physico-chemical factors on biomass accumulation in Gazi mangrove forest.

iii.   Determine the relationship between the above and below ground biomass accumulation in each mangrove species zone of the Gazi mangrove forest.

iv.   Determine the variation in total biomass accumulation and AGB: BGB ratios of mangrove species in different zones of the Gazi mangrove forest.

1.5   Hypotheses

H_o: No significant difference in forest structure between the three blocks of Gazi Bay mangrove forest.

H_o: Soil physico-chemical factors have no significant relationship on biomass accumulation in Gazi mangrove forest.

H_o: There is no significant relationship between above and below ground biomass accumulation in each mangrove species zone of the Gazi mangrove forest.

H_o: There is no significant difference in total biomass accumulation of mangrove species in different zones of Gazi mangrove forest.

CHAPTER TWO

2.0   LITERATURE REVIEW

2.1   Mangrove environment

Mangroves belong to a small group of higher plants which have been successful in colonizing tropical intertidal areas. The best conditions for mangrove development include tropical temperatures, shoreline free of strong waves and tidal action, salt water with periodic freshwater inundation, and fine grained alluvium deposit (Tomlinson, 1994). An often observed attribute of mangroves ecosystem is the horizontal distribution of species or zonation (Macnae, 1968). Certain species of mangroves are noted to fringe the seaward side where tidal inundations are frequent while others occur on the elevated side of the intertidal area. Multiple environmental gradients such as frequency of inundation, temperature, rainfall, salinity and oxygen concentration operate to control species association in mangroves (Snedaker, 1989; Saenger, 2002). Typical zonation patterns observed in the Indo-West Pacific region show *Sonneratia alba* and *Avicennia marina* occupying the lowest intertidal zones while *Rhizophora mucronata* and some species such as *Bruguiera gymnorrhiza* and *Ceriops tagal* occupy the mid-intertidal zones (Macnae, 1968; Kairo, 2001). In some forest formation, *Avicennia marina* will exhibit double zonation, with species occurring in the high and low intertidal zones (Dahdouh-Guebas *et al.*, 2004a).

Mangroves are adapted to the harsh environment in several ways which include: possession of pneumatophores for gaseous exchange, processes such as salt exclusion, and in some species, salt secretion and viviparous seed development (Tomlinson, 1994). Mangrove trees deal with salt

stress by filtration of the soil water at root level and by secretion of salt crystals via salt glands on their leaves (Sobrado, 2005).

Mangroves provide a wide range of goods and services. They provide people with wood products for construction and fuel wood (Saenger, 2002; FAO, 2007b). These forests act as natural barriers against strong waves and other natural oceanic catastrophes. During the 2004 tsunami incidence in South East Asia, shorelines with healthy mangroves were found to suffer relatively less loss of human lives and property than those denuded of mangroves (Dahdouh-Guebas *et al.*, 2005). In fisheries, mangrove ecosystems serve as nursery and feeding grounds for commercial and artisanal fisheries, and are important habitats and feeding grounds for a range of benthic and pelagic marine animals and bird species. Today they have been identified as major sinks of carbon.

2.2   Mangrove forest structure

The architecture of a mangrove forest is influenced by the magnitudes and periodicities of such forcing functions as tides, nutrients, hydroperiod, and stressors such as hurricanes, drought, salt accumulation, and frost. These in turn determine the basal area of the stem(s), the, height, overall density and the species diversity of the forest stand. Tidal regime and the hydroperiod are the most important component of the energy signature of the mangrove forest (Lugo and Snedaker, 1974).

2.3   Productivity of mangroves

Mangroves are among the most productive systems on earth with a mean production of 8.8 t C ha^{-1} yr^{-1} (Jennerjahn and Ittekkot, 2002). This translates to a global average of 218 ± 72 Tg C yr^{-1} (Bouillon *et al.*, 2008). Productivity in mangroves is to a large extent related to age, dominant

species, hydrology and locality in relation to geomorphology and latitude, climate, and management regime (Komiyama *et al.*, 2008). The most productive systems are the riverine forests followed by the basin, fringe and finally the dwarf as influenced by the environmental functions (Twilley *et al.*, 1992).

Three main methods are used for estimating forest biomass: the harvest method, the mean-tree method, and the allometric method. In a mature mangrove forest, the total weight of an individual tree often reaches several tons (Komiyama *et al.*, 2005). Therefore, the harvest method cannot be easily used in mature forests and in itself is not reproducible because all trees must be destructively harvested. The mean-tree method is utilized only in forests with a homogeneous tree size distribution, such as plantations. The allometric method estimates the whole or partial weight of a tree from measurable tree dimensions, including trunk diameter and height, using allometric equations. This is a nondestructive method and is thus useful for estimating temporal changes in forest biomass by means of subsequent measurements. However, the site- and species-specific dependencies of allometric equations pose a problem to researchers because tree weight measurement in mangrove forests is labor-intensive.

Most biomass work in mangroves has been in above ground biomass (AGB) with relatively less study on below ground (BGB) (Ong *et al.*, 1995). The most reliable estimates of mangrove productivity comes from well managed plantations in S. E. Asia where biomass accumulation of 18 t ha^{-1} yr^{-1} has been realized in a 10 year old stand of *Rhizophora apiculata* (Ong *et al.*, 1995). In Thailand, above ground biomass increment ranging from 14-33 t ha^{-1} yr^{-1} was found in plantations of *Kandelia candel* aged between 6 and 14 years. In Matang forest of Malaysian Peninsular, above ground biomass accumulation was found to be 24.48 t ha^{-1}yr^{-1} (Ong *et al.*,

1995); whereas in Australia Clough (1998) estimated above ground biomass accumulation of 5.9 t ha^{-1} yr^{-1} equivalent to 2.9 t C ha^{-1} yr^{-1}. Biomass accumulation rates in Western Indian Ocean (WIO) region exists only for Gazi Bay in the south coast of Kenya; where 11 t ha^{-1} yr^{-1} (or 5.48 t C ha^{-1} yr^{-1}) was recorded from a 12-year old *Rhizophora* plantation (Kairo *et al.*, 2008).

Below ground biomass is logistically more difficult to measure than AGB (Vogt *et al.*, 1998). Perhaps not surprisingly then, they are referred to as the "hidden half"(Jackson *et al.*, 1996). Knowledge of root biomass and productivity is critical for understanding tradeoffs between shoot and root carbon allocation as well as ecosystem carbon cycling. In terrestrial forests, below-ground biomass usually accounts for ~20% of the total biomass (Cairns *et al.*, 1997). In contrast, the below-ground biomass in mangroves often represents 30-60% of the total biomass (Golley *et al.*, 1962; Tamooh *et al.*, 2008). In some cases below ground biomass may exceed above-ground biomass by a factor of four (Saintilan, 1997). Knowledge of below-ground processes is, therefore, key to understanding mangrove ecosystem functions.

In the Everglades mangrove forests in Florida, root productivity ranged from 0.2 t C ha^{-1} yr^{-1} to 0.47 t C ha^{-1} yr^{-1} while in Hinchinbrook channel, accumulation of carbon below ground was estimated at 0.2 t C ha^{-1} yr^{-1} in stands dominated by *Rhizophora* species to 3.8 t C ha^{-1} yr^{-1} in stands dominated by non–*Rhizophora* species (Clough, 1998). Looking at the shoot: root ratio, in a 20-year-old plantation of the Matang mangrove forest, Ong *et al.*, (1995) reported above-ground biomass increment of 24.4 t ha^{-1} yr^{-1} compared to 9.6 t ha^{-1} yr^{-1} for the below ground accumulation. Results of the above studies represent a root: shoot (R:S) ratio of about 1: 3. This ratio was higher than the 1:4 root: shoot ratio obtained from a study on tropical moist forest in Brazil (Brown, 1997).

Fine root production represents a large proportion of total annual net primary production in most ecosystems being concentrated on the lateral branches that arise from the perennial roots (Komiyama *et al.*, 1987). Fine roots in mangroves contribute between 24% and 45% of the total live below ground root biomass depending on the species (Tamooh *et al.*, 2008). In contrast, the proportion of fine root biomass to the total root biomass in terrestrial forest is low ranging from 0.2% to 17.9%. This high productivity of fine roots may be attributed to higher below ground carbon allocation (Tamooh *et al.*, 2008). Coarse roots contribute more to the total biomass than fine roots in terrestrial ecosystems. However mangrove fine roots contribute up to 66% of the total biomass (Komiyama *et al.*, 1987).

2.4   Mangrove phenology

Phenological studies are involved with the observation and documentation of the timings of life history events of plants. Such events include periods of maximum leaf appearance, leaf fall, flowering, fruiting and their relationship to seasonal changes (Duke, 1988). Detailed year to year information on these traits helps in the understanding of the adaptations, dispersal, survival and distribution of plant species. Mangrove species display phenological events which are staggered in time and space. The plants may either stagger their phenological activity to avoid competition for pollination and dispersal agents or may opt for clumping of phenological activity to attract the pollinators and dispersers or to swamp the predators (Duke, 1988). Mangrove phenology can be used as an indicator of mangrove productivity in terms of leaf gain and leaf fall and also through its reproductive capacity in terms of flowering and fruiting. Knowledge on phenology would therefore help in understanding the period of maximum root growth as more vegetative growth leads to investment in below ground biomass. It also helps to understand the period of fruit formation and hence seed availability. At Gazi pilot area, Wang'ondu *et al.* (2010) found

Ceriops and *Rhizophora* fruiting all year round but maximum fall of propagules was observed between April and July; whereas in *Avicennia* and *Sonneratia* maximum production was experienced in April-May and October -November periods respectively.

2.5   Threats to mangroves

Worldwide mangrove forests have been estimated to have covered 75% of the tropical coasts Valiela *et al*. (2001) but human pressure, including; overexploitation, conversion and pollution effects have reduced their global range to less than 50% of the total original cover. Currently the mangrove forests cover is less than 1% of the earth's continental surface estimated at 137,760 km^2 distributed in 118 countries and territories (Giri *et al.*, 2011). This represents a 12% decline from the earlier estimate of 1.5 million km^2 (Giri *et al.*, 2011). Relative sea-level rise projected at 0.18-0.59 m by the end of the 21st century, exacerbated by climate change could be the greatest threat to mangroves (Gilman *et al.*, 2008). This vulnerability may be due to the inability of the mangroves to keep pace with the sea level rise. Rates of mangrove loss may be as high as or higher than rates of losses of upland tropical wet forests (Valiela *et al.*, 2001; FAO, 2007a). Current exploitation rates are expected to continue unless mangrove forests are protected as a valuable resource. Given their accelerating rate of loss, mangrove forests may at least functionally disappear in as little as 100 years (Duke *et al.*, 2007). Such a scenario would negatively affect ecosystems and the livelihood of coastal communities.

The annual average loss of mangroves in Africa is estimated at between 20 – 30% (FAO, 2007a). Recent estimates of mangrove loss in Kenya point to an average of 18% in a period of 25 years between 1985 and 2010 (Kirui *et al.*, 2012). Major threats to mangroves of Kenya are over-exploitation, conversion of mangrove areas to other land uses and oil pollution. Over harvesting

has seriously depleted the availability of quality poles from most mangrove areas (Abuodha and Kairo, 2001). Along the northern Kenyan coast, conversion of mangrove areas for solar salt works and pond culture for fish farming is localized in Ngomeni and in peri-urban area of Mombasa, mangroves have been killed through oil spills (Abuodha and Kairo, 2001).

2.6   Mangroves and climate change

Climate change has introduced new dimensions to the efforts to conserve and restore mangrove forests. The importance of mangroves as our first line of coastal defense against natural and climate related disasters (e.g. tropical storms, wave surges) has been increasingly recognized over the past decade, especially since the 2004 tsunami. The protective roles of mangroves (e.g. erosion reduction, wave attenuation, sediment accretion and storm wave abatement) will be increasingly needed to protect shorelines against both rising sea levels and the increase in frequency and strength of extreme weather events. Over the past decade or so, there has also been increasing interest in the role that mangroves play in global carbon budgets and carbon cycles. Recent findings estimate that mangrove forest soils can sequester as much as six times the CO_2 of tropical rainforests per hectare per year (Donato *et al.*, 2011). Avoiding mangrove deforestation may not only prevent CO_2 release, but play a more significant role in addition to sequestration than would be achieved by other forest types. There is growing evidence and consensus that the management of coastal blue carbon ecosystems, through conservation, to avoid loss and degradation, restoration and sustainable use has strong potential to be a transformational tool and an important opportunity in the current portfolio of climate change mitigation strategies.

Kenya Marine and Fisheries Research Institute (KMFRI) is teaming up with national and international partners in developing projects to address mitigation and adaptations of mangroves to changing climate. Perhaps, the most innovative of these projects is "Mikoko Pamoja"; a small scale carbon feasibility project on mangroves being piloted in Gazi Bay, in the south coast of Kenya. Using an initial area of 117 ha of mangroves of Gazi, an estimated US$ 15,000 yr^{-1} will be generated from the sale of approximately 3000 t CO_2 equivalent sequestered carbon. The current study is of significance as the biomass accumulation estimates will predict future biomass trends and act as a pointer to the role these forests play in climate change mitigation. The estimates will be used in future negotiations for carbon credits. This study is part of a long term KMFRI/Earthwatch Institute research on biodiversity and ecosystem functioning of the mangrove forests of Kenya.

