Laboratory of Plant Sciences
and Nature Management

Ecology and Restoration of Mangrove Systems in Kenya

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Thesis submitted in fulfillment of the requirements for the degree of Doctor of Philosophy in Science (Ph.D).

Promoter: Prof. Nico Koedam

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Laboratory of General Botany
and Nature Management

Ecology and Restoration of Mangrove Forests in Kenya

...wild boars and other savage live in them." **Du Terte, (1667)**

Mangrove forests in Kenya with *Rhizophora mucronata*

James Gitundu KAIRO
Ph.D. Dissertation
Mangrove Ecology
& Silviculture

Promoter: Prof. Nico Koedam.

Annex thesis

The 'ecological footprint'-concept quantifies more accurately the level of human pressure on the environment than the commonly used concept of 'carrying capacity'

DECLARATION

This thesis is my original work and has not been submitted for award of a degree in any other university.

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DEDICATION

In memory of the late

Eunice Wangûi Kagûre (Mama Carol)

there's
nothin' greater
than what you know,
w'at you understan', n' w'at you desire to achieve!..
when shattered, no snooze
keep on movin'
till end.

Keep on movin'!

The nature of mangrove environment, Mida creek, Kenya

PREFACE

This Ph.D. dissertation marks the climax of my academic work that started way back in 1973 when I was only allowed to write on a ground 'tablet'. Reminiscing my days as a young boy, myths prevented us from collecting or even touching eggs laid by wading birds that nested in the 'massive' wetland that bordered my rural home in Kenya. Not until my university years in Nairobi did I come to learn and appreciate the important roles played by wetlands – both ecological, economic and environmental. But it was too late! The 'massive' wetland in my rural home, had been reclaimed for agriculture and human settlement. The crane birds that used to perform ritual dances in the wetland were gone! In their place I see buildings, dykes, hamlets and a poorer generation. *Where did the birds go?* My quest to restore the degraded wetlands started here.

My thesis is not about the fascinating wetland birds, but rather about mangroves - 'forests growing at the edge of tropical and subtropical seas'. In addition to providing a range of products that people need, including building materials, firewood, tannins, fodder and herbal medicine, mangroves are of invaluable local and global ecologic, economic and social importance. Mangroves serve as nursery and feeding sites for many species of fish, mollusks and crustacean. Mangroves also serve as filters for sediments that threaten siltation of coral reefs and help to control water quality (Odum & Heald, 1972; Robertson *et al.* 1992).

Despite the growing recognition of the economic and ecological importance of mangroves, these forests are disappearing fast from the face of the earth. A rate exceeding 1% by area per annum (Robertson & Alongi, 1992). This thesis concerns the assessment of mangrove forests in Kenya in terms of wood resources, and their regeneration potential. The work is divided into 6 chapters.

Chapter 1 presents a global picture of mangroves, what they are, their value, threats and efforts being made to address the problems. Mangroves once occupied 75% of the tropical coasts worldwide (McGill, 1959), but anthropogenic pressures have reduced the global range of the forests to less than 50%. Based on remote sensing technology, the current area of mangrove in the world is estimated to be between 180,000 km^2 and 200,000 km^2 (Spalding *et al.* 1997).

Mangrove forests in Kenya are estimated to occupy about 54,000 ha, 70% of which occurs in Lamu district. There are 9 recorded mangrove species in Kenya. The principal species are *Rhizophora mucronata* and *Ceriops tagal* which form more than 70% of the forests.

The most important use of mangrove forests in Kenya is as wood for building and heating. The coastal people are largely dependent on mangrove poles for the framework of their houses. Historically mangrove poles were an important export item from the Kenyan coast to the treeless Arab countries (Rawlins, 1957). Over-exploitation led to a ban of mangrove exportation in 1982, a move that affected the coastal economy enormously (Kokwaro, 1985).

Chapter 2 provides a description of the study area – the Kenyan coast. The coastline runs for approximately 574 km in a NNE and SSE direction, between latitudes 1°40'S and 4°25'S and longitudes 41°34' E and 39°17'E. The agro-climatological zones along the Kenyan coast differ markedly from the north to the south. The relative humidity is higher in the south than in the north. The ocean current regime also differs from the south to the north, providing nutrient poor water in the south and nutrient rich water in the north (McClanahan, 1988). These differences in climate and ocean currents cause a strong divide between the vegetation types such that the northern mangroves in Lamu are structurally more complex than the southern mangroves in Mida creek.

What structural parameters best describe a 'healthy mangrove forest'? Is the measurement of forest cover enough indicator of guaranteeing a 'healthy system? What is the minimum number of juveniles required to ensure adequate natural regeneration of the forest after logging? These are among the issues addressed in chapters 3 and 4 of my thesis.

Chapter 3 details mangroves of Mida creek, defined in this study as 'young secondary mangrove stand that is vigorously growing, but subjected to periodic harvest. While we may be contented with the good natural regeneration that has taken place in Mida, close analysis reveals that Mida mangroves are in fact degenerating. What was harvested is not what is coming up. Mangrove harvesting in Kenya proceeds in a selective manner. *Rhizophora mucronata* is the preferred mangrove species because it produces poles that are hard, tall and straight. The most merchantable pole size is the *boriti,* with butt diameter range of 11.0 – 13.5 cm. Others are *mazio* (diameter 7.5– 11 cm) and *pau* (5.0 – 7.5 cm). Poles greater than 15.0 cm diameter (*banaa*) are of less economic value and are therefore left standing in the forest. Excessive removal of *boriti* and *mazio* sized poles has created complex mangrove silvicultural problems in Kenya. The overgrown *banaa* canopy shade out juveniles and young trees and cause them to be crooked as they try to grow in an open space inside the closed forest canopy.

Chapter 4 is about the application of remote sensing and GIS technology in mapping the mangrove forests within and adjacent to the Marine Protected Area (MPA) of Kiunga, Lamu. Remote sensing and GIS are increasingly used in mangrove forestry worldwide to assist in gathering and analysing images acquired from aircrafts, satellites and even balloons The notable advantages of using GIS include the ability to store, retrieve and analyse various types of information rapidly and making this information available as required. Thise study revealed the presence of 2.4 x 10^6 m^3 of mangrove wood within and adjacent to Kiunga Marine National Reserve (KMNR), in 16,035.94 ha. The stand volume ranged from 6.85 m^3/ha to 710.0 m^3/ha. The average stand volume was 145.88 m^3/ha, which corresponds to a stocking rate of 1736 stems/ha. Given its high potential productivity and regeneration, mangroves within and adjacent to KMNR have excellent prospects for sustainable exploitation.

The management of mangroves as renewable resources poses severe problems in that natural regeneration seems to be insufficient where large-scale operations have taken place. To sustain the yield of these forests there is a need to address both artificial and natural regeneration methods. Artificial mangrove planting in Asia has been promising in solving the problems of limited supply of mangrove products as well as maintaining the overall ecological balance of the coastal system. In **Chapter 5**, assessment is made of the above ground biomass increment of mangrove plantations that were established at Gazi bay in 1991. The above ground biomass of a 5-year old *Rhizophora* plantation was calculated at 20.25 t dry matter ha^{-1} for trees with stem diameter greater than 5.0 cm.

Finally in **Chapter 6**, a comparative analysis of mangrove forests along the Kenya coast is provided. Emphasis is given to the mangrove areas where this study was done. The variation of mangrove forest structure in Kenya occurs due to differences in environmental settings as well as differences in the levels of human pressure. Mangroves north of Tana river are river and tidal dominated systems, with a lower human pressure than mangroves south of the Tana river.

NEDERLANDSE SAMENVATTING

Deze doctoraatsthesis markeert de climax van mijn academische activiteiten die in 1973 begonnen. Dit werk handelt over mangroven – 'bossen aan de marge van tropische en subtropische zeeën'. Naast de provisie van een reeks voor de mens noodzakelijke producten, waaronder constructiemateriaal, brandstof, looistoffen, veevoeder en kruidmedicijnen, zijn mangroven van onschatbaar lokaal en globaal ecologisch, economisch en sociaal belang. Mangroven fungeren als belangrijke kraamkamers en als voedingsgronden voor vele soorten vis, mollusken en schaaldieren. Mangroven dienen eveneens als filters voor sedimenten die koraalriffen dreigen te verzilten en helpen tevens de waterkwaliteit te controleren.

In Kenya wordt de oppervlakte aan mangrovewouden geschat op ongeveer 54 000 ha. De hoogste concentratie van deze wouden bevindt zich in het gebied ten Noorden van de rivierdelta van de Tana in het Lamu-district. De mangroven van Kenya worden bedreigd door het aselectieve onttrekken van houtproducten en door de conversie naar een andere landbezetting, zoals visvijvers en zoutwerken. Het verlies aan mangrove heeft een rechtstreeks gevolg voor de locale economie zoals wordt aangetoond door de verhoogde kusterosie, het tekort aan constructiemateriaal en brandhout en een reductie van de visserij.

Er is daarom een dringende nood aan het onderzoek naar het ecologische en socio-economische belang van mangroven in Kenya, met inbegrip van de productie van hout en brandhout, het belang voor de visserij, de bescherming van de kustlijn en de natuurlijke regeneratie van commerciële mangrovesoorten. Vraagstellingen m.b.t. de vereiste hoeveelheid bomen dat aanwezig moet zijn teneinde een degelijke natuurlijke regeneratie te verzekeren moeten beantwoord worden. Er moet ook geweten zijn welke het minimum aantal juvenielen is vereist voor een adekwate opslag.

De algemene doelstelling van deze studie was het evalueren van de natuurlijke regeneratiestatus en het constructiehoutpotentieel van de mangrovewouden in Kenya met het oog op een beter beheer gebaseerd op het principe van duurzame productie. De andere doelstelling was het onderzoek naar de het herstelmechanisme van sinds 1991 in Kenya gerestaureerde mangrovegebieden. Dit laatste krijgt globaal steeds een groter belang als gevolg van de negatieve impacten door menselijke activiteiten zoals de kaalkap van mangroven voor houtproducten, de conversie van mangrovegebieden voor ander landgebruik zoals aquacultuur en de effecten van de doorsnee vervuiling in stedelijke centra. Op basis van de analyse van de toename aan bovengrondse biomassa, wordt de specifieke dynamiek van herstelde mangrovewouden besproken en wordt een ontwikkelingsmodel voorgesteld voor verschillende mangrovesoorten.

In Kenya werden producten uit mangrove-ecosystemen, vooral hout, gebruikt en verhandeld gedurende eeuwen. Vroege historische bestanden tonen aan dat sinds 200 vóór Christus mangrovehout een belangrijk commercieel product was tussen Oost-Afrika en de woestijnlanden van Arabië. De meest gegeerde mangrovesoort is *Rhizophora mucronata* omwille van zijn hard hout en zijn rechte, lange stam. De meest verhandelbare stamdikte is de *boriti* met een diameter tussen 11,0 en 13,5 cm. Andere dikteklassen zijn *mazio* (diameter tussen 7,5 en 11 cm) en *pau* (5,0 – 7,5 cm). Stammen dikker dan 15,0 cm diameter (*banaa*) zijn van minder economische waarde en blijven daarom onaangeroerd in het bos. De langdurige selectieve druk op stammen uit de *boriti*- en de *mazio*-klasse heeft complexe mangrovebosbouwkundige problemen gecreëerd in Mida Creek. De overkoepelende *banaa*-kruin overschaduwt juvenielen en jonge bomen en veroorzaken abnormale groeivormen waar deze laatste proberen te groeien in een open plek doch onder de gesloten boskruin. Op

plaatsen met een open kruin, wordt het oorspronkelijke *Rhizophora*-woud langzaam ingenomen door een *Ceriops*-woud aangezien deze laatste een hoger kolonisatiepotentieel bezit.

Mangrove-aanplanting en –beheer kent een lange geschiedenis in Zuid-Oost Azië. Op het schiereiland Maleisië werden de Matang-mangroven bijvoorbeeld beheerd voor de productie van brandstof sinds 1902. Deze activiteit verzekert een aanzienlijke tewerkstelling van de lokale bevolking terwijl het gebruik van houtproducten uit de mangrove voor constructiehout en houtskool een significante bijdrage levert aan de economie van het land. Matang geeft ook bescherming tegen kusterosie en stelt broedgronden voor vissen, visvangst, brandhout en constructiemateriaal ter beschikking. In Kenya is het gebruik van mangroveherbebossing ter voorziening van mangrovegoederen en –diensten nog niet volledig van de grond gekomen. In de huidige studie werd een evaluatie gedaan van het herstelproces van mangrove-aanplantingen die sinds 1991 in Gazi werden opgezet. De bovengrondse biomassa van een 5 jaar oude *Rhizophora*-aanplanting werd berekend op 20,25 ton droog materiaal per hectare voor bomen met een stamdiameter groter dan 5,0 cm. De in deze studie opgemeten jaarlijkse diametertoename van 1,06 ± 0,23 cm/jaar voor een jonge *Rhizophora*-aanplanting (n = 10) was hoger dan vergelijkbare waarden van 0,73 cm/jaar gepubliceerd voor Maleisië.

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One of the greatest pleasures of studying mangrove forest management has been that it has introduced me to a wide range of interesting people. This thesis would not have been possible in its present form without the scientific discussions and advice of the following: Samuel Snedaker, Jenesio Kinyamario, Farid Dahdouh-Guebas, Mokohito Kogo, Eric Slim and the late Mama Adelaide Semesi were generous with their time and were never too busy to discuss the latest development in mangrove forestry research. Jacob Raj was an entertaining host who shared his many interesting insights. Ben Kivyatu provided professional guidance on forest mensuration and management. Thanks are also due to Philip Polk, Nannette Polk, Els Martens, Robin Lewis III, Wankja Ferguson, Clement Kahuki, Ann Robertson, Edward van den Berghe, Peter Wass, Ludwig Triest, Marc van Molle, Alfredo Quarto, Nils Kautsky (from whom I first heard the Ecological Footprint Concept), Anouk Verheyden, Chris Horril, Mats Björk, Kandasamy Kathiseran, Marco Vannini, Norman Duke, Frank Dehairs, and Mark Smith. All gave their help freely and willingly, in many cases at considerable inconvenience to themselves.

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Lastly, I extend my sincere gratitude to my dear wife Caroline Wanjirû Gitûndû, you have always been there to wipe 'mud' from my body and mind, and to cheer my soul. Then when our son came I opted to call him **R**(hizophora) **X**(ylocarpus), but with our anxiety we settled for ALEX (alias $\mathbf{R_X}$) …. I hope there will be some tall *Rhizophora* left by the time Alex knows how to calculate his own 'ecological footprint'. The tallest *Rhizophora* recorded in this study was 27 m in Kiunga.

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TABLE OF CONVERSION FACTORS

centimeter (cm)	=	0.394 inches
cubic meters (m^3)	=	35.31 cubic feet
hectare (ha)	=	2.471 acre
kilometre (km)	=	0.6214 miles, 1000 m
Tonne, ton (t)	=	1,000 kg
score	=	20 poles

LIST OF ABBREVIATIONS

BSP	Biodiversity Support Program, USA.
DRSRS	Department of Resource Survey and Remote Sensing, Ministry of Planning and National Heritage, Nairobi
ECOMAMA	Ecological Marine Management, Postgraduate program, VUB
EHWS	Extreme High Water at spring tide; cf., ELWS
FAO	Food and Agriculture Organization of the United Nations
FD	Kenya Forest Department
GIS	Geographic Information System
KEFRI	Kenya Forestry Research Institute, Muguga
KMFRI	Kenya Marine and Fisheries Research Institute, Mombasa
KWS	Kenya Wildlife Service, Nairobi
MPA	Marine Protected Area
SAREC	Swedish Agency on Research Cooperation, Sweden
SIDA	Swedish International Development Agency, Sweden
UNESCO	United Nations Educational, Scientific and Cultural Organization
USA	United States of America
VUBAROS	Vrije Universiteit Brussel Adviaad voor Ontwikkelingssamenwerking
VLIR	Vlaamse Interuniversitaire Raad
VUB	Vrije Universiteit Brussel, Belgium
WWF	World Wide Fund for Nature, *also* World Wildlife Fund for Nature
WWFEARPO	World Wildlife Fund for Nature, East African Regional Program Office

GLOSSARY

Crown closure (also crown cover) – Ground area occupied by tree canopy. In this study high dense forests have greater than 80% cover, while degraded forests have less than 40% cover.