2.7   Mangrove forest at Gazi Bay

2.7.1   Climate at Gazi Bay

The climate in Gazi Bay is typical of that of the Kenyan coast and is principally influenced by monsoon winds. Total annual precipitation varies between 1000 mm and 1600 mm with a bimodal pattern of distribution (Fig. 1). The long rains fall from April to August under the influence of the Southeast monsoon winds, while the short rains fall between October and November under the influence of the northeast monsoon winds. It is normally hot and humid with an average annual air temperature of about 28°C with little seasonal variation. Air temperature in Gazi Bay varies between 24°C and 39°C. Relative humidity is about 95% due to the close proximity to the sea. The mangroves are not continuously under the direct influence of freshwater because the two rivers, Kidogoweni in the north and Mkurumji in the south draining

into the Bay are seasonal and dependent on the amount of rainfall from inland. Groundwater seepage is also restricted to a few points.
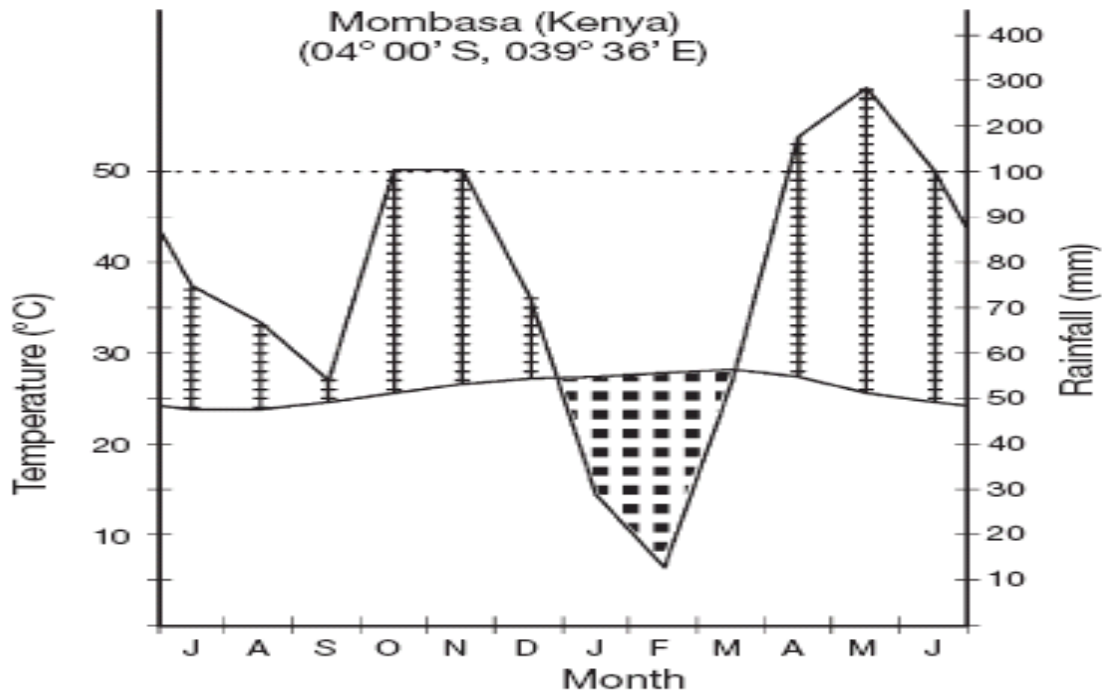
Fig. 1: Mean monthly rainfall (upper continuous line) and temperature (lower continuous line) patterns at South Coast. Kenya Lieth *et al*. (1999) for the periods 1890–1985 (rainfall) and 1931–1990 (temperature) complemented with data from the Meteorological Department in Mombasa for the periods 1986 – 2001 (rainfall) and 1991–2001 (temperature).

2.7.2 Mangrove species at Gazi Bay

Gazi mangrove formation closely resembles other mangrove forests of Kenya. All species of mangroves described in the Western Indian Ocean (WIO) region occur in Gazi. The dominant species are *Rhizophora mucronata* (Lam)*, Ceriops tagal* (Perr.) C.B.Robinson*, Avicennia marina (Forsks)* Vierh.*, Bruguiera gymnorrhiza* (Lam)*, Sonneratia alba* (Sm)*;* which contributes more than 80% of the Gazi mangrove formation (Table 1). Other species are *Xylocarpus granatum*

(Koen)*, Xylocarpus mollucensis* (Koen)*, Heritiera littoralis (*Dryand ex H.Ait*) and Lumnitzera racemosa* Willd (Kairo *et al.*, 2008).

 Table 1: Mangrove species found in Kenya

Species	Local name	Family name
Rhizophora mucronata	Mkoko	Rhizophoraceae
Bruguiera gymnorrhiza	Muia	Rhizophoraceae
Ceriops tagal	Mkandaa	Rhizophoraceae
Sonneratia alba	Mlilana	Lythraceae
Avicennia marina	Mchu	Acanthaceae
Lumnitzera racemosa	Kikandaa	Combretaceae
Xylocarpus granatum	Mkomafi	Meliaceae
Xylocarpus mollucensis	Mkomafi dume	Meliaceae
Heritiera littoralis	Msikundazi	Malvaceae

*(Family names according to the Angiosperm Phylogeny Group (APG) III Taxonomy classification of mangroves).

The mangrove species in Gazi exhibit zonation. *Sonneratia alba* forms the outermost zone towards the open water followed by pure or mixed stands of *Rhizophora mucronata* or mixed stands of *Rhizophora mucronata* and *Bruguiera gymnorrhiza* and in turn these stands are followed by pure stands of *Ceriops tagal* and *Avicennia marina* (Fig. 2). Along the creeks, *Avicennia marina* usually replaces *Sonneratia alba* and these *Avicennia marina* trees are much taller (12.5-18.0 m) than those on the elevated areas (2.5-3.0 m, shrub type).

2.7.3 Mangrove exploitation and restoration at Gazi Bay

Gazi Bay mangrove forests were heavily exploited in the 1970s for industrial use. This left large denuded areas with no natural regeneration (Kairo, 1995; Bosire *et al.*, 2005). The mangroves of Gazi have continued to be heavily exploited for the extraction of wood fuel especially firewood as well as for building poles by the local population (Abuodha and Kairo, 2001).
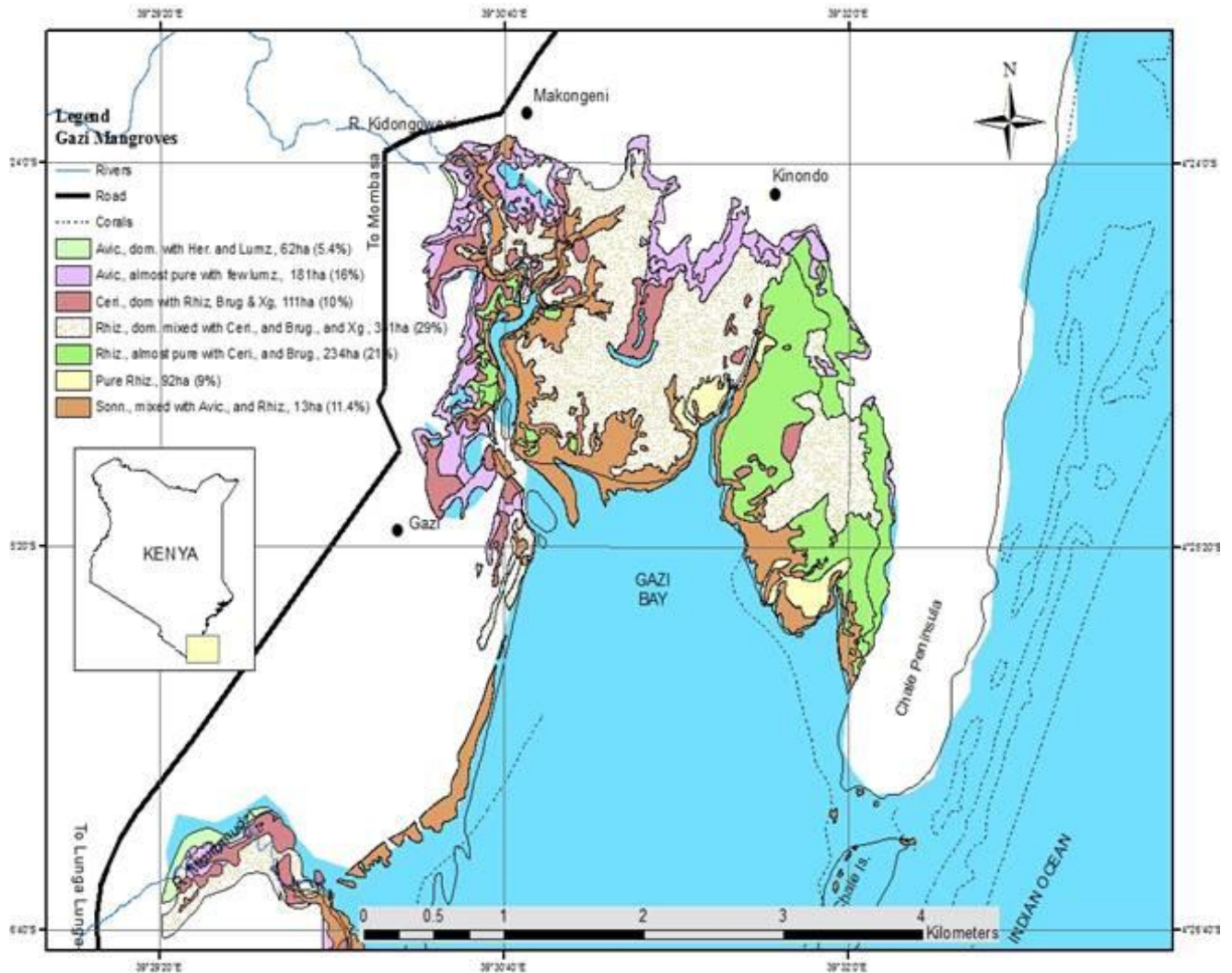
Fig. 2: Vegetation map of Gazi mangrove forest showing the distribution of mangrove species. (Source GIS centre, KMFRI).

Sedimentation caused by shoreline change and El-Niño weather has also contributed to death of mangroves at Gazi (Dahdouh-Guebas *et al.*, 2004b). To address this problem, Kenya Marine and Fisheries Research Institute (KMFRI) initiated trial restoration of degraded mangrove areas at Gazi Bay in the 1990, which have continued to date (Kairo *et al.*, 2001).

CHAPTER THREE

3.0   MATERIALS AND METHODS

3.1   Study site

The study was conducted at Gazi Bay (4^o25'S, and 39^o30'E) on the southern coast of Kenya, about 55 km from Mombasa city (Fig. 3).
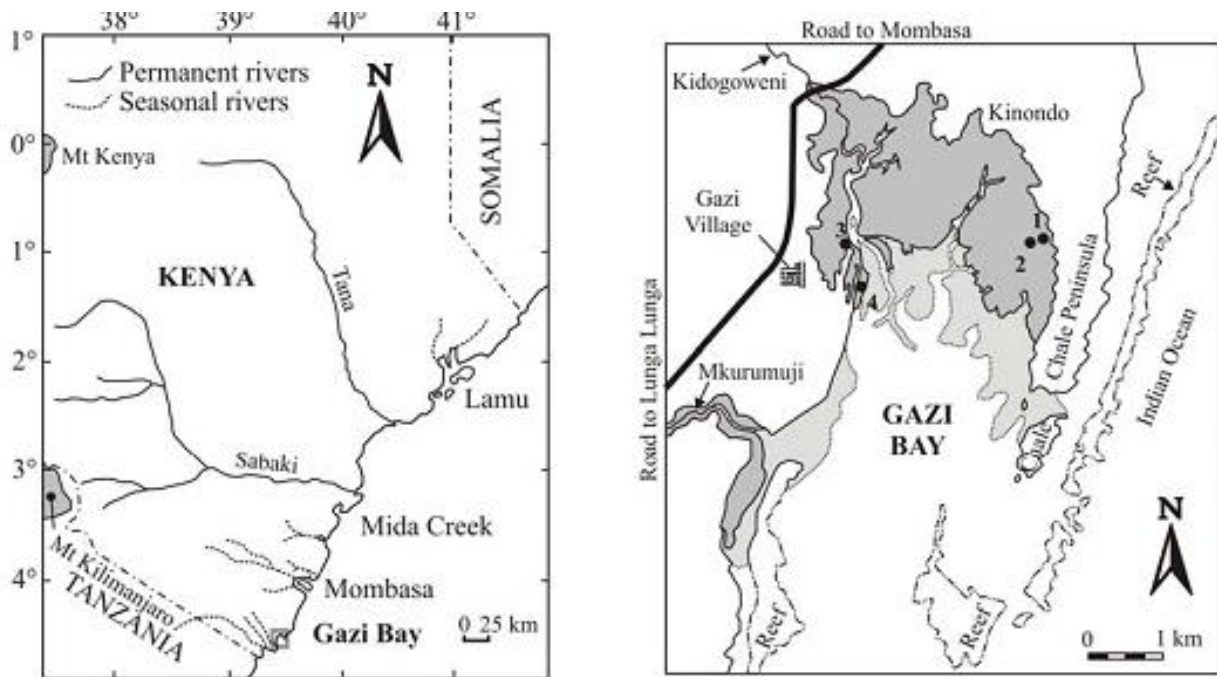
Fig. 3: Map of the study site, in the mangrove forest of Gazi Bay on the Kenyan Coast. (Source: Bosire *et al*., 2003).

The embayment has a surface area of 18 km^2. It is sheltered from strong waves by the presence of the Chale peninsula to the east and a fringing coral reef to the south. The area under mangroves in Gazi has been estimated at 615 ha (Kairo *et al.*, 2001). The Gazi Bay mangrove forest area is within a tidal amplitude of about 3.8 m with a maximum of 4.1 m (Kenya Ports Authority tide tables for Kilindini, Mombasa) and is characterized by a sloping topography

(Matthijs *et al.*, 1999). It is penetrated by two tidal creeks. The western creek has an inland continuation as the river Kidogoweni, while the eastern creek has no such fresh water input. In the study of forest structure, using indices such as tree DBH, height, canopy cover, stand density quality of trees and regeneration rates, the Gazi mangrove forest was divided into three forest blocks based on the two creeks. The western block is the forest west of the Kidogoweni (western) creek near Gazi village, while the eastern block is to the east of the Kinondo (eastern) creek near Kinondo village. The middle forest block lies in between the two creeks and next to Makongeni village. Determination of soil physico-chemical factors, biomass accumulation and leaf phenology were studied on the western block.

3.2   Study design

Stratified random study design was used and comprised of four zones across the topographic gradient of the western forest block representing the dominant mangrove species in Gazi. The seaward zone comprised of *Sonneratia alba*, the second, third and upper zones were represented by *Rhizophora mucronata*, *Ceriops tagal* and *Avicennia marina*, respectively. For *Rhizophora mucronata* and *Avicennia marina* zones, two sites were chosen at different locations based on the growth and structural attributes of the vegetation. *Avicennia marina* in site referred to as "A" in this study was in an area with dwarf mangroves close to the landward side while *A. marina* in site referred to as "B" was on the seaward side. *Rhizophora mucronata* in site referred as "A" in this study was at a lower tidal level with closed canopy and less regeneration while *Rhizophora mucronata* in site referred to as "B" in the study was in an open canopy and high regeneration. *Ceriops tagal* stand consisted of stunted mature trees barely 2.0 m tall with a closed canopy. Three plots measuring 10 m × 10 m were marked in each site at a distance of 30 m, giving a total of 18 plots (Fig. 4).