Compartment (in GIS): A forest cover polygon. Inventory Compartment is part of the reference key for identifying the geographic location of Inventory samples.

Deforestation: The clearing of forests, conversion of forestland to non-forest uses.

Felling cycle (also cutting cycle): The interval between main felling in the same area under selective system. A 20 year felling cycle is proposed for *boriti* sized poles for Lamu mangroves.

Forest cover type (also **cover type** or **forest types**) a descriptive term used to groups of trees having similar characteristics, growing in the same conditions, and having the same utilization. In this study 9 forest types are distinguished.

Mangrove management plan: A concise plan setting out all the requirements, controls and activities to be applied over space and time in a logical sequence to arrive at the desired objectives. There is no management plan for mangroves of Kenya.

Multiple use: More than one use of an area at one time. It is possible to practice fish culture (silvo-fishery) and bee farming (silvo-apiculture) in mangrove areas without affecting the functioning of the forest system.

Poles: The merchantable part of the mangrove stem. In Kenya mangrove poles are categorized and marketed based on their diameter classes (see Chap. 2). *Boriti* poles are 11.5 – 13.5 cm diameter (see table 26, pg. 70).

Propagule: A dispersal unit in mangroves. At times being referred to as seed.

Reafforestation (US Reforestation): Replant (an area of land) with forest trees.

Rotation age: The time it takes for a tree to grow to the desired size. It takes approximately 37 years for a *Rhizophora* tree to reach *boriti*-sized pole.

Sapling: A sprouted propagule also referred to as seedling or wildling.

Silviculture An area managed for the production of timber and other forest produce or maintained under woody vegetation for such indirect benefits as protection against flood or recreation.

Sustainable forest management: Utilization of forest resources without compromising their use by present and future generations.

Tree biomass: The biomass of vegetation classified as trees including foliage, trunk, roots and branches.

CHAPTER 1

A review of the ecology and restoration of mangroves systems

Major output of Chapter 1

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A review of the ecology and restoration of mangroves systems

Abstract

The restoration of mangroves has received a lot of attention world wide for several reasons. Firstly, the long ignored ecological and environmental values of mangrove forests have been documented for many mangrove areas in the world. Secondly, there is a high subsistence dependence on natural resources from mangrove forests. In addition, large losses of mangroves have occurred throughout the world leading to coastal erosion, decline of fishery resources and other environmental consequences, some of which in need of urgent attention. Finally, governments throughout the world are showing commitments towards sustainable use of mangrove areas. The present chapter synthesizes the activities of mangrove conservation and management around the world with particular emphasis on Eastern Africa. As will be noted in this chapter, extensive research has been carried out on the ecology, structure and functioning of the mangrove ecosystem. However, the findings have not been interpreted in a management framework, thus mangrove forests around the world continue to be over-exploited, converted to aquaculture ponds, and polluted. It is strongly argued here that links between research and sustainable management of mangrove ecosystems should be established.

1.1. Introduction

Mangrove ecosystems or 'mangal' (Macnae, 1968) occur worldwide along tropical and sub-tropical coastlines (Chapman, 1976; Tomlinson, 1986). These forests consist of a group of seventy species (including hybrids) of trees, shrubs and a ground fern that share common adaptations to saline and brackish waters (Tomlinson, 1986; Ball, 1988; Duke, 1992; Duke *et al.*, 1998). The high rates of productivity of mangroves (Alongi, 1998) support complex pelagic and benthic food webs (e.g. Odum & Heald, 1975; Robertson *et al.*, 1992; Primavera, 1995) and dense colonies of resident and migratory birds (Klein *et al.*, 1995). For centuries, mangroves have provided a range of products that people use including timber, firewood, finfish, shell fish, local medicine, animal fodder and vegetables (Hamilton & Snedaker, 1984; Dahdouh-Guebas *et al.*, 2000a). Mangroves also filter land run-off (Thom, 1967), and control coastal erosion (Davis, 1940).

Mangrove forests are estimated to have occupied 75% of the tropical coasts worldwide (McGill, 1959; Chapman, 1976), but anthropogenic pressures have reduced the global range of these forests to less than 50% of the original total cover (Saenger *et al.*, 1983; Spalding *et al.*, 1997). A recent global survey identified urbanization, agriculture, tourism and aquaculture development as the primary global threats to mangroves (Linden & Jernelov, 1980; Farnsworth & Ellison, 1997b). Despite repeated claims that mangroves can be managed sustainably (e.g. Hamilton & Snedaker, 1984; FAO, 1994), managed (and unmanaged) mangroves continue to be degraded and disappear at a rate estimated to exceed 1% per year (Saenger *et al.*, 1983; Ong, 1995). As a result, current attention is focused on the conservation of the remaining less-impacted mangroves throughout the world (e.g. Clough, 1993; Spalding *et al.*, 1997) and restoration of the degraded mangroves (Field, 1996; Kaly & Jones, 1998; Kairo *et al.*, 2001).

There is an urgent need therefore to manage mangroves as multiple use systems for higher and sustainable yield. This implies perturbation of the ecosystem without loss of productivity. Sustainable development has been defined as the development of mangrove lands and waterways in a way in which the system's resilience is not degraded and biological productivity is protected for the benefit of the present and future generations (Field, 1998a). Sustainable development of mangrove system is one that is stable and gives equal value to all the resource units extractable from the forest.

In order to achieve sustainable forest management there is need to assess the trends in forest conditions over time. One way to characterize mangrove ecosystem and monitor changes is through the assessment of forest structure (Holdridge *et al.,* 1971; Cintron & Schaeffer-Novelli, 1984; Dahdouh-Guebas, 2001), these aspects being closely linked to forest productivity (Odum and Heald, 1975). Some of the structural parameters used are: tree height, stem diameter, basal area, crown diameter and leaf area index (Cintron & Schaeffer-Novelli, 1984; Azariah *et al.*, 1992), from which other attributes like stand density and volume can be derived. Structural studies have been used to describe the mangroves of Puerto Rico (Lugo *et al.,* 1978); mangrove stands in Florida, Mexico and Costa Rica (Pool *et al.,* 1977) among others. In Kenya, where mangroves cover 54,000 ha, descriptive studies are numerous (Graham, 1929, Walter & Steiner, 1936; Sauer, 1965; Kokwaro, 1985), but very little quantitative work has been done on mangrove forest structure and productivity.

Two main reasons prompted this study. Firstly, mangrove forests in the north and south of the River Tana delta in Kenya were observed to vary significantly in distribution, size range and abundance, and hence, it was necessary to obtain a quantitative comparison of the adults of the principal species and seedling establishment in selected sites along the coast. Secondly, and more importantly, to assess the recovery processes of the mangrove plantations established since 1991 in Kenya (Kairo, 1995a; Kairo, 1995b). The latter is becoming increasingly important globally due to increasing degradation of mangroves worldwide brought about by human activities such as over-exploitation of wood resources (Hussein, 1995), conversion of mangrove area for other land uses such as aquaculture (Primavera, 1995) and pollution effects that are common in urban centers (Burns *et al.*, 1994). Based on the analysis of above-ground biomass increment, the mitigation processes of the restored areas are discussed and development models proposed for different mangrove species.

1.2. Mangrove biogeography

Global distribution patterns of present mangrove species have been reviewed extensively (e.g., Chapman, 1976; Tomlinson, 1986; Duke, 1992; Ricklefs & Latham, 1993; Duke *et al.,* 1998). Rather than repeating these, I draw attention to key details. All mangroves are restricted to the tropical and subtropical coasts between 32° N and 38° S (Duke, 1992). They occur in a diversity of geomophological settings (Thom, 1967; Thom; 1982; Twilley, 1995), ranging from the vast riverine and estuarine mangroves of Southeast Asia, the Sundarbans of Bangladesh and India, to isolated mangrove cays that have developed atop carbonate sands and coral rubbles in the Caribbean and Micronesia. Latitudinal limits of mangroves are by temperature pattern; both sea-surface and air temperatures (Blasco, 1984; Dahdouh-Guebas & Koedam, 2001). Rainfall and fresh water runoff have a strong influence over mangrove forest structure, largely through the reduction of salinity (Pool *et al.*, 1977; Saenger *et al.,* 1983; Corlet, 1986; Tack & Polk, 1999). In areas with low, irregular or limited seasonal rainfall the forest structure is reduced although the same species may be present (Putz & Chan, 1986).

Tomlinson (1986) has divided the geographical distribution of mangroves into two groups: the Eastern and Western group (Fig. 1.1). The Eastern group broadly corresponds to the Indo-Pacific region and includes the mangroves of eastern Africa, the Red Sea, India, South East Asia, Southern Japan, the Philippines, Australia, New- Zealand and the South Pacific Archipelago, as Far East as Samoa. The Western group comprises of the Atlantic coasts of Africa and the Americas, the Gulf of Mexico, the Pacific coasts of tropical America and the Galapagos Islands. These two regions have quite different floristic inventories, and the eastern region has approximately five times the number of species found in the western region (Spalding *et al.,* 1997). Overall species richness of mangroves declines from a peak of about thirty species in Southeast Asia to less than 10 in the West Africa - America region (Duke, 1992).

Only one mangrove fern, *Acrostichum aureum* L., occurs in both the eastern and western hemispheres. Three genera (i.e. *Acrostichum*, *Avicennia* and *Rhizophora*) occur in both hemispheres. The family Rhizophoraceae comprising *Bruguiera*, *Ceriops*, *Rhizophora* and *Kandelia* is represented in most mangrove forests. *Bruguiera gymorrhiza* (L.) Lamk. has the broadest distribution, ranging from East Africa to Samoa (Chapman, 1976; Tomlinson, 1986; Spalding *et al*., 1997).

Previous researchers (e.g. Schimper, 1903) hypothesized that all mangrove taxa originated in the Indo-west Pacific, but more recent studies are in favour of plate tectonics and continental drift in determining the current global patterns of mangrove species diversity (Ricklefs & Latham, 1993; Duke, 1995; Dodd *et al*., 1998; Duke *et. al.,* 1998; Saenger, 1998). These latter studies have hypothesized a Cretaceous-Tertiary origin for most mangrove genera on the shores of Tethys Sea, separating the northern supercontinent of Laurasia from the southern Gondwanaland. Modern distributions are hypothesized to result from adaptive radiation following dispersal across Atlantic and Pacific oceans, continental drift, the closure of Tethys Sea and global cooling (in Miocene), and finally the uplift of Panamanian Isthmus (approximately 3 m.y.a), which isolated the Pacific mangrove flora from the Atlantic flora (Duke, 1995; Saenger, 1998; Ellison *et al.,* 1999).

1.3. Global status of mangroves

The exact area of currently existing mangroves is still not known for several countries in the world. Based on the application of remote sensing technology and estimates from literature the total area of mangroves in the world has been estimated to be between 180,000 and 200,000 km^2 (Saenger *et al.,* 1983; Spalding *et al.,* 1997, Blasco *et al*., 1998). Approximately 112 countries and territories have mangrove resources within their borders (Spalding *et al.,* 1997). Some of the largest mangroves are found in Indonesia (42,550 km^2), Australia (11,500 km^2), Brazil (13,400 km^2) and Nigeria (10,515 km^2). In total these countries have some 43% of the world's mangroves (Fig. 1.2). Indonesia alone has 23% of the world total (Spalding *et al.,* 1997).

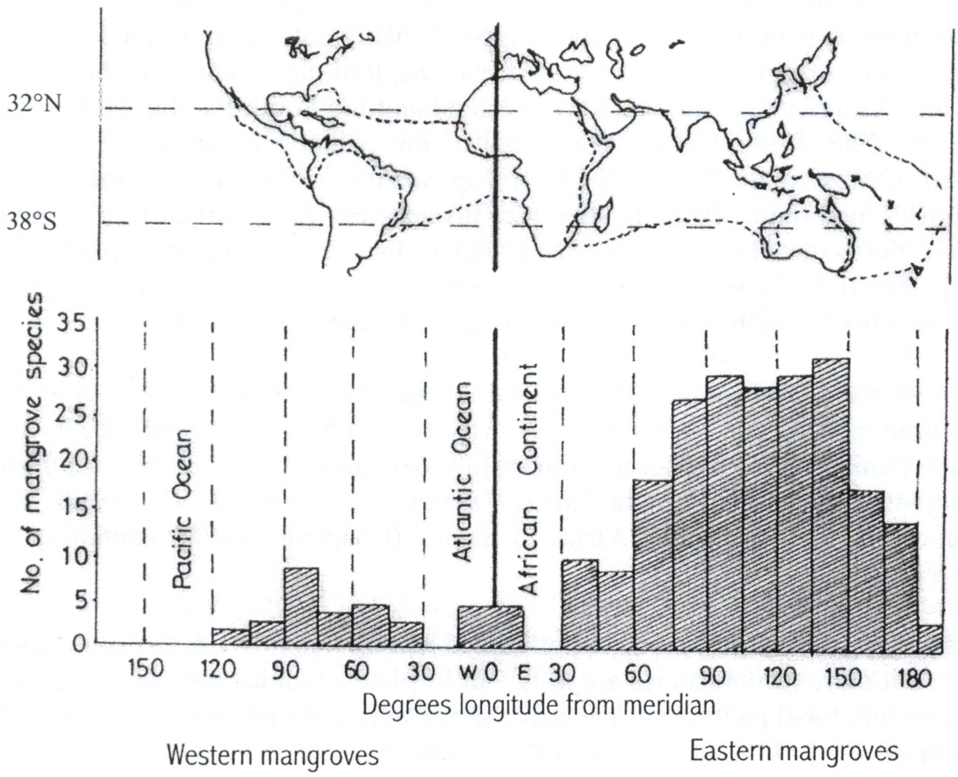


Fig. 1.1. Global distribution of mangroves. Above: approximate limits for all species. *Below*: Histogram showing approximately number of species per 15° of longitude. Overall, species richness is higher in the Eastern group (*Modified from* Tomlinson, 1986).

It is estimated that half of the world mangroves have been destroyed (Saenger *et al.,* 1983). In Southeast Asia for example, the loss figures for four countries are: Malaysia - 12% from 1980 to 1990; Philippines - 4000 km^2 originally to 1,600 km^2 today; Thailand - 5,500 km^2 in 1961 to 2,470 km^2 in 1986 and Vietnam - 4,000 km^2 originally to 2,525 km^2 today (Spalding *et al.,* 1997). These losses have largely been attributed to anthropogenic pressures such as over-harvesting for timber and fuelwood production (Walsh, 1974; Hussein, 1995), reclamation for aquaculture and salt-pond construction (Baird & Quarto, 1994; Primavera, 1995), and mining, pollution and damming of rivers that alter water salinity Lewis, 1990; Wolanski, 1992). Oil spills have impacted mangroves dramatically in the Caribbean (Ellison & Fansworth, 1996), but little documentation exists for other parts of the world (Burns *et al.*, 1994).

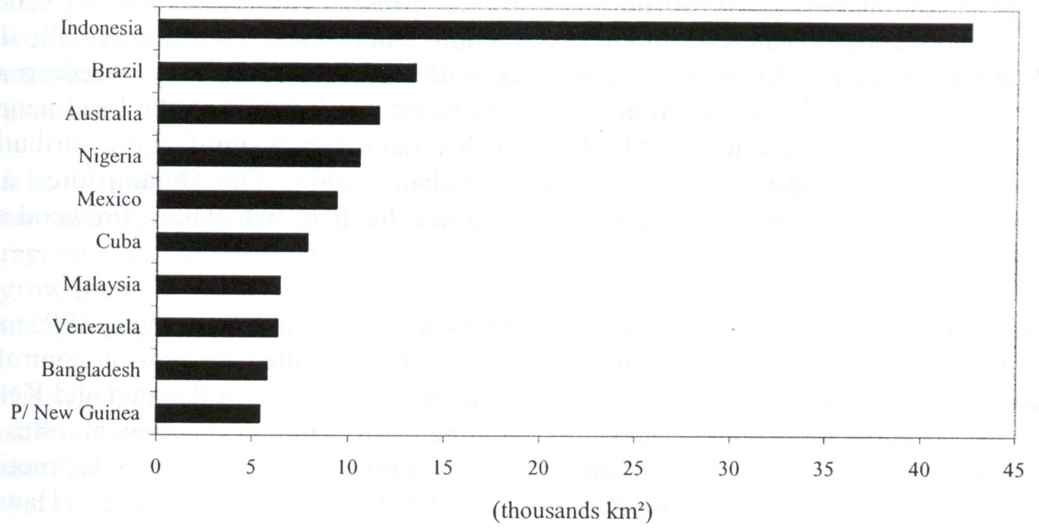


Fig. 1.2. Area of mangroves in top ten countries (*Data source:* Spalding *et al.*, 1997)

A major threat to mangrove wetlands in the world today is their conversion to areas of aquaculture. After the development of intensive shrimp farming techniques in Taiwan in the 1970's, there was a sudden rush into modern shrimp farming in Southeast Asia later spreading to the Caribbean and Latin America (Ellison & Fansworth, 1996). In the Indo-Western Pacific region alone, 1.2 million hectares of mangroves had been converted to aquaculture ponds by 1991 (Primavera, 1995).

The relationship between mangrove and fishery productivity has been documented for many areas (e.g. Lewis *et al.*, 1985; Twilley, 1993; Primavera, 1995, Baran & Hambrey, 1998). It is common to hear that fish and shrimp catches decline where mangroves have been removed (Martosubroto & Naamin, 1977; Baran, 1999). Similar losses are asserted where mangroves are cleared for aquaculture, but quantification for these losses are scarce. Folke *et al.*, 1998) have used the ecological foot print concept (Wackernagel & Rees, 1996) to quantify the ecosystem support area that is required to support shrimp farming in mangroves. From these calculations they suggest that a semi-intensive shrimp farm requires a mangrove area that is 35-190 times larger than the surface area of the pond. Clearly, integrated management of mangrove forestry and fisheries is urgently required. In East Africa, where the aquaculture and mariculture operations are just beginning (Semesi, 1998), there are real opportunities to develop mangrove-friendly aquaculture that may be truly sustainable.

1.4. History of mangrove restoration and management

Mangrove silviculture (the planting, management and harvesting of mangrove trees) has been practiced since the 18th century in Southeast Asia (e.g. Watson, 1928). Perhaps the longest recorded history of mangrove management for timber is in the Sundarbans. The 6,000 km^2 of mangrove forests that cover the Sundarbans region of India and Bangladesh, were managed since 1769 and detailed work-plans prepared in 1893-1894 (Chowdhury & Chowdhury, 1994). A parallel example is given by the 40,000 ha mangroves of Matang (Malaysia) that have been managed for purposes of sustainable timber production since 1902 (Watson, 1928). The management regime includes plantings of mangroves; with subsequent thinning, weeding and harvesting of mature trees. The operation provides significant employment to the local people, and the use of mangrove wood products for timber and charcoal makes a significant contribution to the economy of the west coast Peninsular Malaysia (Chan, 1996). The Matang forest also provides protection against coastal erosion, breeding grounds for fish, fish stakes, firewood and building materials.

More recently mangroves have been managed for integrated fish culture (Primavera, 1995) and for eco-tourism (Bacon, 1987). Planting mangroves has also been applied for erosion control in Florida (Teas, 1977), and for experimental analysis of mangrove biology in Panama and Kenya (Rabinowitz, 1978, Kairo, 1995a). Beginning with the realization of ecological roles of mangroves (Odum & Heald, 1975) and the passage of laws protecting them from destruction, many small plantings for mitigating environmental damage have occurred for example in Hawaii, Burma and Fiji (Hamilton & Snedaker, 1984). Mangroves have also been planted to restore a forest killed as a result of an oil spill (Duke, 1995).

In East Africa information on earlier mangrove plantation practices is scanty. Reference is made to mangrove planting in Lamu, Kenya, after the trees were clear-felled during the First World War (1914 - 1918) by Smith and McKenzie Company (Rawlins, 1957; Roberts & Ruara, 1967). In Tanzania, attempts to replant mangroves in the abandoned saltpans of Tanga district failed probably because of environmental factors (e.g. soil salinity and acidification) as well as poor species selection (Semesi and Howell, 1992).

Mangrove restoration has a big potential to increase the mangrove resource base, provide employment to local population, protect fragile tropical coastlines and perhaps also to enhance biodiversity and fisheries productivity. Mangrove afforestation is already proceeding at a large scale in Bangladesh, India and Vietnam principally to provide protection in typhoon-prone areas as well as to generate direct economic benefits to the people (*e.g.* Saenger and Siddique, 1993). Though plantation productivity has been shown to decline over many decades (e.g. Gong & Ong; 1990; 1995), given the chance, restored mangroves may develop into mature forests with many of the structural and functional characteristics of mature mangrove system. In Vietnam for example, low diversity planting has given way to higher diversity forests, provided the reforested area is not harvested (Twilley *et al.*, 2000).

1.4.1 Factors that affect restoration success

As noted above, mangrove forests worldwide are threatened ecosystems. The causes for their destruction range from human induced stresses (*cited above*) as well as natural disasters (Jiménez, 1985). Frequently the mangrove stands are permanently destroyed, but under some conditions the forests regenerate or can be restored. In very rare cases, new areas can also be created for mangrove growth (Saenger & Siddique, 1993). When contemplating mangrove rehabilitation, special attention must be paid to soil stability and flooding regime (Pulver, 1976), site elevation (Hoffman *et al*, 1985; Bacon & Alleng, 1992), salinity and fresh water runoff (Jiménez, 1990), tidal and wave energy (Lewis, 1982; Field, 1996), propagule availability (Loyche, 1989; Kairo, 1995a), propagule predation (Dahdouh-Guebas *et al.,* 1997, 1998;

Dahdouh-Guebas, 2001), spacing and thinning of mangroves (FAO, 1985; Kairo *et al.*, 2001), weed eradication (Saenger and Siddique, 1993), nursery techniques (Siddique *et al.*, 1993), monitoring (Lewis, 1990), community participation (Kairo, 1995b) and total cost of restoration measures (Field,1998a).

It is difficult to generalize planting sites for successful restoration, as this will depend on local environmental conditions and the species to be planted. It is generally agreed that the hydrologic regime is the single most important overall site condition governing the survival and subsequent growth of the mangrove seedlings (Field, 1996; 1998b; Elster, 2000). It is important that mangrove plantings be carried out on low energy areas where erosion is minimal (Kairo, 1995a).

Knowledge of mangrove species zonation is essential in determining suitable areas for growing different mangrove species. Rabinowitz (1978) has suggested three hypotheses to explain the mechanism of mangrove species zonation. The simplest mechanism to account for zonation is that each species of mangrove has a narrow range of tolerance of environmental variables (e.g. salinity, tidal flooding, shading, elevation of the land etc.) that restricts it to the zone in which it customarily resides. Where these tolerance zones have little overlap, pure zonation occurs. For example in Kenya, *Sonneratia* is found growing on the seaward fringe because it cannot tolerate wide fluctuations in salt concentrations, while *Ceriops* and *Avicennia* can tolerate high salinity levels found on the landward side of the intertidal areas (Kairo, 1995a). For these reasons, *Sonneratia alba* Sm. should be planted in low, muddy areas closer to the sea. In the marginal dry landward side, species like *Ceriops tagal* (Perr.) C. B. Robinson and *Avicennia marina* (Forsk.) Vierh. may be planted (Kairo, 1995a).

Under the physiological preference hypothesis, each mangrove species has a distinct preferred portion of the swamp where it grows best, but its tolerance range is sufficiently broad that, in the absence of another species, it would grow over a wide intertidal area. Under these conditions individual mangrove species is a superior in its home swamp and excludes competitors where pure stands occur. Incase mixing occurs during seeding season, competitive exclusion of species can be expected.

The third hypothesis is that competition anarchy does occur whenever there is a single site best for all mangrove species. If the site happens to be optimal for all species, it may be occupied by 'α-mangroves' to the exclusion of others (Rabinowitz, 1978). For example, reef corals compete for space in a manner similar to plants and are arranged in a dominance hierarchy that determines which species will occupy optimal habitats (Porter, 1974).

Two approaches have been used in the restoration of degraded mangrove areas. These are natural and artificial regeneration.

1.4.2 Natural regeneration

This approach uses naturally occurring mangrove propagules as the source for regeneration. The composition of the regenerated species depends on the species mix of the neighboring population. In the family Rhizophoraceae, propagules furnished with pointed hypocotyls fall freely from the parent and can plant themselves into the mud (La Rue & Muzik, 1954), or they may be stranded and planted away from the parent plant (Rabinowitz, 1978). Whether mangroves disperse through *self-planting* or *stranding* strategies (Van Speybroeck, 1992) will depend on the forest conditions (cut or not cut), tides, as well as the stability of the soils. Harvesting too many trees from the forest diminishes soil stability, which causes the propagules and saplings to be washed away by the tides and makes natural regeneration impossible. The major problem of the natural regeneration method as observed in Kenya is that the recruits may not necessarily be of the same species removed (Kairo & Gwada, 1998).

1.4.3 Artificial regeneration

Artificial regeneration of mangroves involves hand planting of desired propagules and saplings at the selected intertidal area. Planting of mangroves has successfully been done in Malaysia, India, Philippines and Vietnam (*cited above*).

Techniques used in artificial regeneration include; most commonly the use of propagules, sometimes the use of saplings (of less than 1.2 m high), and rarely the use of small trees (of up to 6 m high). Although these methods have remained virtually unchanged since Watson (1928), they are continuously being rediscovered worldwide as the prerequisite to restoration efforts (Kogo *et al*., 1987; Qureshi, 1990; Siddique *et al.,* 1993; Kairo, 1995a; SFFL, 1997; Elster, 2000).

In a mangrove plantation experiment in Kenya, Kairo (1995b) found that the survival of the transplanted saplings or propagules was better (80 - 100% of 70,000 after 24 months) than for transplanted small trees (< 5% after 12 months). Planting of nursery saplings gave a higher survival rate (80-100% after 24 months) compared to transplanting of wildings.

There are several advantages of using artificial regeneration: the species composition and distribution can be controlled, genetically improved stocks can be introduced and, pest infestation can be controlled (Field, 1998a). Although artificial regeneration provides a tool of returning life into the degraded mangrove ecosystems, many problems befall this option. Artificial regeneration can be expensive particularly in areas where hydrological regime has been modified. The techniques of mangrove planting have not been perfected for many species. Most mangrove restoration projects have used families, Rhizophoraceae, Sonneratiaceae and Avicinniaceae. This has led to poor site and species selections. Another disadvantage of artificial regeneration is the long-term loss of ecological productivity as evidenced by simplification of the systems from mixed to monoculture plantations.

1.4.4 Monitoring of restored areas

Once the restoration programs have been completed, it is essential to monitor recovery processes (or lack thereof) of the plots. These are similar activities that would normally be taken in any forestry project. In a restored mangrove forest in Kenya, significant differences in faunal composition and diversity were observed 5 years after planting (Bosire, 1999). The density of soil-infauna taxa was significantly higher ($\chi^2_{(0.05,1df)} = 81$, $p = 0.0000$) in the restored system than in naked (cleared) system; and there was no significant difference ($\chi^2_{(0.05,1df)} = 2.67$, $p = 0.102$) in the density of soil in-fauna taxa between the restored and the natural systems. In the present study, the above-ground biomass of mangrove plantation established since 1991 is investigated (Chapter 5).

1.5. Mangrove structure and geomorphology

Mangroves have been classified into different types according to their structural and functional characteristics (Golley *et al.*, 1962). Hypersaline or drought-stressed areas tend to support sparse assemblages of scrubby trees that are short, brittle, and exceedingly slow growing relative to trees growing in riverine or basin mangroves (Twilley, 1995). Lugo & Snedaker (1974) recognized six mangrove community types in Florida alone, which arose from the geomophological settings in which the trees occurred (Ellison & Farnsworth, 1996) and from differential limitations of nutrients, especially phosphorus (Feller, 1995). Thom (1982) developed the idea that geomorphic and hydrologic characteristics of the coastal zone are important to the structure of mangroves. The landform characteristics of a coastal region together with environmental processes control the basic patterns in mangrove forest structure and growth. Thom (1982) defined five basic types of environmental settings based upon the relative influence of rivers, rainfall, tidal amplitude, turbidity, and wave energies on coastal processes. These consists of Setting I, River dominated (allochthonous); Setting II, tide-dominated (allochthonous); Setting III, wave dominated barrier lagoons (autochthonous); Setting IV, coasts with combination of Settings I and III (having high wave energy and river dominated); and Setting V, drowned river valley complex. To these Twilley (1995) has added Setting VI, reef environmental setting that include carbonate processes.

The concept that Thom used - of using terrestrial environmental settings to explain mangrove processes from a geomorphological perspective - is similar to the functional classification of mangrove ecosystems of Lugo and Snedaker (1974). The environmental inputs that were used by Thom to determine specific environmental settings include rainfall, river discharge, turbidity, tidal amplitude and wave power. These 'energy signatures' (as defined by Odum, 1968) are the major forcing functions of mangroves and together with biotic factors will regulate the photosynthetic energy capture and its conversion into forest structure. Stressors like drought, hurricanes, siltation, hypersalinity commonly occur in mangrove stands draining energy that could otherwise be allocated to greater structures. Some human induced stressors short circuit natural pathways (e.g. diversion of fresh water caused by channelization); or accelerate natural processes (e.g. higher remineralization caused by thermal enrichment); while still others eliminate material pathways by the removal of forest structure (e.g. logging of the forest). The structural attributes of a given forest stand represent the maximum possible forcing function (energy signature) at the site. As one would expect, sites with similar energy signatures should develop similar structural characteristics (Lugo and Snedaker, 1974). In chapter 6 of this thesis an attempt is made to classify mangroves of Kenya using the environmental settings of Thom (1982), functional relationships of Lugo & Snedaker (1974) and forcing functions as described by Odum (1968).

One of the most studied structural attributes of mangroves concerns the horizontal distribution of species along the intertidal gradient (*see* e.g. review by Smith, 1992). Certain species of mangroves are noted to occupy the seaward fringes of swamps, while others occur more commonly in the upland reaches, albeit with considerable overlap. Zonation patterns in mangroves have been described for Malaysia (Watson, 1928), east Africa (Walter & Steiner, 1936, Macnae, 1968), Papua New Guinea (Johnstone, 1983), Indonesia (Van Steenis, 1957), Florida (Davis, 1940) and Panama (1978). Reasons for zonation has variously been attributed to microtopography or tidal elevation (Watson, 1928; Macnae, 1968), particle size characteristics and chemistry of underlying sediment (Clarke and Allaway, 1993; McKee, 1995), response to geomorphological factors (Thom, 1967), salinity (Ball, 1988; 1998), differential dispersal of propagule (Rabinowitz, 1978), dispersal mechanisms (Van Speybroeck, 1992; Clarke, 1993), interspecific competition (Clarke & Hannon, 1971; Ball, 1980), differential predation of propagules (Smith *et al.,* 1989; Osborne & Smith, 1990; Dahdouh-Guebas *et al.*, 1998) and sulphide concentration and levels of soil aeration (Matthijs *et al.,* 2000). The idea that zonation recapitulates succession (Davis, 1940) has been criticized (e.g. Rabinowitz, 1978) as it does not apply in many forests (Lugo and Snedaker, 1974).

In the numerous phytosociological studies of mangrove ecosystem most authors have given specific examples of mangrove zonation (see review by Smith, 1992), few papers (e.g., Rabinowitz, 1978; Lugo, 1980; Bunt & Williams, 1981; Bunt, 1996) provide rigorous experimental tests of the hypotheses that attempt to explain why spatial pattern of mangroves occurs. Recent experimental work (*cited above*) provides conflicting results and does not allow for generalization about the existence of zonation and the causative factors for distribution patterns.

1.6. Mangroves in Kenya: Status and conservation

The most extensive mangrove forests in Kenya are in Lamu and the Tana river districts. Less extensive mangroves are found in Funzi-Shirazi area near the mouth of River Ramisi and in Vanga where river Umba opens close to the Kenya-Tanzania border. Small and isolated patches of mangroves are scattered along several coastal indentations like Mida, Mtwapa, Gazi and Kilifi creeks (Fig. 1.3).