3.3   Physico-chemical factors

3.3.1   Measurement of height above datum

In order to measure height above datum (HAD), the highest tidal level (Kilindini tides table 2011) for the day was marked to form the benchmark or initial reference point for subsequent measurements. The height above datum of this point was noted by use of the day's estimate from the Kilindini tides table. A transparent hose pipe with water was laid on the ground with one end of the water in the pipe being at the reference point.
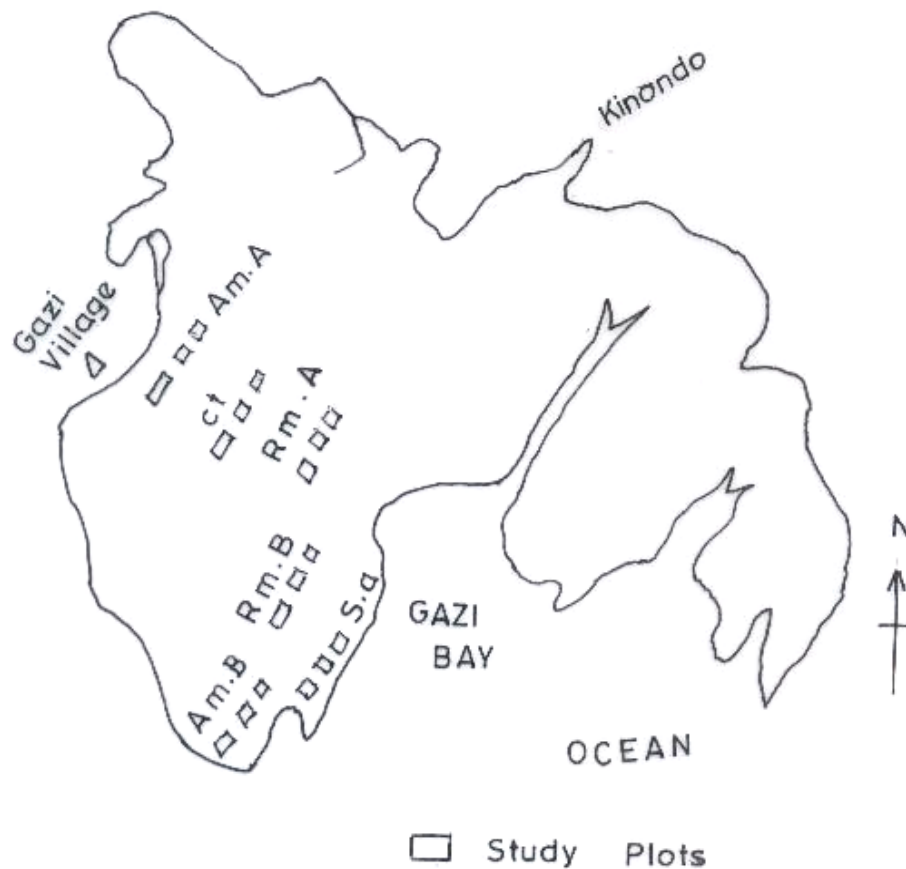
Fig. 4: Plots layout for the present study at Gazi mangrove forest. (Am, Ct. Rm and Sa refer to *Avicennia marina, Ceriops tagal, Rhizophora mucronata and Sonneratia* alba zones respectively).

The pipe was stretched towards the next plot seawards being raised gently until there was no water movement. A ruler held vertically to the water mark was used to measure the height from the ground. By subtracting this height from that of the reference point, the relative height of the plot was deduced. This was repeated passing through the plots towards the sea.

3.3.2   Measurement of redox potential and pH

For the physico-chemical soil characteristics, sediment was collected monthly from four randomly selected points within the plot at depths of 10 cm and 40 cm. Sediment redox potential and pH were measured using a multimeter (HANNA HI 8424 microcomputer pH meter).

3.3.3   Sediment surface water salinity and temperature

In the same plots, sediment samples for salinity measurement were collected from four random points, mixed and carried in sample bags. In the laboratory, the samples were centrifuged to extract the interstitial water. A hand held refractometer (ATAGO, Tokyo, Japan) was used to measure salinity. Measurements on sediment surface water temperatures were done *in situ* at four random points within the plot.

3.3.4   Sediment grain size analysis

Surface scrapes of sediment samples approximately 50 grams were taken from four random locations in each plot for granulometric analysis. In the laboratory, the sediment samples were weighed and oven-dried at 80°C for 24 hours, after which the sediments was reweighed to obtain the percentage moisture content. For grain size analysis, about 25 grams of the dry sediment of each sample was treated with 10 ml of aqueous sodium hexametaphosphate and passed through a series of sieves of varying mesh aperture; ranging from 63 to 500 μm mesh-size. From this, the relative percentage of each of the particles in the sediment was obtained.

3.4   Assessment of mangrove forest structure

3.4.1   Structural attributes of mangroves

All mangrove trees with Diameter at Breast Height (DBH) $\geq$ 5.0 cm were identified and their position marked. The following parameters were measured; tree height (m), crown cover (%), and stem diameter (DBH) (cm) at 130 cm above the ground (D_{130}) for *Avicennia marina* and *Sonneratia alba*. In *Ceriops tagal,* stem diameter (DBH) was taken at 100 cm above ground due to the low height of the trees while in the case of *Rhizophora mucronata* trees, stem diameter was taken 30 cm above the highest prop root. The basal area (BA) of each species was calculated as the sum of the cross sectional areas (CSA) of all trees of the species (m^2 ha^{-1}) at breast height. See (Equation (a), below). Stem density was calculated as the sum of the number of stems per plot, divided by the area of the plot in m^2 multiplied by 10,000. See (Equation (b), below). The importance value index of each species (IV) (a measure that indicates the relative contribution of a plant species to the structure of a stand) was calculated by summing its relative density, relative frequency and relative dominance (Cintron and Schaeffer-Novelli, 1984). See (Equation (c), below). The complexity indices (I_c) of each forest zone, (a measure of how complex or structurally developed a vegetation stand is) was computed as the product of number of species, basal area (BA) (m^2 ha^{-1}), maximum tree height (m) and stem density (D, ha^{-1}) $\times$ 10^{-5} (Holdridge *et al.*, 1971). See (Equation (d) below).

a) BA (m^2 ha^{-1}) = Sum of CSA /plot area (m^2) x 10,000
b) Stem density (Stems ha^{-1}) = No of stems in plot /plot area (m^2) x 10,000

c) IV = Relative density + relative frequency + relative dominance

d) I_c = Number of species $\times$ BA (m^2 ha^{-1}) $\times$ max. tree height (m) $\times$ density (ha^{-1}) $\times$ 10^{-5}

3.4.2 Quality of the mangrove poles

To assess wood quality, trees were categorized into three form classes, 1, 2 and 3 based on the suitability of the main stem in construction. Trees with straight poles were assigned form 1 while those with intermediate poles that need slight modification before building were assigned form 2. Crooked poles which are unsuitable for building were assigned form class 3.

3.4.3 Natural regeneration

Linear regeneration sampling (LRS) was used to assess composition and pattern of natural regeneration according to (Sukardjo, 1987; FAO, 1994; Kairo *et al.*, 2002a). Inside (5 x 5) m^2 subplots (within the main (10 x 10) m^2 quadrats), occurrence of juveniles of different species was recorded and grouped according to their height classes and arbitrarily assigned, Regeneration Classes (RC) I, II or III. The ratio of RCI: II: III was used to assess the adequacy of natural regeneration (FAO, 1994). Seedlings less than 40 cm in height were classified as regeneration class 1 (RCI). Saplings of between 40 cm and 150 cm height were classified as RCII, while RCIII represented small trees with heights greater than 1.5 m but with a DBH less than 2.5.cm.

3.5 Biomass accumulation estimates

3.5.1 Above ground biomass accumulation

In each of the 18 plots measuring 10 m × 10 m, twelve trees were randomly selected in each plot for monitoring increment in stem diameter and height. Above ground biomass accumulation was estimated once after every four months for one year by taking measurements of tree height (m) and stem diameter. A general allometric equation developed for the mangrove forests of the Kenyan coast, (In biomass = -2.29711+ (ln DBH × 2.54528) (R^2 = 0.90) by Cohen (2011) was used to calculate above ground biomass. Although several allometric equations with good

coefficient of determination ($R^2 > 0.90$) exist for the mangrove species of Gazi Bay e.g. (Slim *et al.*, 1996; Kirui *et al.*, 2006; Kairo *et al.*, 2009), these were not used in this study to calculate the above ground biomass for several reasons. Firstly, they were species specific and secondly, previous equations were based on small data set (n = 8 - 55 trees compared to n = 337 trees by Cohen (2011)). Moreover some of the equations when tested were found to overestimate the biomass at low DBH e.g Kirui *et al*. (2006) reduced by a factor of 1.8 at low DBH but reduced it by a factor of 1.5 when DBH is increased.

3.5.2   Below ground biomass increment

Below ground biomass increment was estimated using the root in-growth core method described by Vogt *et al*. (1998). In each of the 18 plots, two rectangular cores of 80 cm long by 20 cm width and 60 cm deep were made in areas between the trees. All the sediment in the cores was removed and the coarse roots (> 3mm) in diameter were sorted out. The roots were macerated into tiny pieces, mixed with the sediment and returned to the core to restore nutrients. The positions of the cores was marked using plastic pipes pegged at each corner of the core. After one year, the cores were retrieved and new roots sorted out into the different size classes (< 3 mm, 3-5 mm,5-10 mm, 10-20 mm, and >20 mm). The roots were weighed and oven-dried at 80°C to a constant dry weight and reweighed to calculate the wet: dry weight ratio.

3.5.3   Total biomass and ratio of BGB: ABG: accumulation

Total biomass accumulation was calculated as the sum of above and belowground biomass accumulation. The ratio of BGB to AGB was calculated as the below ground biomass accumulation divided by the above ground biomass accumulation.

3.5.4   Leaf phenology

In each of the 12 randomly selected trees per plot, 6 twigs distributed in the crown canopy were tagged for phenological shoot observations. Leaves present on the selected twig were all numbered consecutively on the adaxial surface using a xylene free permanent marker and care taken to prevent damage of the leaf epidermis. In subsequent sampling, any unnumbered leaves in the upper parts of the twig were treated as newly emerged. Loss of numbered leaves was recorded. The same twigs were carefully monitored for reproductive structures (buds, flowers and fruits) monthly for one year. Study on phenology was important to determine the periods of rapid growth as well as the time seeds were available for propagation.

3.6   Data analysis

Data analysis was carried out using Microsoft ® Excel spreadsheet 2007, MINTAB or Statistica packages. All data were tested for normality and normalized where necessary for parametric tests. Mean values of data sets collected from two different *Avicennia* and *Rhizophora* sites were subjected to significance tests using single classification ANOVA. Since the data from the two sites were not significantly different for all cases tested, the data were pooled before subjecting them to further analysis. ANOVA tests were used to compare mean biomass accumulation among the species. The Pearson's product-moment correlation coefficient was used to determine the relationship between selected soil physico-chemical factors and biomass accumulation.

CHAPTER FOUR

4.0   RESULTS

4.1   Soil physico-chemical factors

4.1.1   Height above datum of the four mangrove zones

The height above datum (HAD) occupied by the four mangrove species was distinct for each

species. *Sonneratia alba* occurred in the lower tidal zone on the seaward margin at a mean HAD

of 1.70 ± 0.02. Adjacent to this zone was the *Rhizophora mucronata* zone at a mean HAD of

2.53 ± 0.01m. *Ceriops tagal* occurred in the middle intertidal zone at HAD of 2.86 ± 0.01 m

while *Avicennia marina* occupied the higher tidal zone on the landward margin at HAD $3.47 \pm$

0.2 m (Means $\pm$ 1 S.E) Fig 5.
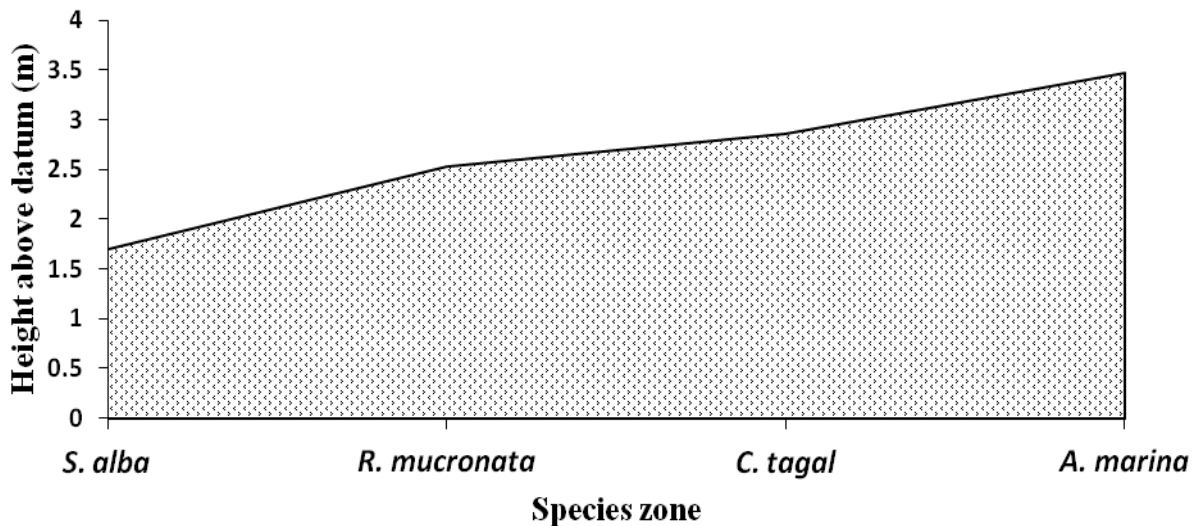
Fig. 5: Species zone from the sea to the landward margin.

4.1.2 Sediment physico-chemical factors

In the *Sonneratia alba* species zone, salinity levels varied from a high of 32.0 ± 0.2‰ during the dry season (January – April) to a low of 30.0 ± 0.6‰ during the wet season (May – September). Redox potential varied from a high value of 56.0 ± 10 mV during the dry period to a low of value of -158.0 ± 19 mV during the wet season. At the same time, pH ranged from a median value of 6.2 during the dry season (January – April), to a median value of 5.8 during the wet season (May – September). Temperature conditions varied between 32.0 ± 0.2 °C in the dry season (January to April) to 30.0 ± 0.4 °C during the wet season (May to September).

In the *Rhizophora mucronata* species zone, salinity levels varied from a high of 32.5 ± 0.2‰ during the dry season (January – April) to a low of 29.5 ± 0.6‰ during the wet season (May – September). Redox potential varied from a high value of -115.0 ± 26 mV during the dry period to a low of value of -215.0 ± 9.3 mV during the wet season. At the same time, pH range remained constant at 6 0 in both seasons. Temperature conditions varied between 30.0 ± 0.4 °C in the dry season (January to April) to 39.9 ± 0.2 °C during the wet season (May to September).

Salinity levels in the *Ceriops tagal* species zone, varied from a high of 33.0 ± 0.2‰ during the dry season (January – April) to a low of 32.0 ± 0.2‰ during the wet season (May – September). Redox potential varied from a high value of -112.0 ± 58 mV during the dry period to a low value of -197.0 ± 62 mV during the wet season. At the same time, pH ranged from a median value of 6.1 during the dry season (January – April), to a median value of 5.2 during the wet season (May – September). Temperature conditions varied between 38.0 ± 0.2 °C in the dry season (January to April) to 32.0 ± 0.2 °C during the wet season (May to September).