All the 9 mangrove species recorded in the eastern Africa region are represented in Kenya (Graham, 1929; Macnae, 1968; Kokwaro, 1985; Semesi, 1992, Table 1.1). The nine species display characteristic zonation pattern that was previously not well known (Macnae, 1968). Typical zonation patterns from for instance at Gazi bay show *Sonneratia alba* Sm. and *Rhizophora mucronata* Lam. occupying the lowest intertidal zones; *Ceriops tagal* (Perr.) C. B. Robinson and *Avicennia marina* (Forsk.) Vierh. in the mid-intertidal areas; and *Lumnitzera racemosa* Willd. and *Heritiera littoralis* Dryand in Aint. in the highest intertidal area (Fig. 1.4). *Bruguiera gymnorrhiza* (L.) does not form a distinct zonation of mangrove in Kenya but occurs interspersed with *Rhizophora* and *Ceriops*. 'Double zonation' (Macnae,1968; Dahdouh-Guebas *et al.,* (in review - a) is displayed by *Avicennia.* This is a situation in which a species may be abundant in two different disconnected zones of the forest.

1.6.1. Historical perspectives

Mangroves have played a long and important role in the history of human activity on the East African coast. Records indicate that along with slave and ivory trades, mangrove poles made up a major regional trade commodity by the 9^{th} century (M. Niebuhr, 1792 *Quoted* in Rawlins, 1957). By the beginning of the 20^{th} century Kenya was exporting an annual average of 24,150 scores of mangrove poles from Lamu forests, equivalent to 483,000 poles per year. Between 1941 and 1956 this export averaged 35,451.3 scores (Rawlins, 1957; Fig. 1.5). Unfortunately, over-exploitation and degradation of mangrove forests led to a Presidential ban on further exportation of mangrove poles from Kenya in 1982. Such ban was necessary because of the irreversible deterioration of mangrove resources that was taking place, particularly in the areas south coast of Kenya.

The major obstacles that have hitherto prevented rational use of mangroves in Kenya have been: the sectorial approach of mangrove resource management, lack of community inputs into management efforts; the poverty status of many indigenous coastal communities, lack of alternative livelihood; and a lack of awareness amongst decision makers about the true values of mangroves (Kairo & Kivyatu, 2000). These management problems are compounded by, inadequate knowledge of; silviculture of mangroves, of multiple-use potential of resources and, of the techniques of natural regeneration and reforestation. Apart from experimental plantations for the rehabilitation of deforested mangrove areas (Kairo, 1995a; 1995b; 1997) little effort has been made to restore degraded mangrove systems in Kenya.

Table 1.1. Mangroves of Kenya and their uses

Species name	Local Names (Kiswahili)	Uses	Parts used
Avicennia marina	mchu	bed posts, chair legs, table legs, fencing posts, charcoal, low quality commercial firewood, crushing pole, crushing mortar, serving dishes, drums, boat ribs, board games (bao) Firewood (for home use) Insecticides	thick stems dead stems green stems
Bruguiera gymnorrhiza	muia	high quality commercial firewood, high quality charcoal, construction poles, roof supports, boat paddles, oars, handcart handles, axe handles, pounding poles drums, bee hives	thick mature stems old hollow stems
Ceriops tagal	mkandaa	construction poles, paddles, oars, medium quality commercial firewood dyes (incl. tanning compounds) fishing traps	mature and young stems bark of stems young flexible stems
Lumnitzera racemosa	kikandaa	medium quality commercial firewood and charcoal	mature stems, dead stems
Sonneratia alba	mlilana	canoes, boat ribs, paddles, masts, fishing net floats, timber for window and door frames, medium quality commercial charcoal and firewood	thick mature stems
Rhizophora mucronata	mkoko	construction poles, high quality commercial charcoal, high quality commercial firewood dyes (incl. tanning compounds), medicines, ointments fishing traps weapons	thick mature stems and young stems bark of stems and roots roots young stems
Xylocarpus granatum	mkomafi	high quality timber for bed construction, window and door frames, medium quality commercial charcoal and firewood ointments	mature stems crushed fruits
Xylocarpus mollucensis	mkomafi dume	quality timber for construction and furniture, charcoal	mature stems, dead stems
Heritiera littoralis	msikundazi	charcoal, fire wood, building wood	thick mature stems and young stems

(*Source:* Kairo, 1995b ; Dahdouh-Guebas *et al.*, 2000b ; Omodei-Zoroni & Cortini, 2000).

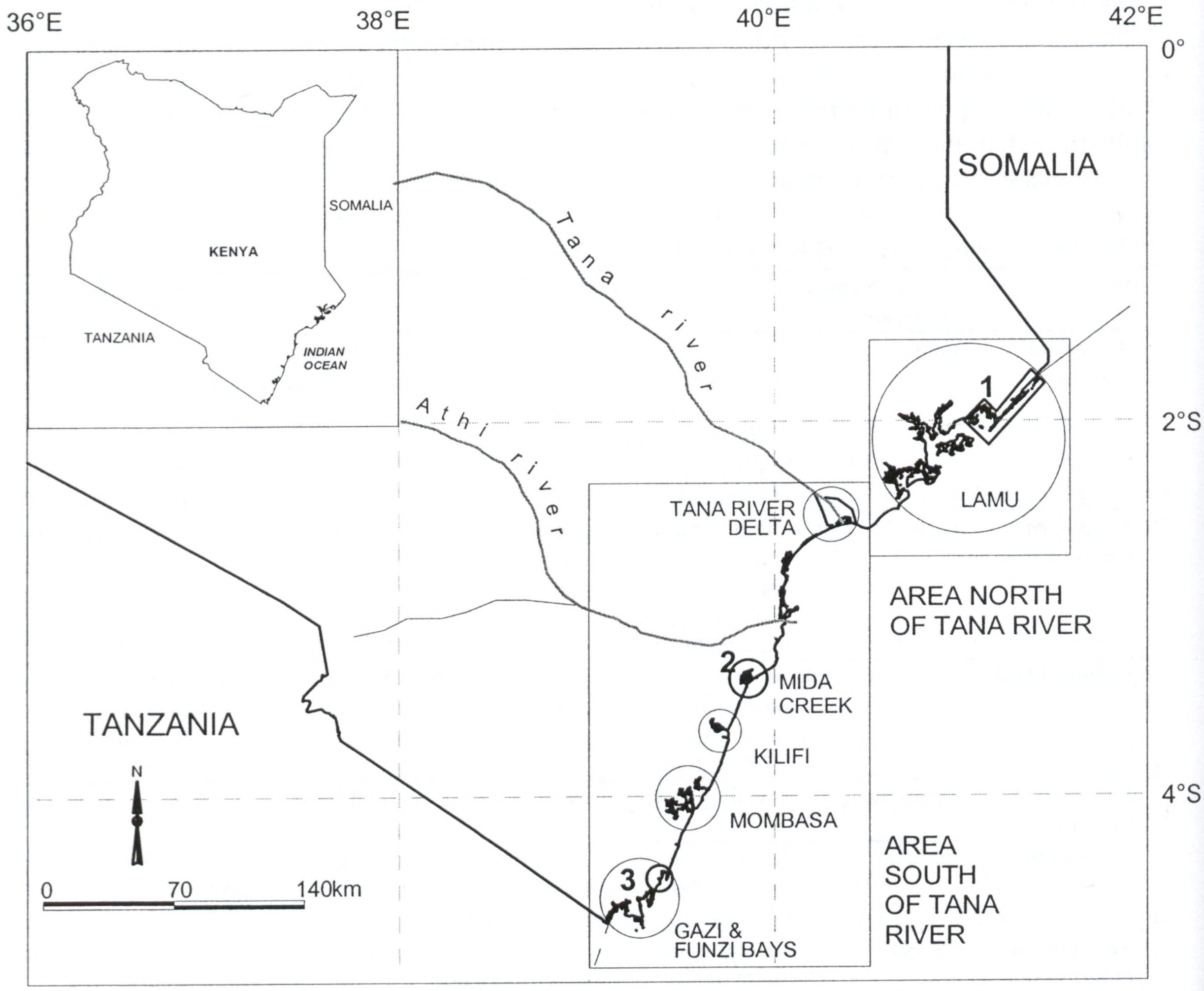


Fig. 1.3. The Kenya coastline showing major mangrove areas. In the present study mangroves of Kenya have been divided into two broad regions; area north and south of the Tana River delta. The numerical values represent pilot areas: **1**- Kiunga Marine National Reserve (KMNR), **2** – Mida creek, **3** – Gazi bay. See chapter 2 for detailed descriptions of the pilot areas.

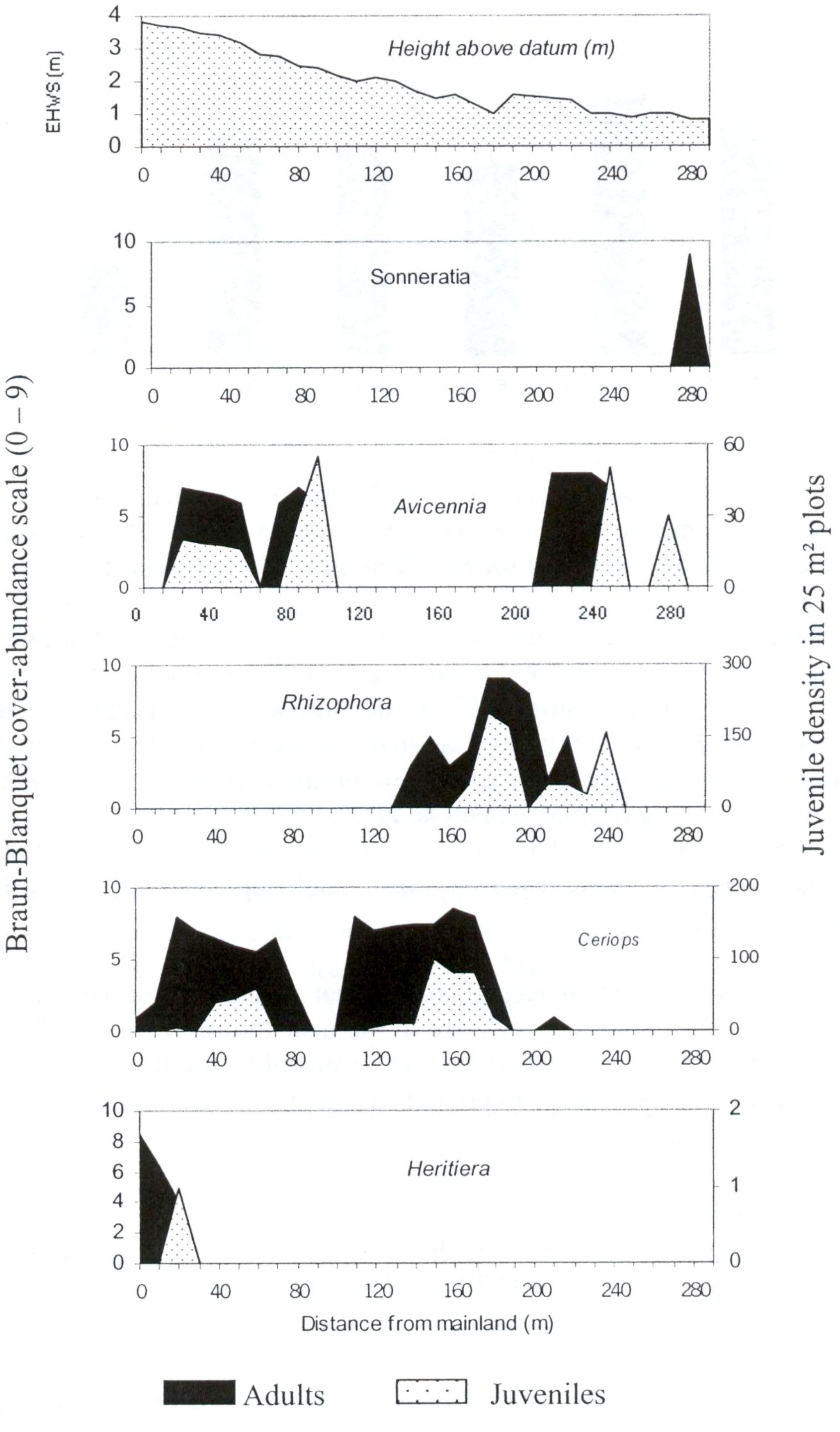


Fig. 1.4. Example of mangrove zonation at Gazi bay, Kenya. EHWS, extreme high water at spring tide. (*Source: Kairo, 1995a*)

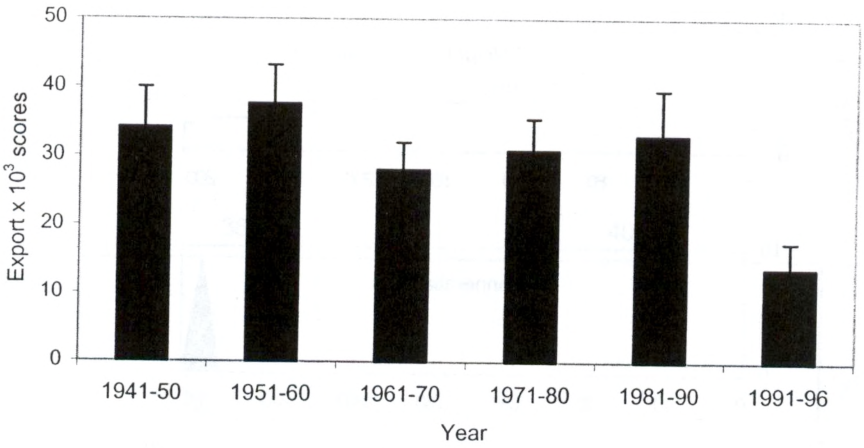


Fig. 1.5. Export of mangroves from Kenya, 1941-1996. From 1980 mangrove harvest in Kenya was mostly for domestic use. Last complete data was in 1996. Error bar denotes standard error of the mean. (*Data sources*: Rawlins, 1957; Forest Records (1950-1997).

Past studies on mangrove forestry in Kenya tend to have concentrated on floristic composition and distribution of species (Graham, 1929; Gallin *et al.,* 1989), economic utilization (Dahdouh-Guebas *et al.,* 2000b, Omodei & Contini, 2000) and regeneration strategies of the principal species (Van Speybroeck, 1992). Work on mangrove benthos has yielded results regarding resource partitioning (Slim *et al.,* 1997) and propagule predation (Dahdouh-Guebas *et al.,* 1997; 1998). Studies on nutrient cycling have also been done (Hemminga *et al.*, 1994; Slim *et al.*, 1997; Middelburg *et al.*, 1996). Quantitative data on mangrove vegetation structure, stocking rates and yield sustainability is lacking, an aspect which has been much neglected until recently for want of resources and personnel.

The increasing coastal development in Kenya means that mangrove forests and other marine ecosystems will be faced with increasing pressure in the near future. Large-scale assessment of the mangrove ecosystem and environmental factors responsible for their structural variations along the coast must represent important components of the database required for the preparation of mangrove management plans.

1.7. Objectives of the study

The overall objective of this study was to evaluate the sustainability of the supply of mangrove goods and services without necessarily affecting the forest ecosystem. More specifically, the objectives were:

1. To examine natural regeneration patterns of commercial mangrove species and timber potential of mangroves forests in selected pilot areas along the Kenyan coast,
2. To conduct mapping and quantitative analysis of mangroves forests in the pilot areas,
3. To assess recovery processes in terms of biomass increment of mangrove plantations established since 1991 at Gazi bay (Kairo, 1995a; 1995b).

CHAPTER 2

DESCRIPTION OF THE STUDY AREA

2.1. Choice of the study sites

Three mangroves sites containing all together 5 distinctive (spatially segregated) populations were chosen. The sites span the Kenyan coastline from the northern limit (Kiunga Marine National Reserve, KMNR, 1°37'S, 41°30'E), to the middle region (Mida creek, 3°20'S, 40°00'E), to the southern limit at Gazi bay (4°25'S, 39°32'E) – Fig. 1.3. The sites were selected in such a way that they represented different forms of mangroves such as fringe, riverine and basin. Mangroves of KMNR represented pristine to semi-pristine forests. Mida creek was a case of disturbed forest undergoing rapid natural regeneration, while Gazi bay represented degraded mangrove forests that would never have recovered without human intervention. Casual observation of mangroves in the study sites suggests that they differ in structure (physiognomy), hence quantitative description of the populations were made to give baseline information and provide a better understanding of their natural ecological patterns.

2.2. Biophysical characteristics

The coastal area of Kenya has a hot and humid tropical climate with an average temperature of 27 °C (McClanahan, 1988). Humidity is high throughout the year, up to 90% relative humidity during the rainy season. Evaporation in this area is double the rainfall, and the annual precipitation rates on the northern coast are only 500 – 900 mm/yr, increasing to 1000 – 1600 mm/yr on the southern coast. Most of the scarce rain falls between April and July, the main rainy season, when soils are inundated for several months. During the dry season (October to mid-March), drought is aggravated by strong trade winds blowing predominantly from the northeast. Rainfall and temperature data for the study sites are presented in Fig. 2.1.

The soils of the coastal areas are predominantly unconsolidated collarine, with poor water holding capacity and extreme alkalinity (Boxem et al., 1988). Sediment deposition is extensive within the sheltered creek waters. Much of these sediments may be originating from the agricultural hinterlands (Oestrom, 1988).

2.2.1 Drainage

Rivers extending into the coastal zone exhibit a high degree of seasonal variability. Only two major rivers draining into Indian Ocean are permanent, the Tana and Sabaki (Fig. 1.3). The Tana river originates on the slopes of Mt. Kenya and Aberdares Ranges then extends for 700 km to the sea. It has a catchment area of 132,000 km². The Sabaki river has its origin as Athi river in the central highlands around Nairobi. When joined by the Tsavo river in its lower basin the river is known as Galana. The river is known as Sabaki when it drains into the sea. The entire Athi-Galana-System extends for 390 km and drains 70,000 km² (Brakel, 1984). River Tana has an annual discharge of 4.7×10^9 m³ while the Sabaki has a discharge of 1.3×10^9 m³ per year (Angweny, 1980).

2.2.2 Oceanography

The seasonal movement of the Inter Tropical Convergence Zone (ITCZ) that engender the long and short rains in Kenya is also responsible for the seasonal shifts in wind direction and velocity at the coast. From April to October, the southeast monsoon (SEM) blows from the south or southeast. From November to March the wind direction reverses to form the northeast monsoons (NEM) blowing from the north (Fig. 2.2). The SE monsoons are associated with the long rains while NE monsoons are responsible for the short rains (Brakel, 1984).

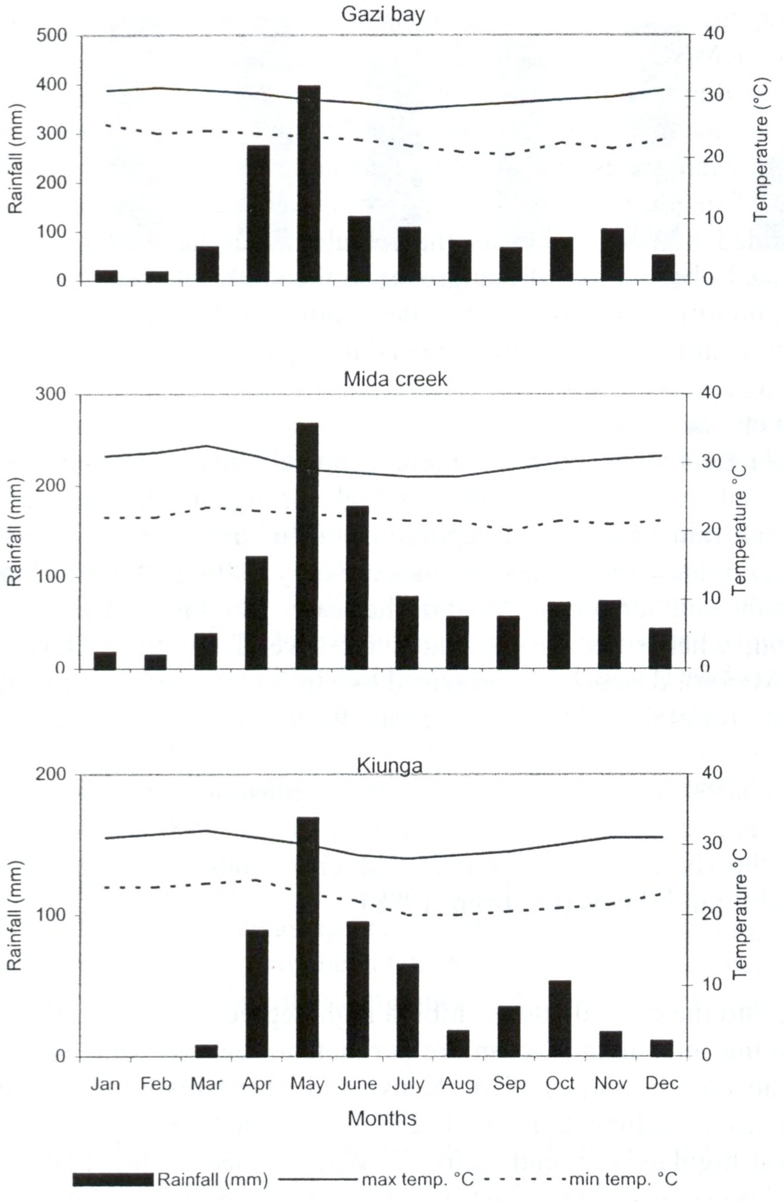


Fig. 2.1. Climatic diagrams of the three pilot areas
(Data source: Jeathold and Smidt, 1976)

Offshore currents along the Kenyan coast are influenced by the above shifts in wind direction, but are not wholly determined by them. During the SEM, the north-flowing East African Coastal Current (EACC) is intensified particularly at the upper 200 m of the water column. (McClanahan, 1988). During NEM, the EACC is weakened and is turned out to the sea when it meets the south flowing Somali Currents at a latitude between 0° and 1°S. The meeting of EACC and Somali currents causes upwellings along the Somali coast which are among the

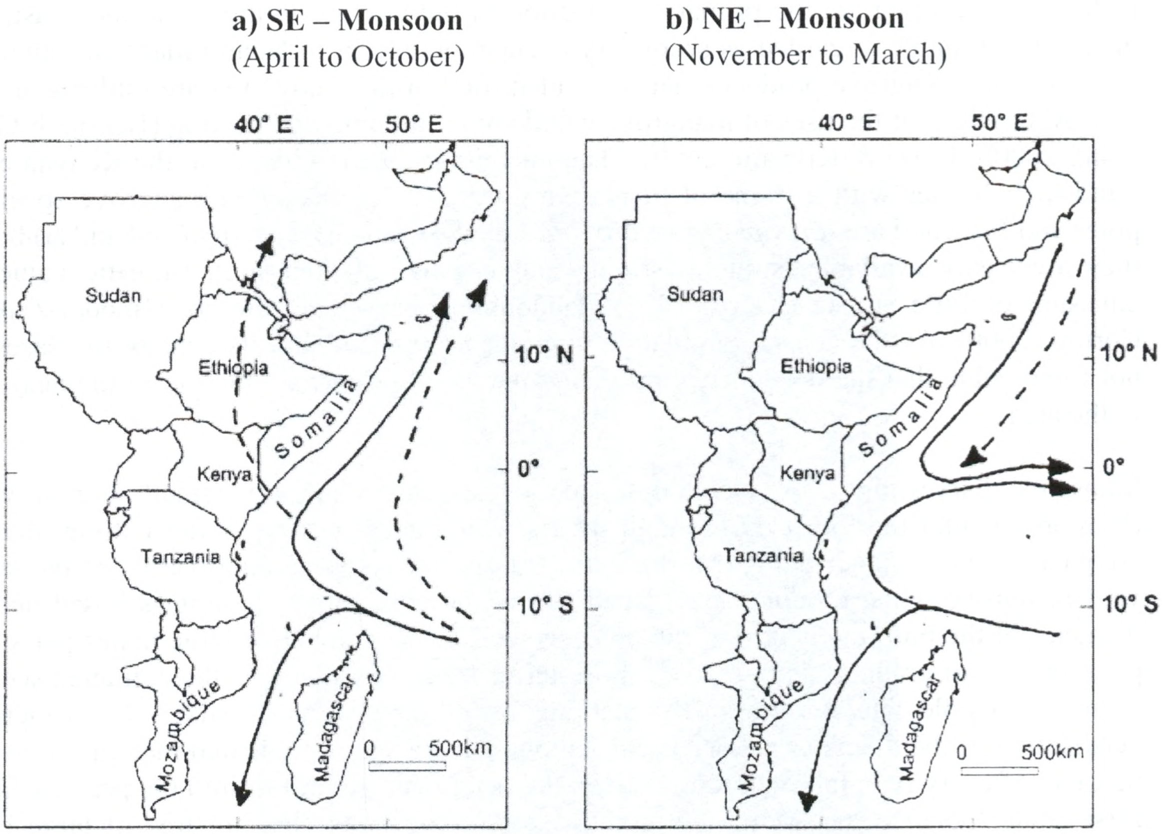


Fig. 2.2. Current patterns (solid line) and wind direction (dashed lines) during (a) the SE and (b) NE monsoons in the East African region (Adapted from NMRF,1991)

most extensive in the world. The upwellings are also responsible for the increased marine productivity in the northern Kenyan coast (Brakel, 1982). The high productivity of the surface waters during the NEM in the Northern Kenya is not reflected in higher organic matter in the sediments. This is because the shelf is narrow and offshore currents are strong. The organic matter is probably not recycled but transported and deposited into the deep sea. Detailed oceanographic research on currents systems in the Indian ocean have recently been carried out by the Netherlands Indian Ocean Programme 1992 – 1993 (Baars, 1992).

The differences in currents, rainfall, up and downwelling, water temperatures and nutrients cause a north-south divide between the marine ecosystems (Baars et al., 1991). The south coast is dominated by coral reefs and benthic productivity associated with low-nutrient water (Ohowa et al., 1997; Woitchik et al., 1997). Northern Kenya (off Lamu archipelago) has cooler nutrient rich water and a greater predominance of planktonic productivity (Baars et al., 1991).

2.3. Socio-economic features

The main ethnic groups living in the villages along the coast are the Swahili of mixed origin, Mijikenda, Bajunis and Shirazi, majority of whom are Muslims.

Fishing and farming are the primary occupation of the villages living along the coast, while mangrove cutting is regarded as secondary occupation except in Ndau village in Lamu. The main uses of mangrove products that were identified in the study area are outlined in Table 1.1. About 90% of the uses of mangrove wood are in building and heating (Dahdouh-Guebas et al., 2000b; Kairo & Kivyatu, 2000). The inhabitants of the villages in the Kenyan coastal build their houses with a frame of mangrove poles. The highly rated mangrove species for poles and firewood are *Rhizophora mucronata* (mkoko) and *Ceriops tagal* (mkandaa) because they are easily available, straight, strong, and because of their high calorific values and emission of little smoke (Kairo, 1992; Dahdouh-Guebas et al., 2000b; Omodei-Zaroni & Cortini, 2000). As the coastal population continues to expand and its density increases, it is not foreseeable that the dependence on mangrove wood products will stop in the near future in the area.

Mangrove harvesting is a male dominated occupation. Normally, small dugout vessels (Mtumbwi) enter the forest during high waters with a cutting crew. After cutting, the poles are packed into a bigger dhow (Mashua) and transported to the landing yard. At the landing yard mangrove wood products are graded before they are sold. Grading is based upon the diameter of the butt, the height of the poles as well as the number of large nodes per straight pole. In case of grading, a government Forester or forest guard counts the extracted scores (1 score = 20 poles) by progressively marking every pole with a chalk. Assessment and verification of the diameter classes is carried out using a set of graduated metallic rings. The butt end of every pole falling within a given diameter class should fit into the prescribed ring. First grade '*boriti*' (*Syn*. Mambore) consists of straight poles that are free of large branch nodes and have a butt diameter range of 11.5 – 13.5 cm, and length of greater than 4 m (Table 2.1).

Commercial harvesting of mangroves is permitted in Gazi and Mida case studies (Kairo, 1992; Dahdouh-Guebas et al., 2000b). In Kiunga, only subsistence harvesting of mangroves is allowed within the reserve; commercial logging is prohibited (Kairo and Kivyatu, 2000).

Table 2.1. Description of different classes of mangrove wood products in Kenya

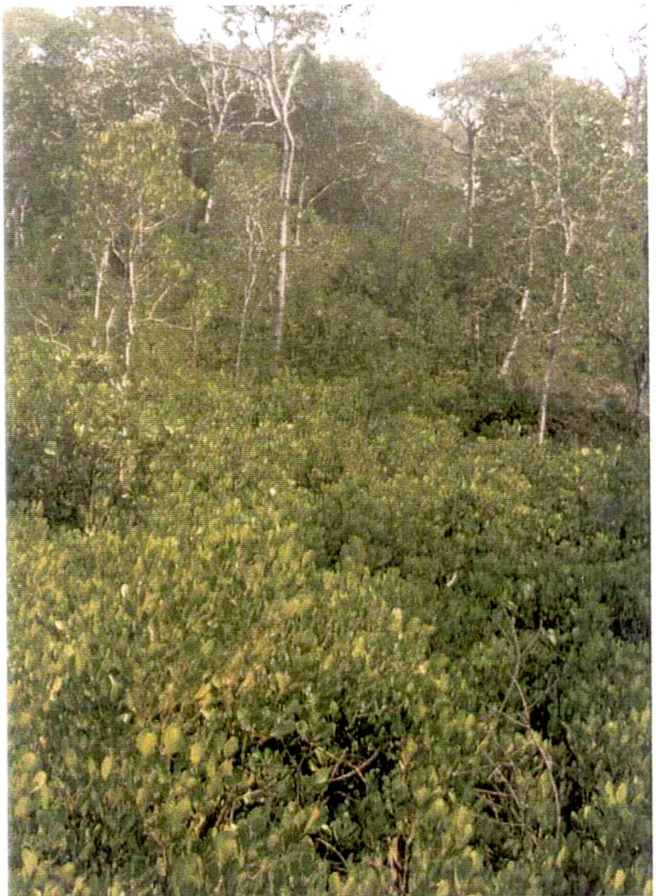
Utilization class	Diameter range (cm)	Length (m)	Unit of trade
fito	<3.5	<4	score
pau	4.0 – 7.5	4	score
mazio	8.0 – 11.0	4	score
boriti	11.5 – 13.5	>4	score
nguzo 1	14.0 – 16.5	>4	score
nguzo 2	17.0 – 20.0	>4	score
nguzo 3	20.5 – 30.0	>4	score
banaa	>30.5	>4	score
Kuni (Fuelwood)	any size	-	m^3

(1 score = 20 poles)

CHAPTER 3

MANGROVES OF MIDA CREEK, KENYA

Natural regeneration status of mangrove forests in Mida creek, Kenya



*Natural regeneration in mangroves of Mida creek is in favour of **C. tagal** (fore front) although the original cover (background) was* mostly ***R. mucronata.***

Major output of Chapter 3

Kairo, J. G. & P. O. Gwada, 1998. Mangroves of Mida Creek, Kenya. In: G. K. Mwatha, E. Fondo, J. Uku & J. U. Kitheka (eds.). *Biodiversity of Mida Creek: Final Technical Report,* pp. 150 – 182

Dahdouh-Guebas, F., C. Mathenge, **J.G. Kairo** & N. Koedam, 2000b. Utilization of mangrove wood products around Mida Creek (Kenya) among subsistence and commercial users. *Economic Botany* 54 (4): 513 -527.

Gwada, P. O. & **J. G. Kairo**. 2001. Litter production in three mangrove forests stands of Mida creek, Kenya. *South African Journal of Botany:* **67** *(*in press).

Kairo, J. G., P. Gwada, F. Dahdouh-Guebas, N. Koedam, D. Van Speybroeck & C. Ochieng, Natural regeneration status of mangrove forests in Mida creek, Kenya. *Submitted*

Natural regeneration status of mangrove forests in Mida creek, Kenya

3.0 ABSTRACT
The structure and regeneration of mangrove vegetation were studied along belt transects in two stations of Mida Creek (3°20'S, 40°00'E): Uyombo and Kirepwe. Based on importance values, the dominant mangrove tree species in Mida are *Ceriops tagal* (Perr.) C. B. Robinson and *Rhizophora mucronata* Lam. Tree density varied between 1,197 trees/ha in Kirepwe to 1,585 tree/ha in Uyombo. Mean tree heights were 6.12 ± 2.86 m (with a DBH of 8.31 ± 7.64 cm) in Uyombo and 9.28 ± 3.47 m (DBH = 13.04 ± 9.03 cm) in Kirepwe. The size-class structure in most localities of Mida showed the presence of more small trees than large ones. Spatial distribution pattern of adults and juveniles varied greatly between sites and they showed a close to uniform pattern ($I_0 << 1$) for trees but a tendency to random distribution ($I_0 = 1$) for juveniles. Challenges facing sustainable management of Mida mangroves are discussed in the light of the above observations.