In the *Avicennia marina* species zone, salinity levels varied from a high of 48.0 ± 0.5‰ during the dry season (January – April) to a low of 32.0 ± 0.1‰ during the wet season (May – September). Redox potential varied from a high value of - 85.0 ± 6.0 mV during the dry period to a low of value of -112.0 ± 58 mV during the wet season. At the same time, pH ranged from a median value of 6.1 during the dry season (January – April), to a median value of 4.7 during the wet season (May – September). Temperature conditions varied between 35.5 ± 0.2 °C in the dry season (January to April) to 32.0 ± 0.2 °C during the wet season (May to September).

Comparison of variation in environmental factors across the zones indicated that substrate salinity levels ranged from a low of 30‰ in the *Sonneratia zone* to a high of 48‰ in the *Avicennia* zone. Salinity was higher during the dry season than in the wet season. There was significant difference in salinity levels across the zones both during the dry season ($F_{(3, 8)} = 13.13$; $p = 0.002$) and the rainy season ($F_{(3, 8)} = 25.87$; $p = 0.000$). Redox potential was the most variable factor among the environmental factors investigated. *Sonneratia* zone registered a high value of 56.0 mV while *Rhizophora* zone recorded a low of -215.0 mV. Redox potential was significantly different across the zones during the wet season ($F_{(3, 8)} = 27.38$; $p = 0.000$). However, the difference was not significant during the dry season ($F_{(3, 8)} = 5.70$; $p = 0. 0.22$). pH was slightly acidic across all zones ranging between 4.7 - 6.5 across the zones. Comparatively lower pH values were observed during the dry season. Substrate surface water temperature ranged from a low mean value of 30.0 °C to a high of 39.9 °C in the four zones investigated. The temperature of the substrate did not differ significantly across the zones during the dry season ($F_{(3, 8)} = 1.87$; $p = 0.214$) but differed significantly during the wet season ($F_{(3, 8)} = 8.08$; $p = 0.008$).

4.1.3 Sediment grain sizes

In the *Sonneratia alba* species zone, proportion of sediments belonging to fine sand, coarse sand and silt clay grain sizes in this zone were 64.4%, 21% and 14.0% respectively (Fig. 6). Proportion of sediments belonging to grain sizes; fine sand, coarse sand and silt clay in the *Rhizophora species* zone were 50%, 38.3% and 11.8% respectively. In *Ceriops tagal* species zones, the proportion of sediments belonging to different grain size classes in this zone were 57.3%, 35% and 7.7% for silt clay, fine sand and coarse sand respectively. In *Avicennia marina* species zone, the proportions of sediments belonging to different grain sizes were 64%, 20.5% and 12.9% for fine sand, coarse sand and silt clay respectively.
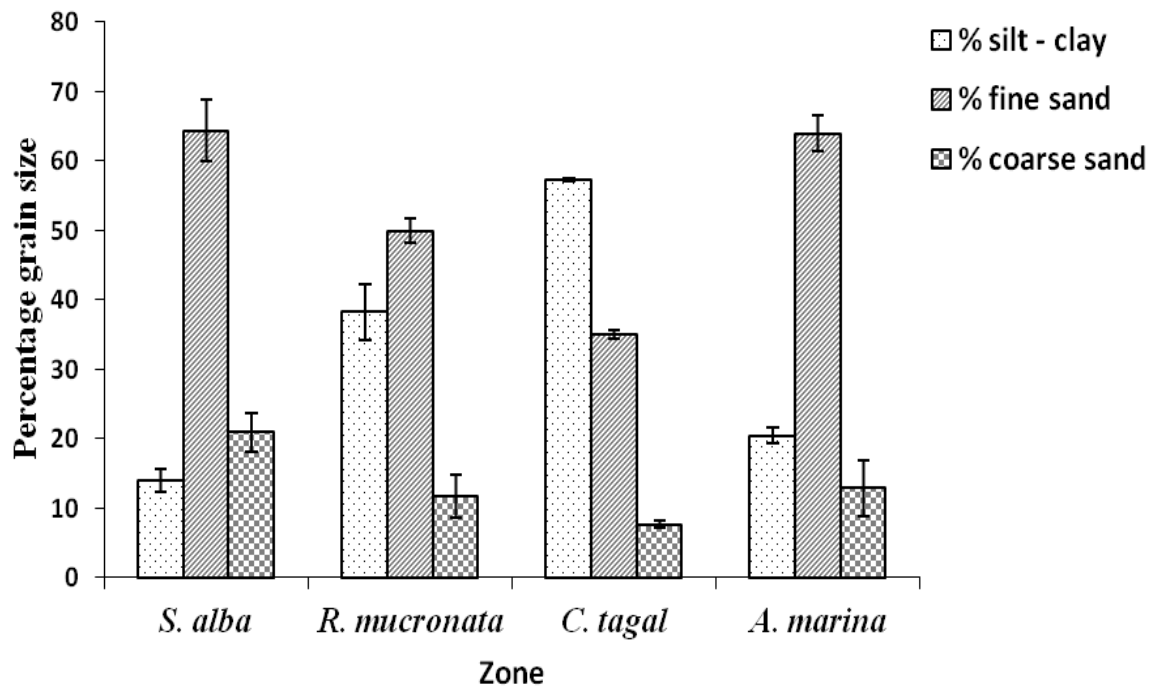
Fig. 6: Percentage contribution of different grain sizes to the total sediment weight in different forest zones of Gazi mangrove forest.

4.2   Mangrove forest structure

4.2.1   Importance value

The importance values (IV), calculated as the sum of relative derivatives of frequency, dominance and density of the main mangrove species in the study site ranged from 3.7 for *Sonneratia alba* to 191.3 for *Rhizophora mucronata* (Table 2). *Rhizophora mucronata* had the highest IV values of 87.2, 146.9 and 191.3 in the western, middle and eastern forest blocks respectively. *Ceriops tagal*, was second with importance value of 67.7, 48.7 and 23.3 for the western, middle and eastern blocks respectively. *Avicennia marina* recorded importance value of 65.1, 46.6 and 21.5 for the western, middle and eastern forest blocks respectively. At the same time, *Bruguiera gymnorrhiza* recorded importance value of 7.4, 46.6 and 52.4 for the western, middle and eastern forest blocks respectively while *Xylocarpus granatum* had an importance value of 59.2, 7.6 and 4.4 for the western, middle and eastern forest blocks respectively. *Sonneratia alba* had the lowest IV values of 13.0, 3.7 and 7.0 for the western, middle and eastern forest blocks respectively (Table 2).

Table 2: Structural attributes of western, middle and eastern forest blocks

Forest block	Species	Stems density ha^{-1}	Basal area (m^2 ha^{-1})	Relative (%) Density	Dominance	Frequency	IV
Western (Gazi)	*A. marina*	323.0	3.43	24.69	25.04	15.38	65.1
	B. gymnorrhiza	15.0	0.16	1.15	1.17	5.13	7.4
	C. tagal	377.0	1.46	28.82	10.66	28.21	67.7
	R. mucronata	308.0	4.50	23.55	32.85	30.77	87.2
	S. alba	46.0	0.64	3.52	4.67	5.13	13.3
	X. granatum	238.0	3.51	18.2	25.62	15.38	59.2
	Total	**1307**	**13.70**	**99.92**	**100**	**100**	**300**
Middle (Makongeni)	*A. marina*	153.0	6.37	11.85	26.13	8.57	46.6
	B. gymnorrhiza	133.0	3.97	10.3	16.28	20.0	46.6
	C. tagal	243.0	1.72	18.82	7.05	22.86	48.7
	R. mucronata	739.0	12.10	57.24	49.63	40	146.9
	S. alba	6.0	0.09	0.46	0.37	2.86	3.7
	X. granatum	18.0	0.13	1.39	0.53	5.71	7.6
	Total	**1292**	**24.38**	**100**	**100**	**100**	**300**
Eastern (Kinondo)	*A. marina*	122.0	1.43	10.45	7.49	3.57	21.5
	B. gymnorrhiza	156.0	3.36	13.37	17.63	21.43	52.4
	C. tagal	72.0	0.55	6.17	2.88	14.29	23.3
	R. mucronata	794.0	13.31	68.04	69.72	53.57	191.3
	S. alba	17.0	0.37	1.46	1.94	3.57	7.0
	X. granatum	6.0	0.06	0.51	0.31	3.57	4.4
	Total	**1167**	**19.89**	**100**	**100**	**100**	**300**

4.2.2   Complexity index

Structural complexity index (CI, calculated as the product of number of species, basal area, stand density and mean height x 10^{-5}) revealed that the middle block was the most complex (10.81) while the western block was the least (5.01) complex (Table 3).

Table 3: Summary of structural characteristics of Gazi mangroves

Station	Western			Middle			Eastern		
Diameter class (cm)	5.1–10.0	10.1-15.0	> 15.0	5.1 – 10.0	10.1–15.0	> 15.0	5.1–10.0	10.1–15.0	>15.0
1 No of species	6	5	5	5	6	4	5	5	5
2 Stem density (ha^{-1})	1056	350	281	1520	1024	1024	1195	436	501
3 Mean height (m)	3.70	5.20	6.90	4.80	5.68	6.90	5.33	13.40	23.0
4 Basal area (m ha^{-1})	69.4	25.1	41.9	40.22	48.2	16.5	47.9	21.6	101.0
5 Complexity index*	16.02	2.28	4.06	11.98	16.80	4.66	11.50	6.30	58.20

* The complexity index C.I. equals the product of (1), (2), (3) and (4) divided by 10^5

4.2.3 Tree height and diameter at breast height (DBH) variation across the zones

There were large differences in stem diameter and tree height within and between different mangrove blocks investigated. In the western block, 57% of the trees had a DBH of 5.1 – 9 0 cm, 20% with DBH of 9.1 – 13.0 cm, 13% with DBH of 13.1 - 17.0 cm, 6% with DBH of 17.1 – 20.0 cm and 5% with a DBH greater than 20 0 cm. In the same block, 58% had a height ranging from 2.0 – 4.5 m, 11% with a height ranging between 4.6 – 5.0 m while 30% had a height > 5 m. In the middle block, 37 % of the trees had a DBH of 5.1 – 9 0 cm, 25% with DBH of 9 1 – 13.0 cm, 18% with DBH of 13.1 – 17.0 cm, 8% with a DBH of 17.1 – 20.0 cm and 11% with a DBH greater than 20.0 cm. In the same block, 35% had a height ranging from 2.0 – 4.5 m, 25% with a height ranging between 4.6 – 5.0 m while 40% had a height > 5 m. In the eastern block, 49% of the trees had a DBH of 5.1 – 9 0 cm, 20% with DBH of 9 1 – 13.0 cm, 13% with DBH of 13.1 – 17 0 cm, 5% with DBH of 17.1 – 20.0 cm and 12% with a DBH greater than 20 0 cm. In the same block, 21% had a height ranging from 2.0 – 4.5 m, 30% with a height ranging between 4.6 – 5.0 m while 49% had a height > 5 m (Fig. 7). The relationship between stem density and the DBH size class distribution in all the forest blocks indicated a reverse – J curve (Fig. 8).
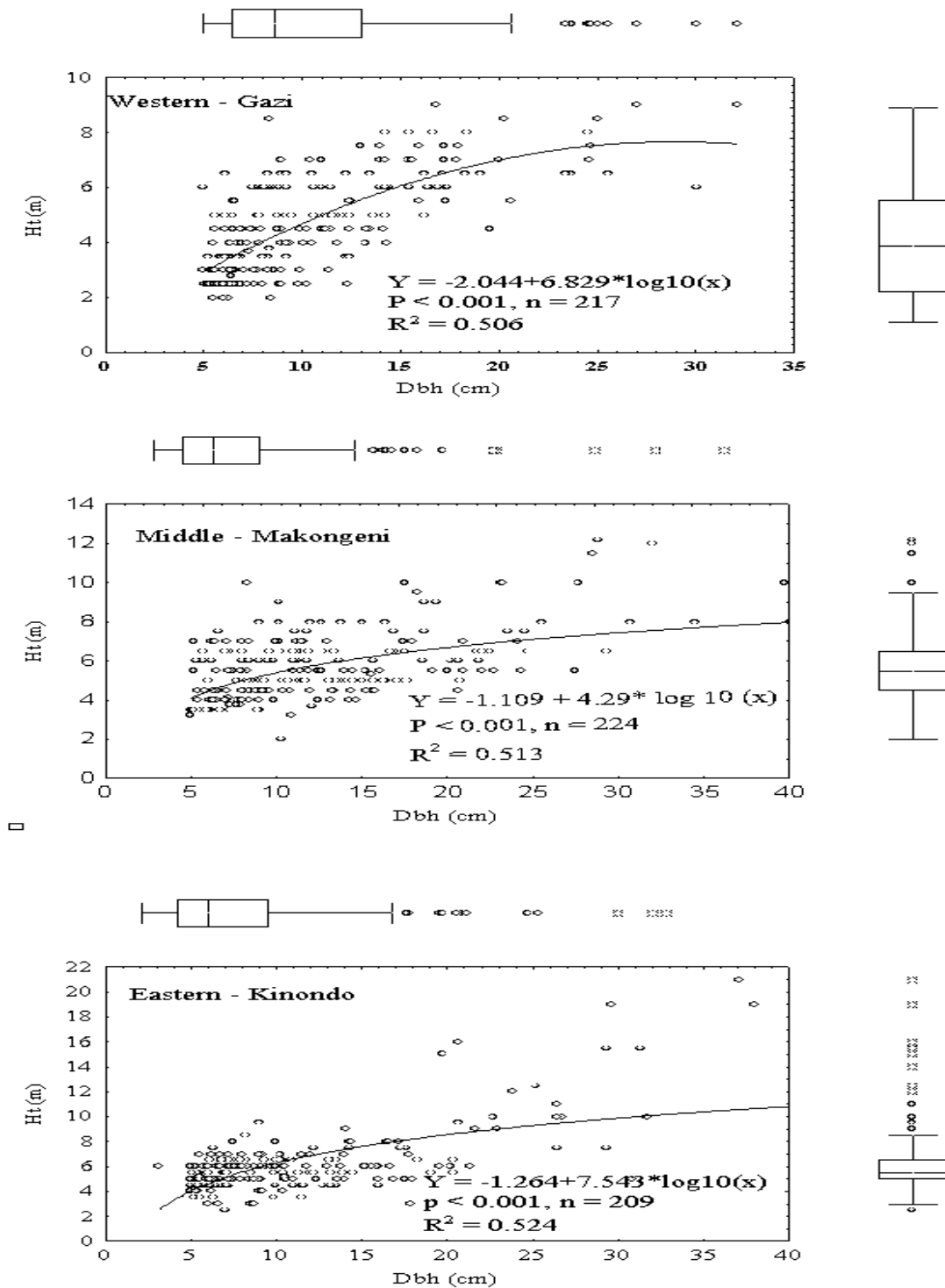
Fig. 7: Height – diameter relationship in the three forest blocks of Gazi mangrove forest. The box plots display percentile distribution of the DBH and heights in the forest blocks. The extremities of the plot correspond to the maximum and minimum observations in the data set. The ends of the boxes are positioned at the 25% and 75% percentile of the data.
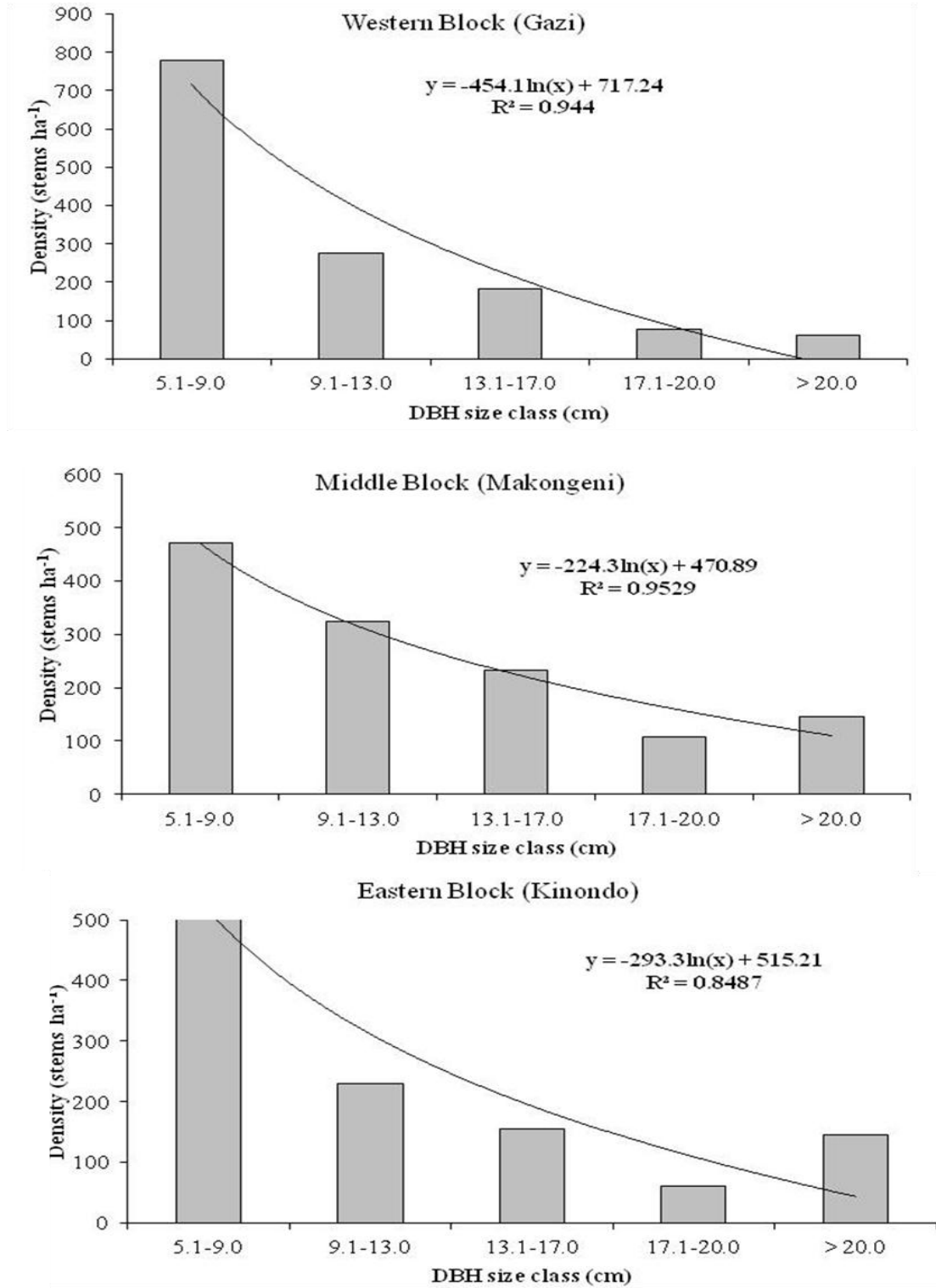
Fig. 8: Stem density and DBH size class relations at Gazi Bay mangrove forest.