Key words: Stocking density, Natural regeneration, mangroves, Mida creek.

3.1 Background information

Mangrove forests in Kenya have traditionally been used as a source of building poles and firewood. Trees of different sizes are harvested, but mostly those of 2.5 to 14 cm in diameter. About 70% of the population along the Kenyan coast depends on mangrove poles for house construction (Wass, 1995), and the recent boom in tourism in the area has led to increasing demand of mangrove poles for construction of restaurants, hotels and holiday resorts (Abuodha & Kairo, 2001).

As the local exploitation of mangrove forests has been limited to the extraction of small diameter poles for construction purposes, there is a considerable standing stock of timber that has no or limited use under the present circumstances. The present management practices are only limited to the licensing of pole extraction, and marking of the extracted poles once they have been removed to a site outside the forest. There are no other silvicultural operations. Quotas for pole extraction are decided annually on unspecified basis. Extraction operations on site are not supervised by the management agencies, nor is any systematic management plan applied. As a consequence the cutters take all they need from the more accessible fringes of the forest, and this has a long-term effect on the structure and functioning of the forest.

There is an urgent need therefore to investigate the ecological and socio-economic importance of mangroves in Kenya including the production of poles and firewood, importance for fisheries production, protection of the coastline and natural regeneration of the commercial mangrove species. Questions like how many trees need to be left growing in order to ensure adequate natural regeneration need to be addressed. We also need to know the minimum number of juveniles required for adequate stocking.

The main objective of the present study was to investigate the natural regeneration and timber potential of the mangrove forests of Mida creek for better management, based on the principal of sustained yield.

3.2 Description of the study site

Mida creek or Watamu Marine National Reserve (3°20'S, 40°00'E) is situated 100 km North of Mombasa in Kilifi district. The reserve was established in 1968, and in 1979 it was designated a World Heritage Site. The reserve contains among other things mangroves, coral reefs, mud-flats and shorebird populations (UNEP/IUCN, 1988). There are 1,746 ha of mangroves in Mida, dominated mainly by mixed stands of *Rhizophora mucronata* and *Ceriops tagal*. Pure zones of *Avicennia, Rhizophora* and *Ceriops* occupy a total of 640.6 ha (or 36.7%) – Fig. 3.1.

For the sake of this study, mangroves of Mida creek were divided into two stations: Kirepwe and Uyombo. The main creek separates the two stations (Fig. 3.1).

Kirepwe covers the eastern side of Mida creek and includes mangroves of Sita, Dabaso and Ndogo Kundu. In the area of the forest approaching Sita seaward (Fig. 3.1), trees attained a height of 20 m and diameters above 18 cm. There are 573 ha of mangroves in Kirepwe.

Uyombo on the western side of the creek stretches from Uyombo village to Majaoni. Because of a large intertidal area, there is a marked difference in the vegetation structure of the seaward and the landward forest in Uyombo. The landward forest is mostly dwarf *Avicennia* while the seaward forests consists of tall *Rhizophora*. The total mangrove cover in Uyombo is 1172 ha.

Floristic composition of mangroves of Mida has been described by Gang & Agatsiva (1992). The forest resembles the fringing mangroves described by Lugo and Snedaker (1974), in that incoming and retreating tidal velocities are low and the dense, well-developed prop roots accumulate large stocks of debris. The forest plays an important role as life support for the Watamu Biosphere Reserve (Gwada & Kairo, 2001). This is in addition to the profound ecological benefits derived from mangroves such as coastal stabilization (Davis, 1940), filtration of land run-off and controlling of floods (Thom, 1982).

3.3 Materials and methods

Stratified sampling technique was used to sample mangroves of Mida. Belt transects of 10 m were established both perpendicular and parallel to the coastline across the forest. Sampling was carried out in 100 m^2 quadrats, that were laid along the transects. A total of 60 quadrats were sampled in Uyombo and 31 in Kirepwe

Within each quadrat all individuals trees greater than 2.5 cm diameter were identified and counted. Vegetation measurements included tree height and stem diameter (dbh); from which were derived tree basal area, species density and frequency (Mueller-Dombois and Ellenberg, 1974; Cintron and Schaeffer-Novelli, 1984). The ecological importance of each species was calculated by summing its relative density, relative frequency and relative dominance (Cintron and Schaeffer-Novelli, 1984). The complexity index of the study sites was obtained as the product of number of species, basal area (m^2/0.1 ha), maximum tree height (m) and number of stems/0.1 ha, times 10^{-3} in a 0.1ha plot (Holdridge *et al.*, 1971).

Tree heights were measured in meters using a Suuto clinometer while stem diameter (at 1.3 m from the ground, DBH), was measured in centimeters using a forest calliper. For *Rhizophora,* stem diameters were measured 30 cm above the highest prop roots, while in *Avicennia marina* (Forsk.) Vierh. 'branches' in a clump were treated as individual stems. A total of 6,275 m^2 (in 60 quadrants) and 3,100 m^2 (in 31 quadrants) were sampled in Uyombo and Kirepwe respectively.

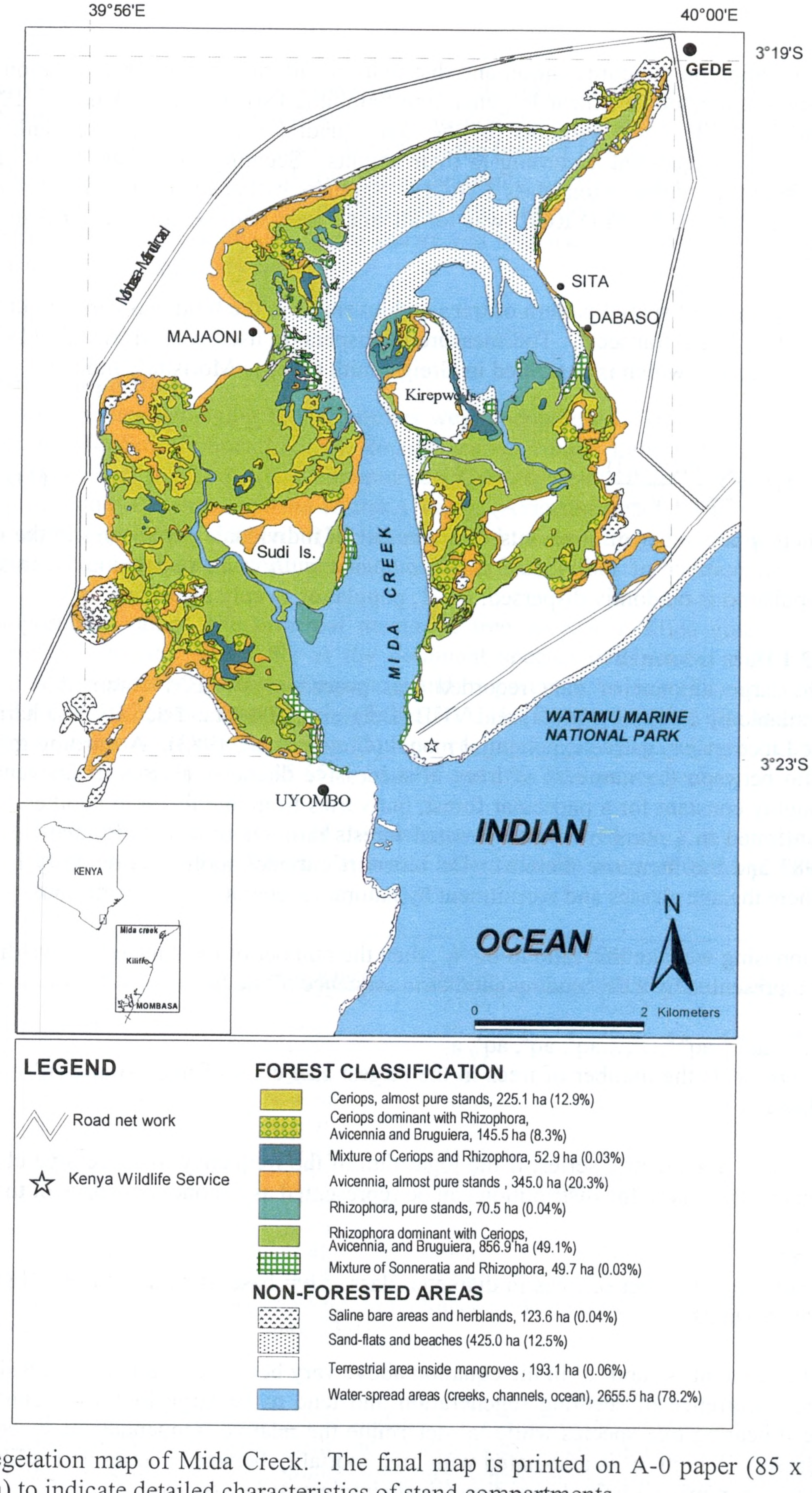


Fig. 3.1. Vegetation map of Mida Creek. The final map is printed on A-0 paper (85 x 59 cm) to indicate detailed characteristics of stand compartments.

Information on the composition and distribution pattern of natural regeneration was obtained using the method of Linear Regeneration Sampling (Srivastava & Khamis, 1978; Sukardjo, 1987). Inside 5 x 5 subplots (of the main quadrats), occurrence of juveniles of different species was recorded according to their heights. Seedlings less than 40 cm in height were classified as regeneration class I (RCI). Saplings of between 40 and 150 cm height were classified as RCII, while RCIII was for all small trees with heights greater than 1.5 m but less than 3.0 m.

The analysis of spatial pattern of trees and juveniles in the field was carried out inside 10 x 10 m^2 plots along transects. The measure of dispersion used was Morisita's (1959) index, the application of which is described in Greig-Smith (1983). Morisita's Index is:

$$I_o = q\sum_{i=1}^{q}\frac{ni(ni-1)}{N(N-1)} \quad (1)$$

where q is number of quadrants, n_i is number of individuals per species in the ith plot, and N is total number of individuals in all q quadrats; $I_o > 1$, population is clustered; $I_o = 1$, population is randomly dispersed; $I_o < 1$, population evenly dispersed.

3.3.1 Data treatment

The large amount of data recorded was processed on IBM compatible computer made available by KMFRI (Kenya) and VUB (Belgium). The stand density was harmonized using De Liocourt's negative exponential model (Clutter *et al.*, 1983). According to the model, the ratio between the numbers of trees in successive diameter classes of uneven-aged stand is roughly constant for a particular forest, but varies from one forest to another. This has been confirmed in a number of uneven-aged forests throughout the world (*see* e.g. Clutter *et al.*, 1983 and the literature therein). De Liocourt's model applies particularly in mixed forests where the age classes and recruitment by natural regeneration are continuous.

Supposing we take this ratio to be 'q', then the number of trees in successive diameter classes is represented by a descending geometric sequence of the form:

$$aq^{n-1}, aq^{n-2}, aq^{n-3}, \ldots\ldots aq^3, aq^2, aq^1, a \quad (1)$$

where 'a' is the number of trees in the largest size class of interest and 'n' is the number of classes.

For such a geometric series, if the logarithm of the frequency in successive classes is plotted against size class, the distribution can be represented as exponential curve of the form:

$$y = ke^{-ax} \quad (2)$$

where; y = number of trees in diameter class x; e = base of natural log (2.718) while k and a are constants.

The constant 'k' and 'a' in the equation above vary between forests and with site. 'k' reflects the occurrence of seedling regeneration and tend to be large in forests containing prolific seed-bearing tree species while 'a' determine the relative frequencies of successive diameter classes . A high 'a' is associated with high mortality between classes and is likely to occur in stands comprising light demanding (shade intolerant) tree species.

All data analysis and graphical presentation were run with IBM compatible STATISTICA 5.5 program. Single classification ANOVA was performed on stocking rates of different size/age classes. Nature of the future forest was derived from the present forest by fitting exponential models to the size-class structures and comparing the results at 0.05 significant levels. Each class interval was considered to be independent and thus included as within-factor repeated measure variable during the analysis. A chi-square test was used to analyse differences in juvenile densities among the study sites.

3,4 Results

3.4.1 Floristic composition

Seven mangrove species belonging to six families were encountered. The common species were *Sonneratia alba* Sm. (Sonneratiaceae), *Rhizophora mucronata* Lam. (Rhizophoraceae), *Bruguiera gymnorrhiza* (L) Lam. (Rhizophoraceae), *Ceriops tagal* (Perr.) C. B. Robinson (Rhizophoraceae) and *Avicennia marina* (Forsk.) Vierh. (Avicenniaceae). The rare species were *Xylocarpus granatum* Koen. (Meliaceae) and *Lumnitzera racemosa* Willd. (Combretaceae). Nomenclature according to Tomlinson (1986).

Based on importance values, the principal mangrove tree species in Mida creek were *R. mucronata* and *C. tagal*. The latter is the dominant species in Uyombo with relative dominance, relative density, relative frequency and importance values (IV) of 37.61%, 56.74%, 78.33% and 172.68% respectively (Table 3.1). In Kirepwe station the forest was dominated by *R. mucronata* whose relative dominance, relative density, relative frequency and importance values were 40.97%, 45.55%, 74.19% and 160.71% respectively.

Table 3.1. Importance Values (I.V.) of the mangroves of Mida Creek, Kenya. All trees larger than 2.5 cm diameter at breast height (DBH) inside 0.01 ha plots were measured.

		Relative values (%)			
Forest block	**Species**	**Dominance**	**Density**	**Frequency**	**I.V.**
Uyombo	*R. mucronata*	64.77	27.36	61.67	153.80
	C. tagal	37.61	56.74	78.33	172.68
	A. marina	34.47	11.97	21.67	68.11
	B. gymnorrhiza	20.48	3.33	30.00	53.81
	X. granatum	1.26	0.30	1.67	2.23
	L. racemosa	0.91	0.30	1.67	2.88
Kirepwe	*R. mucronata*	40.97	45.55	74.19	160.71
	C. tagal	12.89	33.42	83.87	130.18
	A. marina	19.66	11.59	29.03	60.28
	B. gymnorrhiza	20.90	7.01	38.71	66.62
	X. granatum	1.42	0.81	6.45	8.68
	S. alba	4.14	1.62	2.23	7.99

(Total number of plots: Uyombo = 60 (total area = 6,275 m^2), Kirepwe = 31 (total area = 3,100 m^2). Number of individuals encountered: Uyombo = 994, Kirepwe = 331).

The dominant species showed no obvious zonation. *Avicennia marina* and *Lumnitzera racemosa* occupied the landward area, while the middle zone was covered by mostly *C. tagal* and *R. mucronata* mosaic (Fig. 3.2). *Sonneratia alba*, wherever present, occupied the sea margin, but was replaced by giant *A. marina* and *R. mucronata* along small creeks.