4.2.4 Stem density

Mangrove densities in the three forest blocks were 1167, 1292 and 1307 stems ha^{-1} in the eastern, middle and western blocks respectively, mean (1255 ± 44) stems ha^{-1}. The proportional contribution of the species present to total density in the western block was 29% (*Ceriops tagal*), 25% (*Avicennia marina*), 24% (*Rhizophora mucrona*ta)*, 18% (*Xylocarpus granatum*), 4% (*Sonneratia alba*) and 1% (*Bruguiera gymnorrhiza*). In the middle block, the proportional contributions to total density were 57% (*Rhizophora mucrona*ta), 19% (*Ceriops tagal*), 12.0% (*Avicennia marina*), 10% (*Bruguiera gymnorrhiza*), 1.5% (*Xylocarpus granatum*) and 0.5 % (*Sonneratia alba*). Relative contributions to total density in the eastern block were 68% (*Rhizophora mucronata*) 13% (*Bruguiera gymnorrhiza*), 10% (*Avicennia marina*), 6% (*Ceriops tagal*), 1.5% (*Sonneratia alba*), 0.5% (*Xylocarpus granatum*).

4.2.5 Quality classes of the stems in the mangrove forest

In terms of the quality of the poles, the western Gazi forest block had the lowest percentage (2.4%) belonging to form class 1 poles compared to 5.9% for the middle block and 10% for the eastern block. In form 2 size class category, the western block had 34.1% compared to 53% and 54.9% for the middle and eastern blocks respectively whereas in form 3 size class category the western block had 63.6% compared to 41.2% and 35.2% for the middle and eastern blocks respectively (Table 4).

Table 4: Quality classes of the poles in the three forest blocks of Gazi mangrove forest

| Forest block | Species | Quality classes | | | Total |
		1	2	3	
Western (Gazi)	*A. marina*	0	69	254	323
	B. gymnorrhiza	0	8	8	16
	C. tagal	8	177	192	377
	R. mucronata	15	115	177	307
	S. alba	8	23	15	46
	X. granatum	0	54	185	239
	Total	**31**	**446**	**831**	**1307**
	Proportion (%)	**2.4**	**34.1**	**63.6**	
Middle (Makongeni)	*A. marina*	5	92	60	157
	B. gymnorrhiza	11	65	54	130
	C. tagal	16	157	65	238
	R. mucronata	43	352	347	742
	S. alba	0	5	0	5
	X. granatum	0	11	5	16
	Total	**76**	**683**	**531**	**1288**
	Proportion (%)	**5.9**	**53.0**	**41.2**	
Eastern (Kinondo)	*A. marina*	0	67	56	123
	B. gymnorrhiza	33	39	83	155
	C. tagal	6	56	11	73
	R. mucronata	78	461	256	795
	S. alba	0	17	0	17
	X. granatum	0	0	6	6
	Total	**117**	**640**	**412**	**1169**
	Proportion	**10.0**	**54.7**	**35.2**	

4.2.6 Natural regeneration

Density and composition of the natural regeneration classes varied widely across all mangrove forest blocks of Gazi (Table 5). The densities of regeneration class one (RCI) in the western block were 10,423 saplings ha^{-1} representing 48.4% of the total juvenile density. The RCII were 3579 saplings ha^{-1} while RCIII were 7,564 saplings ha^{-1} accounting for 16.6% and 35% respectively (Table 5). In the middle block, the density of RCI was 47,618 saplings ha^{-1} forming 59.6% while the densities of the established saplings RCII and RCIII were 13,614 and 18,608 saplings ha^{-1} representing 17% and 23.3% of the total saplings respectively.

In the eastern block, the density of RCI was 15,966, forming 49.1% while the density of the established saplings RCII and RCIII were 8,138 and 8,412 saplings ha^{-1} respectively, accounting for 25% and 25.9% of the total saplings respectively. Based on the one way ANOVA test, the difference in mean saplings density in the three mangrove forest blocks was not significant (F $_{(2, 6)}$ = 1,163; p = 0.284). Most of the juveniles belonged to *Rhizophora* (56.9%) and *Ceriops* (41%) with the remaining saplings shared between *Bruguiera* (1.9%), *Avicennia* (0.1%) and *Xylocarpus* (0.1%). The regeneration ratios for RCI, RCII and RCIII in the western, middle and eastern forest blocks were 3:1:2, 3:1:1 and 2:1:1 respectively.

Table 5: Juvenile densities (saplings ha^{-1}) in the three forest blocks of Gazi mangrove forest

Site	Species	Regeneration classes			Total (ha^{-1})
		RCI	RCII	RCIII	
Western (Gazi)	*A. marina*	8	42	58	108
	B. gymnorrhiza	23	8	46	77
	C. tagal	5000	17	4 008	9026
	R. mucronata	5385	3454	3377	12216
	S. alba	0	8	0	8
	X. granatum	17	50	75	142
	Total	**10433**	**3579**	**7564**	**21576**
Middle (Makongeni)	*A. marina*	0	0	0	0
	B. gymnorrhiza	783	94	117	994
	C. tagal	41169	6424	7191	54784
	R. mucronata	5666	7092	11300	24058
	S. alba	0	0	0	0
	X. granatum		4	0	4
	Total	**47618**	**13614**	**18608**	**79836**
Eastern (Kinondo)	*A. marina*	22	0	6	28
	B. gymnorrhiza	144	161	1489	1794
	C. tagal	2872	1094	961	4927
	R. mucronata	12928	6883	5950	25761
	S. alba	0	0	0	0
	X. granatum	0	0	6	6
	Total	**15966**	**8138**	**8412**	**32516**

4.3   Biomass accumulation estimates

4.3.1   Above ground biomass accumulation

Above ground biomass accumulation was highest in *Rhizophora* zone with a mean of 7.2 $\pm$ 0.4 t ha^{-1} yr^{-1} (range 6.3 – 7.8) t ha $^{-1}$ yr $^{-1}$ in the study plots. This was followed by the *Sonneratia* zone (mean 6.0 $\pm$ 1.6 t ha^{-1} yr^{-1}; range 2.9 – 7.7 t ha^{-1} yr^{-1}). The *Avicennia* zone had a mean biomass accumulation of 4.2 $\pm$ 0.8 t ha^{-1} yr^{-1} (range; 3.0 -5.6 t ha $^{-1}$ yr $^{-1}$) while the *Ceriops* zone had the least mean biomass accumulation of 2.0 $\pm$ 0.7 t ha^{-1} yr^{-1} and a range from 0.8 – 3.4 t ha^{-1} yr^{-1} (Fig. 9). Using a one way ANOVA test, the difference in mean above ground biomass accumulation of the four species zones was found to be significant (F $_{(3, 8)}$, = 5.42; $p = 0.025$).

Fig. 9: Above ground biomass (AGB) accumulation rates at different vegetation zones of Gazi mangrove forest. (*Ct* = *Ceriops*, Am = *Avicennia*, Sa =*Sonneratia* and Rm = *Rhizophora*).

4.3.2 Below ground biomass accumulation

Roots biomass distribution decreased with depth in all zones (Fig 10). In the *Sonneratia* zone,

76% of the root biomass was concentrated between 0 - 20 cm depth followed by 19% in the 20 –

40 cm depth, with the remaining 5 % occurring in the 40 – 60 cm depth. In the *Avicennia* zone,

58% of the root biomass occurred in the top 0 – 20 cm depth, 34% occurred in the 20 – 40 cm

depth while the remaining 8% occurred in the bottom 40 – 60 cm depth. In the *Rhizophora* zone, 41% of the roots biomass occurred in the top 0-20 cm depth followed by 27% in 20 – 40 cm depth while the remaining 31% occurred in the 40 – 60 cm depth. In the *Ceriop*s zone, root biomass distribution in the 0 – 20 cm, 20 – 40 cm and 40 – 60 cm depths where 84%, 15% and 1% respectively. In all the four zones, the highest percentage of root biomass was concentrated in the top 20 cm while the least biomass was recorded in the 40 – 60 cm depth (Fig. 10). Using a one way ANOVA test, mean percentages of root biomass at 0 – 20 cm depth of the zones investigated were not significantly different (F $_{(3, 8)}$ = 2.96; p = 0.098). There was however a significant difference in the mean percentage of root biomass among zones at the 20 – 40 cm (F $_{(3, 8)}$ = 4.71; p = 0.035) and 40 - 60 cm depths (F $_{(3, 8)}$ = 4.43; p = 0.041).
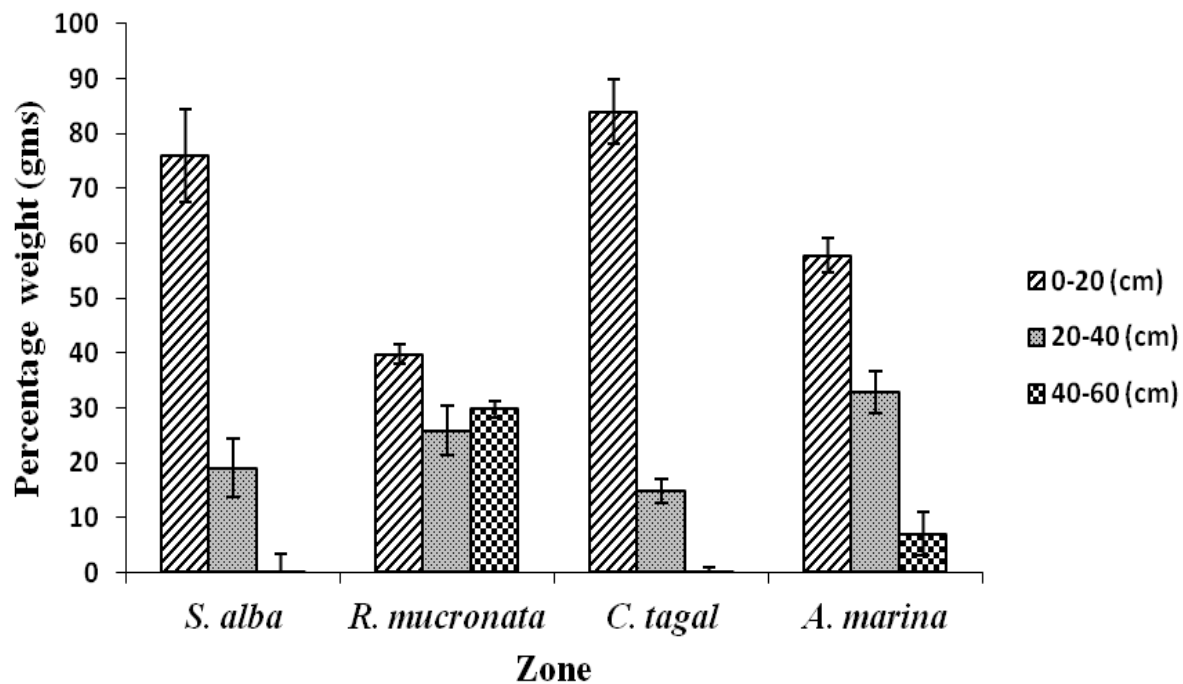
Fig. 10: Percentage root weight distribution by depth in each zone at the Gazi mangrove forest.

Root weight distribution into the four diameter size classes (less than 3 mm, 3 – 5 mm, 5 – 10 mm and more than 10 mm) revealed that higher root weights occurred in the lower size class category (less than 3 mm) in all the zones as compared to the higher size class categories. The lower size class category of less than 3 mm contributed root mean weights of 8, 3, 7 and 3 kg ha^{-1} yr^{-1} in *Sonneratia alba*, *Rhizophora mucronata*, *Ceriops tagal* and *Avicennia marina* zones respectively. In the 3 – 5 mm size class category, the mean root weights of 4, 1, 2 and 3 kg ha^{-1} yr^{-1} for *Sonneratia alba*, *Rhizophora mucronata*, *Ceriops tagal* and *Avicennia marina* zones respectively. In the 5 – 10 mm size class category, the root weights for *Sonneratia alba*, *Rhizophora mucronata*, *Ceriops tagal* and *Avicennia marina* zones were 15, 1, 5 and 3 kg ha^{-1} yr^{-1} respectively. In the higher size class category of more than 10 mm, the root weights were 18, 1, 4 and 5 kg ha^{-1} yr^{-1} for the *Sonneratia alba*, *Rhizophora mucronata*, *Ceriops tagal* and *Avicennia marina* zones respectively.

Below ground biomass accumulation was found to be highest in the *Sonneratia* zone, which had a mean biomass accumulation of 4.5 ± 0.9 t ha^{-1} yr^{-1} (range: 3.9 – 5.5 t ha^{-1} yr^{-1}) followed by the *Avicennia* zone with a mean accumulation of 1.7 ± 0.6 t ha^{-1} yr^{-1} (range: 1.3 – 2.5 t ha^{-1} yr^{-1}). The *Rhizophora* zone had a mean below ground biomass accumulation of 1.3 ± 0.1 t ha^{-1} yr^{-1}, (range; 1.2 – 1.4 t ha^{-1} yr^{-1}) while *Ceriops* had mean of 0.6 ± 0.4 t ha^{-1} yr^{-1}; (range 0.3 – 1.0 t ha^{-1} yr^{-1}) (Fig. 11). Using a one way ANOVA test, the mean below ground biomass accumulation in the zones investigated were found to differ significantly (F$_{(3, 8)}$ = 27.83; p = 0.001).

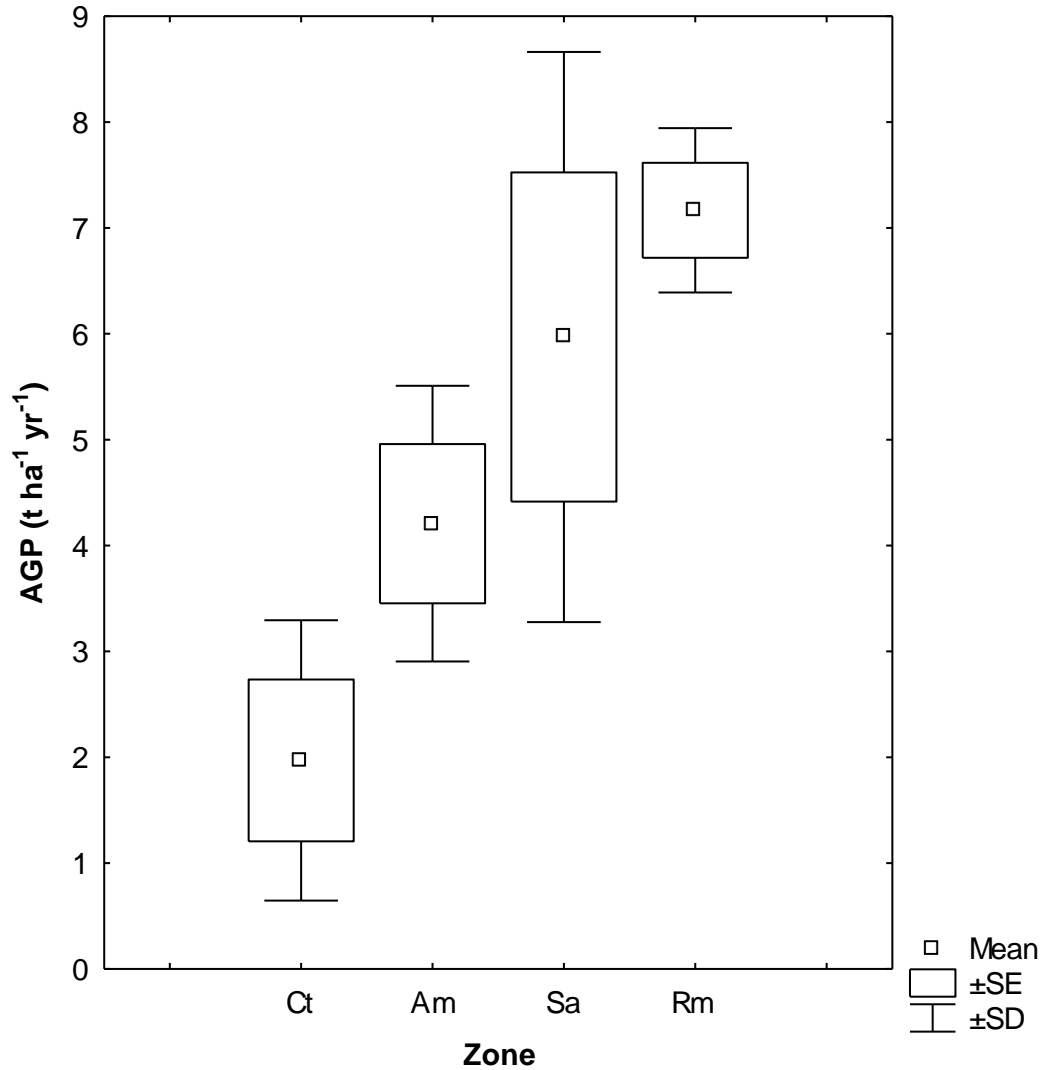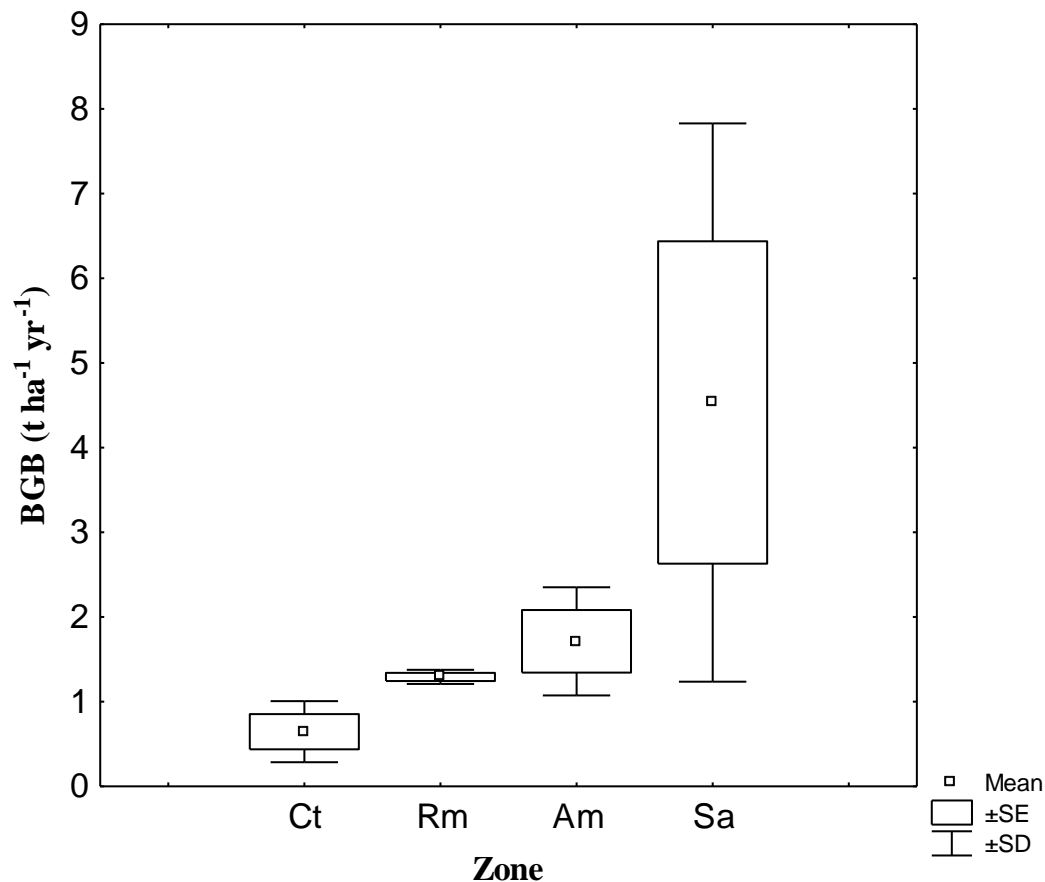**Fig. 11**: Below ground biomass accumulation at different vegetation zones of Gazi mangrove forest**. (*C*t = *Ceriops*, Am = *Avicennia*, Sa =*Sonneratia* and Rm = *Rhizophora*).

4.3 3   Total biomass accumulation and ratio of AGB:BGB

Total biomass accumulation of each species was obtained by pooling its above and below ground biomass accumulation. *Sonneratia alba* zone had the highest accumulation rate with a mean of 10.5 ± 1.9 t ha^{-1} yr^{-1} (range: $8.4 - 11.9$ t ha^{-1} yr^{-1}), followed by *Rhizophora mucronata* zone (8.5 ± 0.8 t ha^{-1} yr^{-1}) (range $7.7 - 9.2$ t ha^{-1} yr^{-1}), *Avicennia marina* zone (5.2 ± 1.8 t ha^{-1} yr^{-1}) (range: $3.3 - 6.9$ t ha^{-1} yr^{-1}) and *Ceriops tagal* zone (2.6 ± 1.5 t ha^{-1} yr^{-1}) (range $1.1 - 4.0$ t ha^{-1} yr^{-1}) (Fig. 12). A one way ANOVA test revealed that the total biomass accumulation was significantly different among the mangrove zones ($F_{(3, 8)} = 15.56; p = 0.001$).
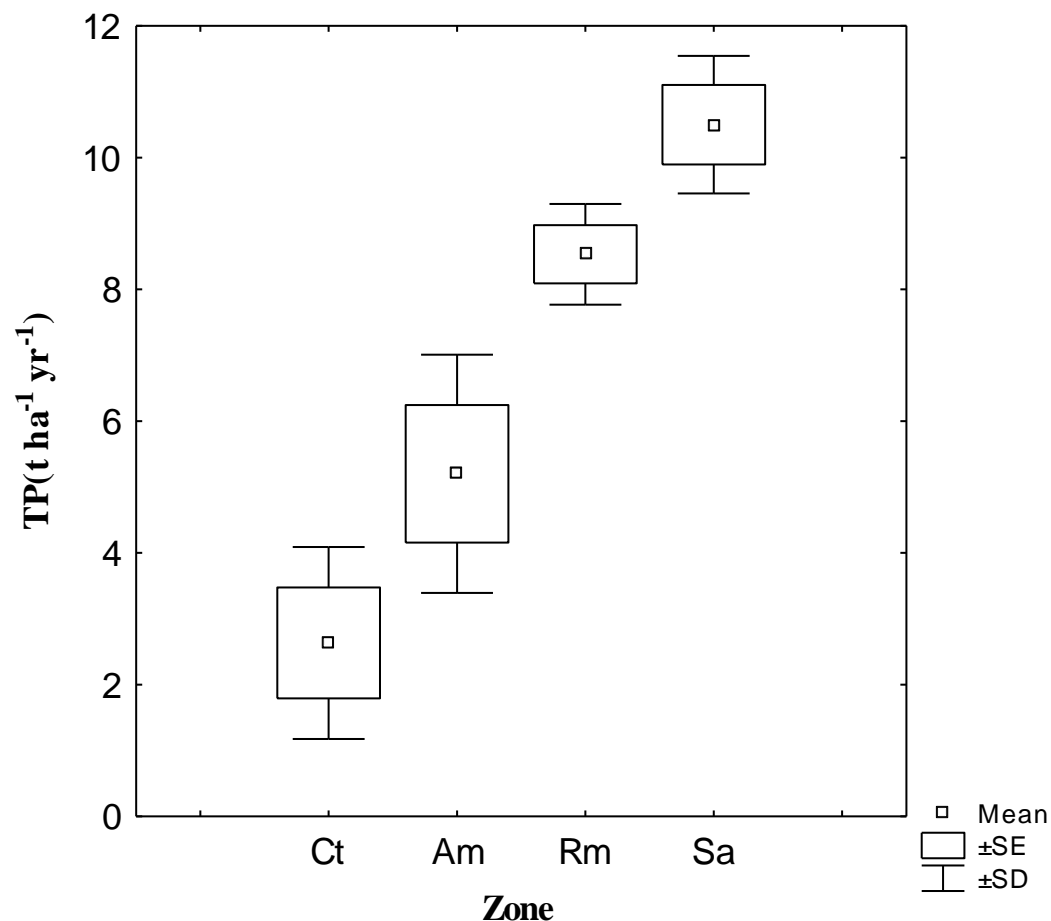
Fig. 12: Total biomass accumulation at different vegetation zones at Gazi mangrove forest. (*C*t = *Ceriops*, Am = *Avicennia*, Sa =*Sonneratia* and Rm = *Rhizophora*).

In the *Sonneratia alba* zone, the ratio of below ground (BG): above ground (AG) biomass accumulation (BG:AG) was almost 1:1 with below ground biomass accumulation accounting for about 43% of the total biomass accumulation. *Avicennia marina* zone had a BG:AG ratio of about 1:2 with the below ground biomass accumulation representing 33% of the total biomass. In the *Ceriops tagal* zone, BG:AG was 1:3 with the below ground biomass accumulation representing 25% of the total biomass. The lowest ratio was observed in the *Rhizophora* zone, which had a BG:AG ratio of 1:6 with a below ground biomass accumulation representing 14% of

the total biomass. A mean below ground to above ground biomass accumulation ratio (BG:AG) of 2:5 was computed for the whole forest.