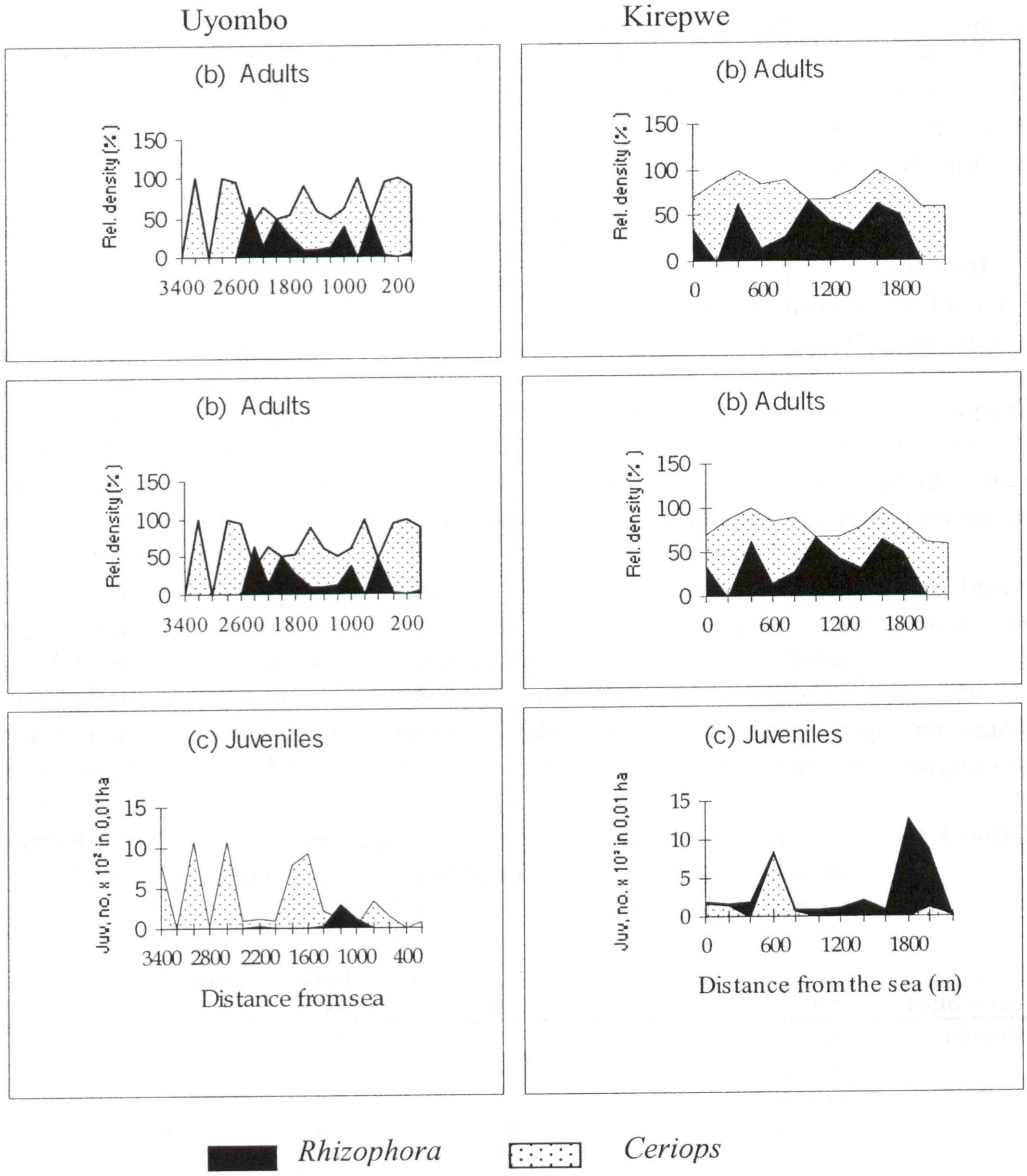


Fig. 3.2. Distribution of mangroves *(Rhizophora mucronata* and *Ceriops tagal)* in two stations of Mida creek, Kenya. Natural regeneration in most parts of Uyombo is dominated by *Ceriops.*

3.4.2 Stocking rates

Table 3.2 gives inventory data for mangroves of Mida creek. There were 1,585 stems/ha of mangroves in Uyombo, out of which 56.72 % were *Ceriops* and 27.32 % *Rhizophora*. The rest comprised of *Avicennia* (11.98 %), *Bruguiera* (3.34 %), *Lumnitzera* (0.32 %) and *Xylocarpus* (0.32 %). Stem density in Kirepwe was 1197 individuals per hectare. Out of these 45.53% were *Rhizophora* and 33.42 % *Ceriops*. Others were *Avicennia* (11.61 %), *Bruguiera* (7.02 %), *Sonneratia* (1.59 %) and *Xylocarpus* (0.84%).

Table 3.2. Stand table for the mangrove forest of Mida Creek. Values in parenthesis indicate percentages.

		Utilization class (diameter in cm)						
Station	Species	Fito/Pau (≤ 6.0)	Mazio (6.1–9.0)	Boriti (9.1-13.0)	Nguzo (13.1-20.0)	Banaa 1 (20.1-35.0)	Banaa 2 (> 35.0)	Density (Stems/ha)
Uyombo	A. mar	61 (32.11)	28 (14.74)	37 (19.47)	45 (23.68)	16 (8.42)	3 (1.58)	190 (11.99)
	B. gym	17 (32.08)	3 (5.66)	2 (3.77)	10 (18.87)	18 (33.96)	3 (5.66)	53 (3.34)
	C. tag	682 (75.86)	93 (10.34)	76 (8.45)	46 (5.12)	2 (0.22)	-	899 (56.72)
	L. rac	-	-	3 (60.00)	2 (40.00)	-	-	5 (0.32)
	R. muc	135 (31.18)	81 (18.71)	76 (17.78)	100 (23.09)	38 (8.98)	2 (0.46)	433 (27.32)
	X. gra	-	2 (40.00)	-	1 (20.00)	2 (40.00)	-	5 (0.32)
	TOTAL	895 (56.47)	207 (13.06)	195 (12.30)	204 (12.87)	76 (4.80)	8 (0.51)	1,585
Kirepwe	*A. mar*	6 (4.32)	17 (13.67)	16 (12.23)	56 (40.29)	35 (25.18)	6 (4.32)	139 (11.61)
	B. gym	16 (19.05)	13 (15.48)	3 (3.57)	16 (19.05)	26 (30.95)	10 (11.90)	84 (7.02)
	C. tag	219 (54.75)	55 (13.75)	48 (12.00)	65 (16.25)	10 (2.50)	3 (0.75)	400 (33.42)
	R. muc	126 (23.08)	26 (4.76)	90 (16.48)	239 (43.77)	65 (11.90)	-	545 (45.53)
	S. alb	-	-	-	3 (15.79)	16 (84.21)	-	19 (1.59)
	X. gra	-	-	-	6 (66.67)	3 (33.33)	-	10 (0.84)
	TOTAL	367 (30.66)	113 (9.44)	158 (13.20)	385 (32.16)	155 (12.95)	19 (1.59)	1,197

A. mar = Avicennia marina; B. gym = Bruguiera gymnorrhiza; C. tag = Ceriops tagal; L. rac = Lumnitzera racemosa; R. muc = Rhizophora mucronata; S. alb = Sonneratia alba; X. gra = Xylocarpus granatum

There were large differences between plots in the densities and sizes of juveniles (Table 3.3 see also Fig. 3.2). Mangrove forest in Mida had a potential to regenerate itself as indicated by a high incidence of RCI seedlings (> 75%). The density of established juveniles (RCII and RCIII) were 50,158 and 22,723 saplings/ha in Uyombo and Kirepwe respectively. Most of the juveniles in Uyombo (85.36%) and Kirepwe (51.40%) were *Ceriops*. Although a few mature trees of *Xylocarpus* and *Sonneratia* were found in both Uyombo and Kirepwe (Table 3.2), they were not available as juveniles.

Table 3.3. Juvenile density (saplings/ha) in Mida creek. Values in parenthesis indicate percentages.

Station	Species	Regeneration Classes RCI 0 - 40 cm	RCII 40.1-150.0 cm	RCIII 150.1-300 cm	Total/ha
Uyombo	*A. mar*	15,751 ± 952.0 (95.1)	806 ± 47.0 (4.9)	5 ± 0.6 (0.0)	16,562 (7.1)
	B. gym	2,155 ± 63.1 (78.2)	510 ± 14.7 (18.5)	92 ± 3.3 (3.3)	2,757 (1.2)
	C. tag	155,192 ± 753.1 (77.2)	43,946 ± 383.3 (22.4)	728 ± 3.3 (0.4)	199,866 (85.6)
	L. rac	-	-	2 (100)	2 (0.0)
	R. muc	10,346 ± 54.6 (71.8)	3,924 ± 20.7 (27.2)	145 ± 0.8 (1.0)	14,315 (6.1)
	TOTAL	**83,344 (78.5)**	**49,186 (21.1)**	**972 (0.4)**	**233,502**
Kirepwe	*A. mar*	903 ± 1223.0 (85.3)	155 ± 14.7 (14.7)	-	1,058 (1.1)
	B. gym	426 ± 39.1 (88.6)	39 ± 5.2 (8.1)	16 ± 3.2 (3.3)	481 (0.5)
	C. tag	38,848 ± 611.4 (75.5)	11,819 ± 143.2 (23.0)	768 ± 15.9 (1.5)	51,435 (51.4)
	R. muc	37,223 ± 668.4 (79.0)	9,465 ± 143.4 (20.1)	461 ± 5.4 (1.0)	47,149 (47.1)
	TOTAL	**77,400 (77.3)**	**21,478 (24.5)**	**1,245 (1.2)**	**100,123**

A. mar = Avicennia marina; B. gym = Bruguiera gymnorrhiza; C. tag = Ceriops tagal; L. rac = Lumnitzera racemosa; R. muc = Rhizophora mucronata; S. alb = Sonneratia alba; X. gra = Xylocarpus granatum

Figure 3.3 shows scattergrams of heights against stem diameters of mangrove forests in Mida creek. There was a significant difference in height ($F_{(1,1363)} = 291.1$, p = 0.0001) and stem diameter ($F_{(1,1363)} = 120.3$, $p = 0.0001$) between mangroves of Kirepwe and Uyombo. In Kirepwe 50% of the trees had a stem diameter of 14 – 25 cm (height: 6 – 12 m), while in Uyombo, 50% of the trees had diameter of 12 – 18 cm (height: 5 – 9 m) – Fig. 3.3a. Fifty percent (50%) of the *Rhizophora* in *Kirepwe* had a stem diameter of 12 – 20 cm (height: 7.5 – 13.0 m). Though Kirepwe station had more straight poles than Uyombo, the general quality of the standing crop in the two stations didn't show any significant difference ($F_{(1,1364)} = 1,017$; $p = 0.3135$).

The most harvested mangrove poles in Kenya are the mazio (DBH range: 8.0 – 11.0 cm) and boriti (DBH range: 11.5 – 13.0 cm) sized poles (Table 2.1). Based simply on the stem diameter, one can concede that mangroves of Mida are stocked with none merchantable pole sizes, either very small (< 5.0 cm) or too large (> 20 cm). There were 579 trees/ha (or 42 %) in Mida creek with stem diameter of less than 5 cm, and only 7 trees/ha (or 0.41%) had diameters greater than 45 cm (Table 3.4). There was more cutting pressure in Uyombo than Kirepwe (Fig. 3.3). Individual mangrove species showed a significant difference ($p < 0.05$) in height and DBH between the two stations. For instance, *Ceriops tagal* had a height of 7.14 ± 0.28 m (DBH: 5.62 ± 0.51 cm) in Kirepwe; compared to a height of 5.28 ± 0.11 m (DBH = 5.62 ± 0.16 cm) in Uyombo.

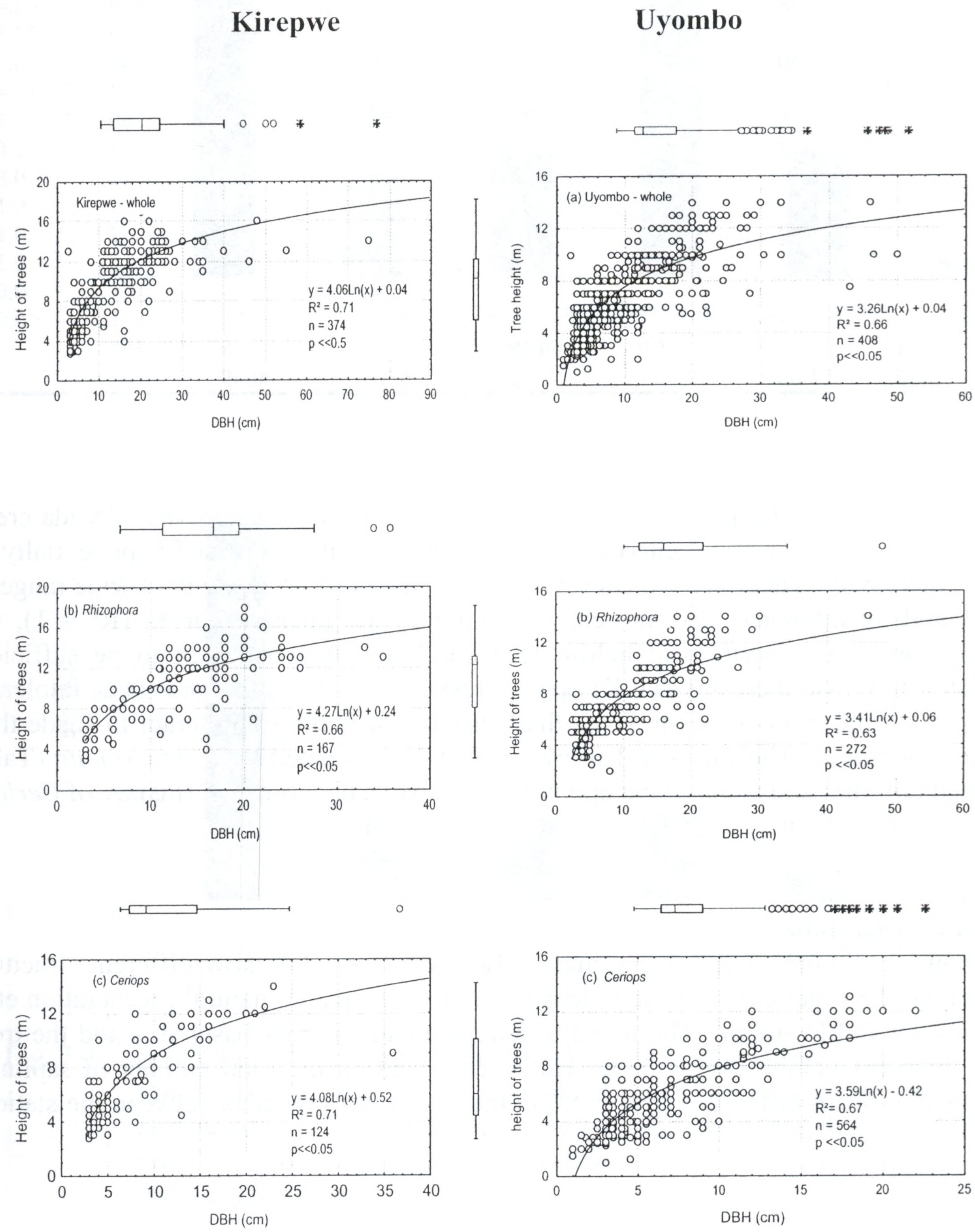


Fig. 3.3. Height-Diameter distribution of mangrove forests in Mida creek: (a) whole, (b) *Rhizophora* , (c) *Ceriops.* The box-plots display percentile distribution in each case. The extremities of the plot correspond to the maximum and minimum observations in the data set. The ends of the box are positioned at the 25% and 75% percentiles of the data set.