4.3.4   Leaf phenology

Leaf emergence ranged from two to four leaves per month for the four species investigated (Fig. 13). *Sonneratia* had the highest leave emergence count of 3.9 ± 2 leaves per twig per month that peaked during the months of October – November but declined onwards throughout the observation period. Mean leaf loss of 3.2 ± 2 leaves per twig per month was recorded for the same species. Hence there was a net gain of 0.7 ± 1 leaf per shoot per month in *Sonneratia alba zone*. In *Rhizophora mucronata* zone, the average leaf emergence and loss was 2.8 ± 2 (range: one to five) and 1.4 ± 1 (range; one to two) respectively resulting in a net gain of 1.4 ± 2 leaves (range 1-3). Higher leave emergence was observed in two peak periods, that corresponded with the wet seasons (October to December, and May to July), while low leaf emergence was observed during the dry season (March to May). In the *Avicennia* zone, leaf emergence and loss ranged from one to seven (mean 2.3 ± 2) and one to two (mean 1.2 ± 2) leaves per twig per month respectively, resulting in a mean net gain of 1.2 ± 2. Reduced leaf emergence rate was noted during the dry months (December to February) while leaf production peaked shortly after the onset of rains towards the end of April. Leaf loss remained low and almost constant throughout the observation period (Fig. 13). The average leaf emergence in *Ceriops* was 3.3 ± 2 leaves per twig per month against a loss of 1.1 ± 1 leaves per shoot per month resulting to a net gain of 2.2 ± 2 leaves per twig per month. In *Ceriops tagal* there was bimodal leaf emergence with peaks coinciding with short rains (October-November) and long rains (May-July). Low leaf production was observed between January and March (Fig. 13).
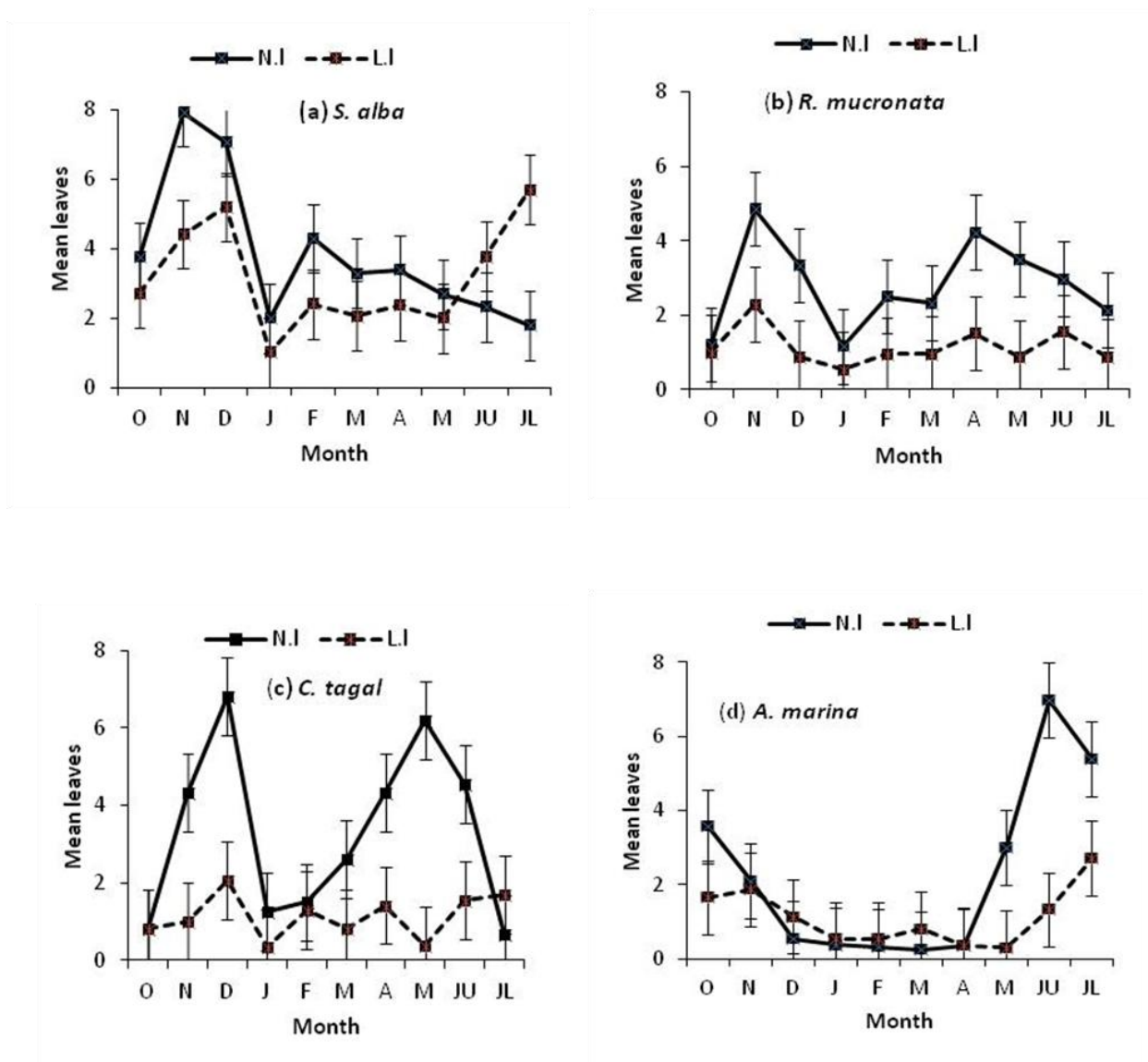
Fig. 13: Mean leaf emergence and loss at different zones of the Gazi mangrove forest (*Means* ±.1 *S.E*). N.l = new leaves, L.l = lost leaves).

4.3.5 Relationships

Among the soil properties investigated, above ground biomass accumulation was negatively correlated to mean salinity of the soil during both the dry and wet seasons. However, the correlation between temperature and above ground biomass accumulation was only significant during the wet season (Table 6). The functional relationship between above ground and below

ground biomass accumulation for each zone can be expressed by the following regression equations:

S. alba zone: BGB = 0.592 ln (AGB) + 2.351, $r^2 = 0.026$

R. mucronata zone: BGB = -1.49 In (AGB) + 3.1622, $r^2 = 0.112$

C. tagal zone: BGB = 0.239In (AGB) + 0.6935, $r^2 = 0.092$

A. marina zone: BGB = 0.493In (AGB) + 1.555, $r^2 = 0.66$

With the exception of the *Avicennia* species zone, all the other species zones had low r^2 values; hence this equation for *Avicennia* species zone is useful in estimating the below ground biomass accumulation from the above ground biomass accumulation while those for *Sonneratia alba, Rhizophora mucronata* and *Ceriops tagal* species zone are of limited value.

Table 6: Pearson correlation coefficient between above ground biomass (AGB) accumulation and selected soil environment properties during the dry season (DS) and rainy season (WS) at Gazi mangrove forest.

Zone		Salinity		Redox		Temperature		pH		n
		DS	WS	DS	WS	DS	WS	DS	WS	
S. alba	r =	-0.990	-0.999	0.663	0.707	0.431	0.287	0.006	0.428	3
	p =	0.023	0.029	0.539	0.501	0.716	0.640	0.950	0.546	
R. mucronata	r =	-0.852	-0.932	0.854	0.813	-0.859	0.135	0.316	0.905	6
	p =	0.031	0.007	0.031	0.049	0.028	0.799	0.620	0.013	
C. tagal	r =	-0.328	-0.960	0.143	0.306	0.135	0.303	0.376	0.370	3
	p =	0.787	0.029	0.629	0.627	0.799	0.804	0.580	0.759	
A. marina	r =	-0.970	-0.973	0.354	0.309	-0.409	0.019	-0.398	0.287	6
	p =	0.001	0.001	0.491	0.551	0.420	0.912	0.434	0.581	

CHAPTER FIVE

5.0   DISCUSSION

5.1   Mangrove forest structure

5.1.1   Importance value (IV) of mangrove species

Structural composition of species in Gazi Bay mangrove forest determined on the basis of the importance value revealed that the dominant species were *Rhizophora mucronata*, followed by *Ceriops tagal*, *Avicennia marina*, *Bruguiera gymnorrhiza*, *Xylocarpus granatum* and *Sonneratia alba*. Similar structural composition is found in other mangrove forests of Kenya such as Kiunga, Kairo *et al*. (2002b) and Vanga in the south coast (Kairo *et al.*, 2012). It has also been observed in other mangrove formations of the West Indian Ocean (WIO) region Macnae (1968), and in the mangrove of Puttalam Lagoon and Dutch Bay of Sri Lanka (Amarasinghe and Balasubramaniam, 1992). A significant difference in height above datum for the four zones confirmed that height above datum contributed to species zonation at Gazi Bay mangrove forest. *Sonneratia alba* occupied the seaward side in the inundation class I of Watson (1928), probably because it cannot withstand wide fluctuations in salinity. The well developed pneumatophores enabled the *Sonneratia* trees to survive under the flooded conditions. Next to *Sonneratia alba* zone is the *Rhizophora mucronata* zone, which falls under inundation class II. The well developed prop roots of *Rhizophor*a trees enable them to withstand high tidal velocities and trap sediments. *Ceriops tagal* zone occur in mid tide region, which fall under inundation class III. *Ceriops* is among the hardest species of mangrove trees with wide salinity tolerance range. Under high saline conditions as in Gazi, *Ceriops* grow to a shrub, while in less saline conditions the species could grow to height above 25 m as in Mida creek (Kairo *et al.*, 2012). *Avicennia marina* occurs on the landward edge which falls under inundation class IV. Similar to *Ceriops,*

Avicennia marina can tolerate high salinity range which it controls through secretion mechanism (Schmitz *et al.*, 2007). *Avicennia* in Gazi displayed double zonation (Wang'ondu *et al.*, 2010). In areas of low salinity on the seaward side, *Avicennia* grow as giant trees of high DBH, whereas in conditions of higher salinity found on the landward side, the species grow as scrub of low productivity.

5.1.2 Complexity index

The high complexity index recorded in the middle forest block indicated that the trees had greater basal area and canopy height as compared to the western and eastern blocks (Table 3) which could be attributed to less harvesting. Overall, the western forest block at Gazi was structurally less complex than the middle and eastern blocks. This is expected as the western forest block bordered human settlement of Gazi village; whereby historical removal of wood products had reduced the quality of mangroves in Gazi (Kairo, 2001). The current study revealed that 63.5% of trees in western block were of quality Class 3, compared to the middle and eastern blocks whose tree quality were mostly of class 1 & 2 (Table 4). Impacts of human on wood quality reduction in Gazi in general was higher than in Mida creek where a large fraction of the poles were of quality class I. Compared to the former, Mida creek is a conservation area where removal of trees is regulated (Kairo *et al.*, 2002a).

5.1.3 Tree height and DBH relationship across zones

Differences in stem diameter and height recorded in the three blocks investigated, with the western forest block having the highest percentage (57%) of low size class trees (Table 4) can be attributed to the proximity to human settlements. The western block was the closest and easily

accessible from Gazi village. Hence this forest block is subjected to a higher exploitation pressure than the other forest blocks.

5.1.4   Stem density

The average density of stems in Gazi mangrove forest was found to be 1255 ± 44, which is comparable to other mangrove areas of Kenya. In the peri-urban mangroves of Mombasa, Mohamed *et al*. (2009) recorded a density of 1264 stems ha^{-1}. Similarly, in Uyombo and Kirepwe of Mida creek, a density of 1585 and 1197 stems ha^{-1} respectively had been registered (Kairo *et al.*, 2002a). In the mangroves of Kiunga, Kairo *et al*. (2002a) recorded a density of 2077 stems ha^{-1} while a density of 1934 trees ha^{-1} was observed in Vanga (Kairo *et al.*, 2012). The stem density of natural stands of mangroves was therefore lower than in the replanted mangroves forest of Gazi whose density had been estimated at over 2500 stems ha^{-1} (Kairo, 2001). This was due to the regular harvesting of the poles in the natural stands unlike in the replanted stands that are not subjected to harvesting. The observed "J" distribution curves (Fig 8) is typical of natural mangrove forests and indicate selective removal of poles from the forests. Low stem density in natural forest stands indicates that mangrove forests in Kenya have been poorly managed. Hence to sustain the supply of the required goods and services, a management plan for mangrove forest similar to other upland forests is needed.

5.1.5   Natural regeneration

The recruitment of juveniles within the western forest block (21,576 juveniles), middle forest block (79,836 juveniles) and eastern forest block (32,516 juveniles) could be considered as adequate since according to FAO (1994), regeneration density of more than 2500 saplings ha^{-1} is considered adequate. In a two year study of saplings survival and structural development, of a

natural and reforested mangroves of Gazi, Bosire *et al.* (2008) observed 50 -61% mortality rate by the end of year two. In the same study, survival rate ranged from 1230 - 5277 saplings ha^{-1}. When these past findings are compared with the results of this study, the indications are that this forest has the potential to regenerate. However more regeneration is observed in reforested areas since reforestation alters local hydrodynamics and other physical –chemical properties (Bosire *et al.*, 2003).

Very little understory was recorded in the *Sonneratia alba* zone. Possible causes of failure in seedling recruitment in the *Sonneratia alba* zone could have resulted from a combination of limited influx of propagules, washing by wave activity, and shading effects. Seedling growth and survival in mangrove environments are compromised under closed canopies due to reduced light (Clarke and Kerrigan, 2002). Canopy gaps do enhance natural mangrove regeneration (Sherman *et al.*, 2000). This is due to reduced resource competition (especially increased light availability) and reduced crab predation. Gradual sediment movement observed in the *Sonneratia alba* zone could be changing the substrate conditions hence making it unfavorable for seedlings establishment.

5.1.6   Quality of the stems in the mangrove forest of Gazi

In Gazi mangrove forest, most of the good quality poles (form class 1) have been removed leaving only 2.4%, 5.9% and 10% in the western, middle and eastern blocks respectively. However, the forest has higher percentages of forms 2 and 3 categories in the forest blocks (form 2; 34.1%, 52.9% and 54.8%: form 3; 63.5%, 41.2% and 35.2% at the western, middle and eastern blocks respectively). Occurrence of higher percentages of form 2 and 3 size class poles is an indication of degraded forest and as such Gazi mangrove forest can therefore be considered as

being degraded. Looking at the relative percentages for the three size class categories, the western forest block appears more degraded than the other two forest blocks. The removal of straight poles from Gazi mangrove forest left out trees with crooked poles of low commercial value (Kairo *et al.*, 2010). This has future implications as this forest may not be capable of providing building poles, an ecosystem service valued by coastal communities. At the same time, the biomass stocks will be reduced. The variation in forest quality between the three locations can be attributed to differences in human pressure. The close proximity of human settlements to mangroves of western block, and the fact that people from across the creek travel to this area to cut trees, results in higher consumptive wood extraction from the forest, which in turn is reflected in diminished mangrove poles. In Kenya, mangrove poles are categorized and marketed based on their diameter classes which include: *Fito/Pau* ($\leq$ 6.0 cm), *Mazio* (8.0 $-$ 11.0 cm), *Boriti* (11.5 $-$ 13.5 cm) and Banaa (20.1 - $\geq$ 35 cm) diameter. Less exploitation in the middle block has resulted to more stems in the larger diameter classes, taller vegetation and a higher total tree density.

5.2 Biomass accumulation estimates

5.2.1 Above ground biomass accumulation

This study found that there was significant difference in above ground biomass accumulation in the four mangrove species zones. This could be attributed to several factors including; age, species structural characteristics, substrate conditions and management systems. The high above ground biomass accumulation in the *R. mucronata* zone is due to the species structural characteristics. Unlike other species, *Rhizophora* has prop roots which could be considered as part of the above ground biomass. Because *R. mucronata* produces better poles, most of the older trees have been harvested in the past leaving out younger trees that are likely to grow faster. Low

above ground biomass accumulation in the *C. tagal* is due to the old age of the trees and the saline substrate which exerts stress on the trees. From the few data that exist on biomass accumulation in natural mangrove stands, above ground biomass accumulation has been reported to range from a low of 2.02 t ha^{-1} yr^{-1} in *Avicennia germinas* dominated stand in Mexico (Day *et al.*, 1996) to a high of 26.7 t ha^{-1} yr^{-1} in *Rhizophora apiculata* in southern Thailand (Christensen, 1978). In Kenya, a 12 year replanted *Rhizophora mucronata*, recorded above ground biomass increment of 8.89 t ha^{-1} yr^{-1} (Kairo *et al.*, 2008). Variations in above ground biomass accumulation may be due to differences in environmental conditions and plant characteristics.

5.2.2   Below ground biomass accumulation

High biomass accumulation of 4.5 ± 0.9 t ha^{-1} yr^{-1}was observed in *Sonneratia alba* zone; while *Ceriops* had biomass of 0.6 ± 0.4 t ha^{-1} yr^{-1}. The difference in the BGB accumulation within the zones could be attributed to inherent characteristics of the species as well as site conditions. Generally, *Sonneratia* is a fast grower than *Ceriops tagal*. In plantation establishment, Kairo *et al*. (2002a) recorded a growth rate of 1.81 m yr^{-1} for *Sonneratia* compared to 0.3 m yr^{-1} in *Ceriops*. Higher fluctuations in salinity levels in the *Avicennia marina* zone could have necessitated more investment in roots for nutrient uptake in the hyper saline conditions as represented by high root: shoot ratio in the *Avicennia* zone. *Rhizophora mucronata* registered a lower below ground biomass accumulation as most of its roots are above ground in the form of prop roots.

Occurrence of a larger percentage of root growth recorded in the upper layer (0-20) cm in all the mangrove zones, confirms that most mangroves are shallow rooted with biomass accumulation declining with depth. Similar results have been found in other studies around the world. In the

Everglade mangroves of America, Castaneda *et al.* (2011) observed that most of the roots (62–85%) were distributed in the shallow root zone. Komiyama *et al*. (2000) in a study on top/root biomass ratio in mangroves of S. East Asia reported a decrease in root biomass with depth. Most studies indicate that fine roots which are important in aeration and nutrient acquisition form the highest biomass and are found close to the surface (Tamooh *et al.*, 2008). Due to anoxic nature of mangrove environment, shallow roots help in increasing gaseous exchange at the rooting zone as well as assimilation of nutrients brought in by tides and runoff.

Mangroves often accumulate large amounts of biomass in their below ground roots leading to significantly high root: shoot ratio compared to terrestrial forests (Komiyama *et al.*, 2000). While below ground biomass represent less than 30% of the total biomass in terrestrial forests, in mangroves root biomass constitute 40 – 60% of the total biomass (Saenger, 1982; Lugo, 1990). However, *Rhizophora mucronata, Ceriops tagal*, and *Avicennia marina* zones had lower below ground biomass accumulation of 15%, 23%, and 33% respectively. The heavy investment in below ground biomass observed in *Sonneratia alba* zone gives the plant stability against high tidal velocities in addition to increasing surface area for gaseous exchange.

Some species such as *A. marina* tend to invest heavily on root biomass, possibly reflecting the challenges of growth in nutrient-poor, hypoxic, unstable soils conditions. A below ground biomass accumulation rate of 1.3 (range: 1.2 – 1.4 t ha^{-1} yr^{-1}) recorded in the present study for *R. mucronata* zone was much higher than the 0.2 t ha^{-1} yr^{-1} for the *Rhizophora apiculata* in the Hinchinbrook channel, Australia (Clough, 1998). Similarly, a 14% below ground biomass contribution to total biomass accumulation was slightly higher than a value of 8.5% reported for the *Rhizophora* species in Malaysia (Ong *et al.*, 1995). Gong and Ong (1990) provided a below-

ground biomass accumulation rate for *A. marina* ranging from 1.2 to 3.6 t ha^{-1} yr^{-1}, which was not different from the results of this study (range: 1.3 – 2.5 t ha^{-1} yr^{-1}). In the Neotropical mangroves of Florida, U.S.A, (McKee and Faulkner, 2000) estimated a biomass accumulation of 1.5 t ha^{-1} yr^{-1} in a mixed forest dominated by *Rhizophora*. In Honduras, Cahoon *et al*. (2003) estimated a below ground biomass increment of 0.27 t ha^{-1} yr^{-1} for *Rhizophora species*.

5.2.3   Total biomass and ratio of AGB:BGB

As observed in the present study, zones on the seaward edge recorded higher total biomass accumulation rates compared to those on the landward edge (Fig 12). Differences in total biomass accumulation rates could be attributed mainly to differences in salinity conditions. The *Sonneratia alba* and *Rhizophora mucronata* zones receives tidal inflows daily, hence salinity does not fluctuate widely. However, the *Avicennia marina* and *Ceriops tagal* zones receive tidal inundation only during spring tide and as such the plants are subjected to a greater range of salinity fluctuation and therefore a higher salinity stress that limit growth. A significant difference in biomass accumulation between the seaward *Sonneratia alba*, *Rhizophora mucronata* zones and the landward *Avicennia marina* and *Ceriops tagal* zones confirms the existence of spatial differences in environmental conditions across the forest complex.

The total biomass accumulation for *Rhizophora mucronata* recorded in this study (8.5 ± 0.8 t ha^{-1}) is higher than the 5.1 t ha^{-1} yr^{-1} reported for 80 years old natural plantation of *Rhizophora apiculata* in Malaysia (Putz and Chan, 1986). Other confounding variables such as forest age, species composition, management regime, and local climatic variation could influence biomass allocation patterns resulting in observed differences in different forests (Kairo *et al.*, 2008; Tamooh *et al.*, 2008). Biomass accumulation has been reported to be higher in plantations than in

natural forests which could be attributed to better management such as the regular spacing that minimize competition and also better climatic and substrate conditions.

In the present study, a high root: shoot ratio of almost 1:1 was confirmed for *Sonneratia alba* zone in which below ground biomass accumulation registered 43% of the total biomass *while Rhizophora* zone recorded the lowest R:S ratio of 1:6. In a 12 year old replanted *Rhizophora mucronata* plantation in Kenya, an BGB:AGB ratio of 1:4 was obtained (Kairo *et al.*, 2008). This difference could have resulted from the difference in management. Whereas the present study was carried out in a natural forest, previous related study was done in a *Rhizophora mucronata* plantation Kairo *et al*. (2008) where management regimes such as the spacing and pruning could have influenced tree growth. A root: shoot biomass accumulation ratio ranging from 1:6 in *Rhizophora* zone to 1:1 in the *Sonneratia* zone with an overall forest ratio of 2:5 recorded in this study was higher than the R:S 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. Similarly, it was higher than R:S ratio of 1:4 recorded from terrestrial forests (Cairns *et al.*, 1997). These findings suggest that mangroves allocate more of their biomass to roots in order to cope with the unstable, soft, anoxic hyper saline and nutrient deficient sediments they grow on and to ensure stabilization and anchorage of the tree (Komiyama *et al.*, 2008).

5.4   Leaf phenology

A notable observation was the wide variation in leaf phenology in the species investigated. *Avicennia marina* was characterized by a unimodal leaf production and loss with a peak production between May and July while *Ceriops tagal* had a bimodal pattern with peak leaf emergence between April – June and November – December. *Rhizophora mucronata* was characterized by a multimodal pattern while leaf production and losses in *Sonneratia alba* was continuous. Earlier studies at Gazi made similar observations for *Rhizophora mucronata* and *Avicennia marina* (Wang'ondu *et al.*, 2010). Leaf production and losses in *Avicennia marina* were found to be unimodal and highly seasonal while leaf gain and loss in *Rhizophora mucronata* were continuous with peak production occurring during the wet season. While working in Gazi, Slim *et al.,* (1996) also observed similar phenological traits for *Rhizophora mucronata* with litter fall peaking during the dry season. In a study on *Rhizophora stylosa* in the Okinawa Island Japan, Sherman *et al*. (2010) observed that leaf production and losses were continuous though losses were more even.

One way by which mangroves regulate cellular salt content is through accumulation of salts in the leaves which are later shed (Ball and Munns, 1992). During dry periods, evapotranspiration is higher with species such as *Rhizophora mucronata* responding by yellowing and shedding of leaves in order to reduce evapotranspiration. Other species of mangroves have been found to exhibit seasonality in litter production as well. For example, in Australia Coupland *et al*. (2005) observed that leaf production was closely linked to leaf fall and that the timing of vegetative and reproductive phenology was likely to coincide with specific climatic conditions such as temperature and rainfall.

5.3   Regression equation on biomass accumulation

The equations generated to describe the relationship between below ground and above ground biomass accumulation, indicated weak relationships for the *Sonneratia alba, Rhizophora mucronata* and *Ceriops tagal* zones. However the relationship for the *Avicennia* zone was stronger and thus from this equation above ground biomass accumulation can be used to predict the below ground biomass accumulation in the *Avicennia marina* zone. The low belowground biomass for the three species could be attributed to the short duration of data collection or a weakness in the methodology used to estimate the below ground biomass accumulation. In a review of the methods used to estimate the below ground biomass, Vogt *et al*. (1996) working in the mangrove forest of Pueto Rico, cautioned on the use of this technique due to the difficulties involved in terms of labor while Sanchez (2006) working in the mangroves of South Florida noted that the in growth core technique could be used to estimate the below ground biomass with considerable success. However the method has its limitation since cutting of the roots during establishment of the in growth core may delay root growth leading to an underestimation of root production. Similar effects could be attributed to the findings of this study.

CHAPTER SIX

6.0 CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

This study aimed at investigating the structure and biomass accumulation rates in the four dominant mangrove zones in Gazi Bay mangrove forest and the environmental factors that influence them. Based on the study findings the following conclusions can be drawn:

Environmental factors have a significant impact on biomass accumulation of the mangrove forest. Among the environmental variables investigated, salinity was found to play a more significant role as more biomass accumulation occurred during the wet season when salinity levels were low.

The relationship between above ground and below ground biomass accumulation was weak in the *Sonneratia*, *Rhizophora* and *Ceriops* species zones but strong for *Avicennia marina* species zone. Hence from the equations generated in this study, only that of *Avicennia marina* in which the below ground biomass accumulation can be predicted from the above ground biomass accumulation.

A combined below ground: above ground ratio in mangroves compared to the ratio for terrestrial vegetation suggests that mangroves accumulate more below ground biomass than terrestrial forests, hence confirming the uniqueness of these forests.

The present study confirmed that there exist significant difference in above ground, below ground and total biomass accumulation between different mangrove species zones.

6.2   Recommendations

6.2.1   Recommended areas for further research

The present study has raised our knowledge on the science of mangroves and carbon capture through biomass accumulation a notch higher and at the same time demonstrating the need for further research. Some of the areas that could be focused for research are:

Research to model ecosystem carbon balance for the entire Gazi Bay mangrove forest. Considering that a lot of biomass is lost through export to neighboring systems as well as through respiration and herbivory, future research in the Gazi Bay mangrove forests should focus on Net Ecosystem Productivity.

Since no research so far in Gazi Bay mangrove forests has established the amount of soil carbon in the deep sediment and in peat, there remains a gap on the long – term carbon burial hence need to carry out more research on soil carbon.

Since this study did not generate a suitable equation for all species zones that could be useful for predicting below ground biomass accumulation using the above ground biomass accumulation, there is need to do more research on the same using a longer period and possibly modifying the in growth core method used to estimate the below ground biomass accumulation.

Another field of interest would be to monitor juvenile growth over a long period which would ultimately help to develop growth models for different mangrove species in Gazi.

6.2.2   Recommendation for policy intervention

Managers and policy makers should tap into this knowledge in the development of policies and protocols that would enable land owners benefit from the evolving carbon market. During

management planning, zones with higher biomass accumulation should be set aside for carbon offset projects while those with less accumulation can be allocated to other utilization activities such as ecotourism, beekeeping, aquaculture etc. This will have wider implication since it will help to reduce Green House Gases (GHGs) emissions through avoided deforestation and conversion.

There is need to scale up the findings of this study to other mangrove forest areas in Kenya especially during the upcoming process of drawing the national mangrove management plan under the newly launched project, Kenya Coast Development Program (KCDP). Biomass accumulation estimates from this study can be up scaled to arrive at the estimate of biomass accumulation for the entire mangrove ecosystem along the Kenyan coast. This will help shed more light on the ecosystem service rendered by the mangroves. Such an understanding will serve as an incentive and would have wide application in market based Payments for Ecosystem Services.

There is need for proper mapping of mangrove forests along the Kenyan coast as well as carrying out vulnerability assessment in all mangrove areas. This will help to establish areas that need protection from degradation and those that can be used for carbon trading.

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Appendix 1: Retrieved roots sorted into size class categories ready for drying

Appendix 2: Dried roots ready to be removed from the oven for weighing

Appendix 3: ANOVA test findings on biomass accumulation

Variable	Source	DF	MS	F	P
AGB	Zone	3	15.328	5.42	0.025
	Error	8	2.826		
BGB	Zone	3	2.148	16.03	0.001
	Error	8	0.134		
TB	Zone	3	36.598	15.56	0.001
	Error	8	2.352		