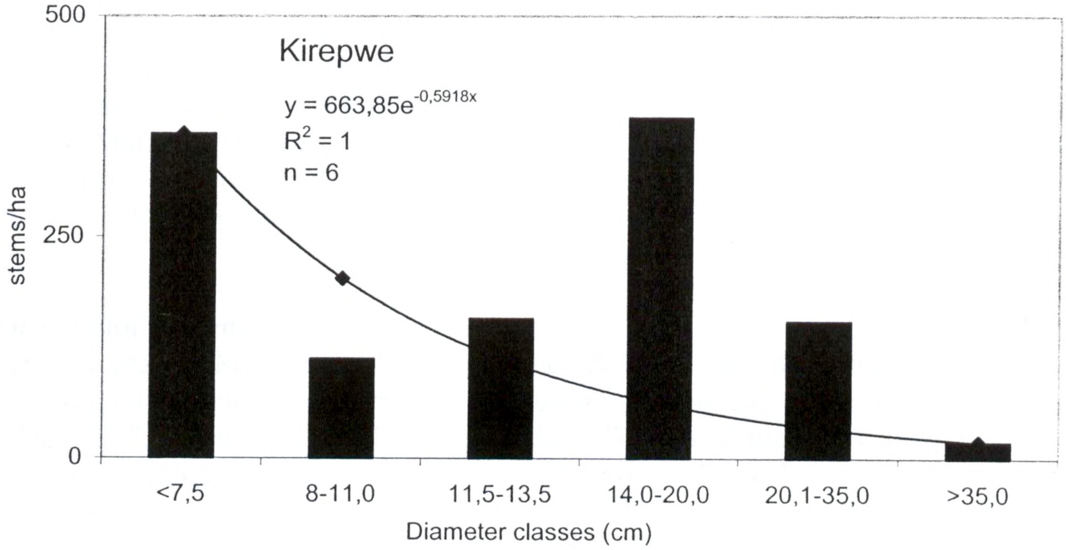
Table 3.4. Diameter and height class distribution in the mangrove forest of Mida Creek based on 10 belt transects (total area = 0.94 ha)

	Height class (m)							
	< 5	5 - 7.5	7.5 - 10	10 - 12.5	12.5 - 15	15 - 17.5	Total	%
DBH (cm)								
< 5	442	128	9	-	-	-	579	42.42
5 – 10	89	129	84	3	-	-	305	22.34
10 – 15	11	40	90	41	9	-	191	13.99
15 – 20	2	9	67	60	42	4	184	13.48
20 – 25	-	5	12	21	21	1	60	4.40
25 – 30	-	1	3	5	12	2	23	1.68
30 – 35	-	-	2	5	5	-	12	0.88
35 – 40	-	-	1	-	1	-	2	0.15
40 – 45	-	2	-	-	-	-	2	0.15
45 – 50	-	-	2	1	1	1	5	0.37
50 – 60	-	-	-	-	1	-	1	0.07
60 – 80	-	-	-	-	1	-	1	0.07
Total	544	314	270	136	93	8	1,365	
%	39.85	23.00	19.78	9.96	6.81	0.59		

Figure 3.4 shows plots of frequency *vs* diameter class data for the mangroves of Mida creek presented in table 3.2. The stand curves show that stem density decreased exponentially as the diameter increased. These are typical reversed "J" curves for stands with a wide range of size classes and by inference also age classes. Given such positive curves ($R^2 = 1$), the evidence for continuous recruitment below 15.0 cm DBH may be taken to be sufficient (Dawkins, 1958). It also indicates that Kirepwe forest contains trees that are shade intolerant (high *a*-value). Field observations indicate that *Rhizophora* is more intolerant to shade than *Ceriops* and *Bruguiera*. The forest in Kirepwe which is dominated by *R. mucronata* (Table 3.1) contained tall trees and a closed canopy with only sparse undergrowth (mainly of *Ceriops tagal*, [Fig. 3.2]) beneath it.

3.4.3 Forest revegetation

The data shown in Figures 3.2; 3.3; 3.4 and in Tables 3.3 and 3.6 show different structural developments of the vegetation (i.e. stem density, basal area, height, natural regeneration etc.) between Kirepwe and Uyombo. The forest in Kirepwe had a higher basal area and the trees were taller than in Uyombo (Table 3.6). However, based on the total number of saplings, there was no significant difference ($p > 0.05$) in the density of juveniles between the stations (Fig. 3.5, Table 3.5).



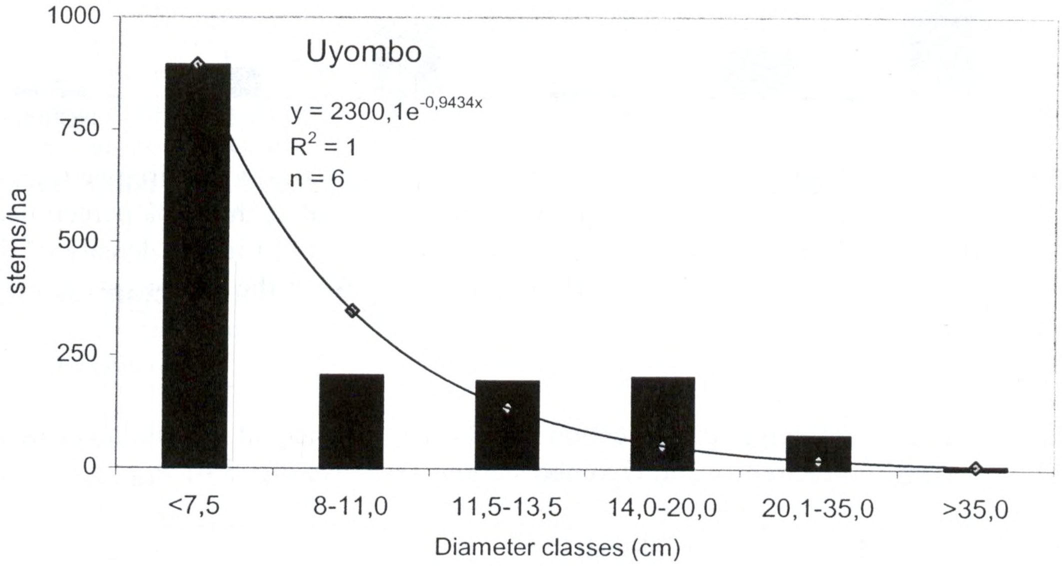


Fig. 3.4. Size class distribution of mangrove forests in Mida creek. A high 'k' value in the stand curve $y = ke^{-ax}$ for Uyombo reflects the occurrence of sporadic natural regeneration in the forest. Kirepwe contains large trees with a closed canopy that prevents light from reaching forest floor, and therefore causing low regeneration as reflected by a high 'a' value.

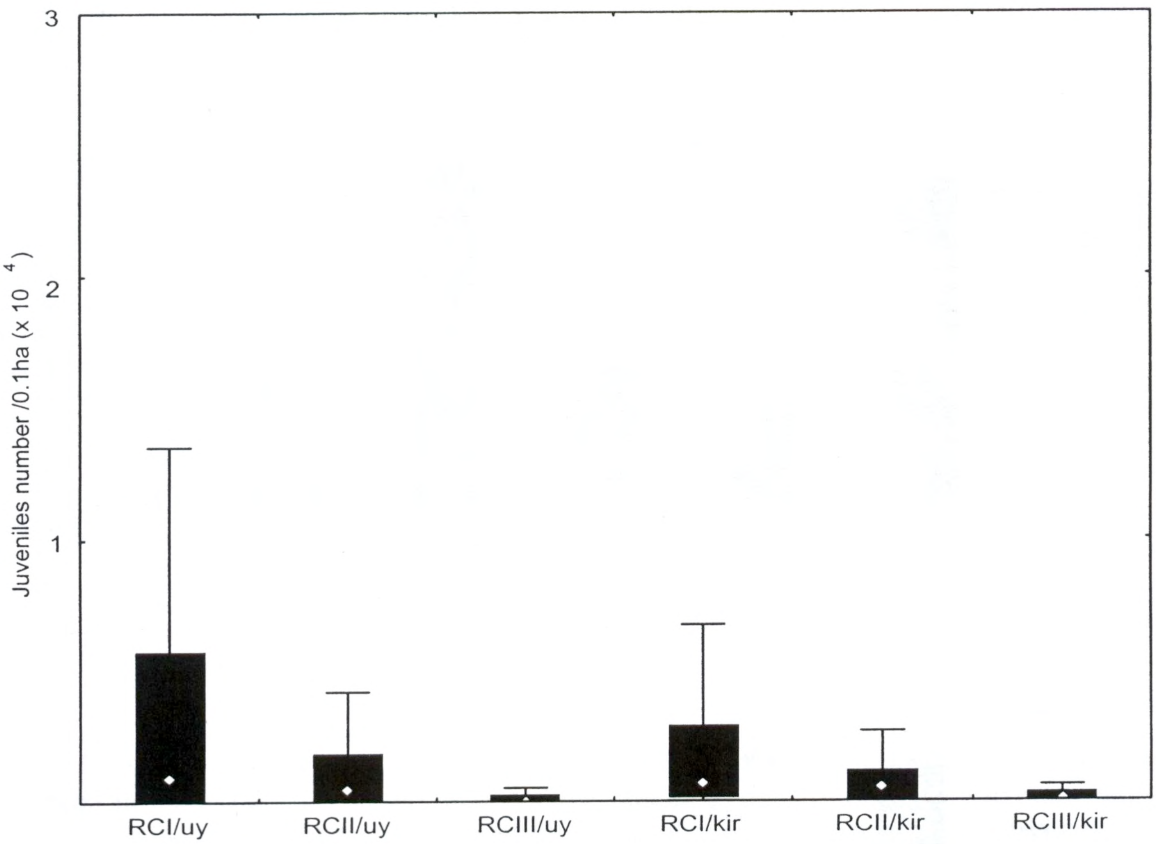


Fig. 3.5. Box-plot display of mangrove saplings in Uyombo (uy) and Kirepwe (kir) stations of Mida creek. The ends of the box are positioned at the 75% percentiles of the data set. There was no significant difference (p >0.05) in the density of different regeneration classes (RCI, RCIII and RCIII) between the stations – *see also* Table 3.5.

Table 3.5. Results of single classification ANOVA with unequal sample sizes of juvenile density in Kirepwe and Uyombo stations (*see also* Fig. 3.4).

Regeneration class (RC)	Mean Square	Mean Square Error	$F_{(1,163;\ \alpha = 0.05)}$	*p*- level
I	1.6×10^9	4.5×10^8	3.62	0.058
II	1.1×10^8	8.9×10^7	1.22	0.269
III	9.7×10^4	2.8×10^5	0.35	0.553

Conclusion: $p > 0.05$. This means that there is no significant difference in juvenile densities in the two stations of Mida creek.

Based simply on tree and sapling densities, Uyombo with an average of 1,585 stems/ha and 248,600 juveniles/ha, had a higher regeneration potential than Kirepwe which had a stem density of 1,197 per hectare and 101,600 juveniles/ha. Both stations have been under concession for many years, thereby opening the canopy and allowing light to reach the forest floor. The density of saplings was much lower in those areas where large trees formed a closed canopy. This was particularly true for mangroves of Kirepwe station in Sita (see Fig.

3.1). However questions like "What is the optimum density of saplings (for each regeneration class) needed for satisfactory forest regeneration?" has not been answered here. To solve the problem, further studies to establish survival and mortality of different mangrove seedlings under natural conditions need to be initiated. This should be part of a wider study on phenology of mangrove forests in Kenya. Empirical studies derived from Matang forests in peninsular Malaysia suggested sapling densities of 5,000 to 10,000 per hectare as sufficient for a good regeneration (UNDP/UNESCO, 1991). Based on this alone, most sites of Mida Creek have a good natural regeneration.

3.5 Discussion and conclusions

Mangrove forests in Mida creek are not pristine. All sites visited during this study had visibly been subjected to human disturbance of varying magnitude, over the last 20 - 30 years (Rawlins, 1957, Graham, 1929, Kokwaro, 1985). These activities have an accumulated effect on the current structure and regeneration of the forest. Table 3.6 is summary results of the vegetation inventories for Mida creek mangroves. The variation in the complexity (as given by C.I.) between Uyombo and Kirepwe is evident. Tree density was higher in Uyombo than Kirepwe for stems less than 10 cm diameter (Fig. 3.4). This results in higher C.I values for low diameter classes in Uyombo than in Kirepwe. The differences in C.I. values between Uyombo and Kirepwe could be due to differences in anthropogenic pressure (Dahdouh-Guebas *et al;* 2001). The proximity of human settlements to mangrove forests in Uyombo results in higher consumptive wood extraction from the forest, which in turn is reflected in diminished mangrove poles of 10 cm diameter and above from the station. In the less accessible areas of Uyombo, however, there were more stems in the larger diameter classes, taller vegetation and a higher stem density.

Table 3.6. Structural indices for the mangrove of Mida Creek

(1) Station	Uyombo				Kirepwe			
(2) Diameter class (cm)	< 5	5 - 10	10 - 15	> 15	< 5	5 - 10	10 - 15	> 15
(3) No. of species	4	5	5	6	4	4	5	6
(4) Stem density ha^{-1}	777	373	195	234	290	226	216	465
(5) Mean height (m)	4.3	6.2	8.1	10.4	5	7.6	10.8	12.1
(6) Basal area (m^2. ha^{-1})	0.89	1.70	2.38	10.87	0.33	1.04	2.85	19.40
(7) Complexity Index *	0.12	0.20	0.19	1.59	0.02	0.07	0.33	6.55

* The complexity index C.I. equals the product of (3), (4), (5) and (6) divided by 10^5 (Holdridge *et al.*, 1971).

The size-class structure (Fig. 3.4 and Table 3.4) in most localities of the study area showed the presence of more small trees than large ones, which again points to the consequences of selective logging of trees. The most harvested mangrove poles are the mazio and boriti sized poles (Table 2.1). These are used in building and construction (Kokwaro, 1985; Dahdouh-Guebas *et al.*, 2000b). Larger poles (of *banaa* and above) are of less economic value and are not exploited in Kenya (FAO, 1993; FD & KWS, 1993). Excessive removal of boriti and mazio poles has created complex mangrove management problems in Kenya. The overgrowing *banaa* canopy shade out juveniles and young trees and cause them to be crooked as they try to grow to a place in the closed forest canopy (Janzen, 1985). Earlier, before the

1970's, when trees passed the *boriti* class they could be cut for bark, fuelwood or as raw material for charcoal (Rawlins, 1957; Roberts and Ruara, 1967; Kokwaro, 1985).

Where the canopy is open, annual propagule recruitments allows adequate natural regeneration to take place and fill the gaps (Hussein, 1995). However, this natural regeneration is not necessarily of the same species as was harvested. Field observation showed that, in a mixed stand of *Ceriops* and *Rhizophora* there was a tendency for natural regeneration to favour *Ceriops,* irrespective of the harvested crop. This adds to silvicultural problems because the desirable *Rhizophora* forest is slowly giving way to the inferior *Ceriops* forest (Kairo *et al.,* submitted). . Though *Ceriops* wood is the hardest among the mangroves in Kenya, *Rhizophora* poles are mostly preferred in the market because they are generally straight and taller than *Ceriops* (Dahdouh-Guebas *et al.,* 2000b).

A forest managed on clear-cutting silvicultural practices and sustained annual yields basis assumes a normal distribution of size and age classes (Chong, 1988). The forest in Mida is akin to that of a selection forest (FAO, 1994). Selective harvesting of the merchantable mazio and boriti sized poles by the cutters, and the consequential creation of gaps in the forest canopy stimulates regeneration that approximates selection forest working. The stand tables obtained for Mida (Table 3.4) can crudely be used to project the constitution of the future managed mangroves of Mida. To do this, the first step will be to harmonize the irregularities in the stem/size class curve and the second step will be to reduce stem density per class. The result of such approximation is presented in Table 3.7. Excess trees in any one size class will require sacrificial cutting and allowing other uses of mangrove wood products e.g. for charcoal and fuelwood production.

Table 3.7. Observed and adjusted stand tables of mangrove forests in Mida

Diameter Classes (cm)	< 5	5-10	10-15	15-20	20-25	25-30	30-40	40-60	60-80	Total per ha.
Observed density/ha	579	305	191	184	60	23	14	8	1	1365
Adjusted* density/ha	579	261	118	53	24	11	5	2	1	1055

* Derived using an exponential function $y = 1282.4\ e^{-0.7952x}$, *where;* y = number of trees in diameter class x; e = base of natural log (2.718). There was no significant difference ($F_{(1,16)} = 0.1441$, $p = 0.709$) between the observed and the adjusted stem densities.

The sapling density varied greatly between localities but was on average very high, which implies adequate recruitment in most localities (Table, 3.3; Fig. 3.2). The examination of dispersion pattern showed a close to uniform pattern ($I_0 << 1$) of trees but a tendency to random distribution ($I_0 = 1$) for juveniles (Fig. 3.6). The near randomness of sapling population may be the result of redistribution of propagules by tidal action (Rabinowitz, 1978; Van Speybroeck, 1992). To assess effective stocking all regeneration classes must be considered. Saplings of RCII/III have higher incremental volume, older mortality, lower mortality and contribute more significantly towards final crop stocking (FAO, 1994). While working on mangroves of Coasta Rica, Chong (1988), formulated "equivalent regeneration values" for different regeneration classes (RCI: RCII: RCIII). A regeneration ratio of 6:3:1 was found to be an effective stocking rate for saplings. In our case the "equivalent regeneration values" for Uyombo and Kirepwe was calculated as 86:51:1 and 62:17:1

respectively. If the management objectives of Mida mangroves is to have a dense forest cover (>60%), irrespective of species, then there will be no need of replanting degraded mangroves since the present study approves that Mida forest can recover itself. However, if management objective is to promote sustainable production of the superior *Rhizophora*, then sacrificial removal of excess *Ceriops* may have to be done.

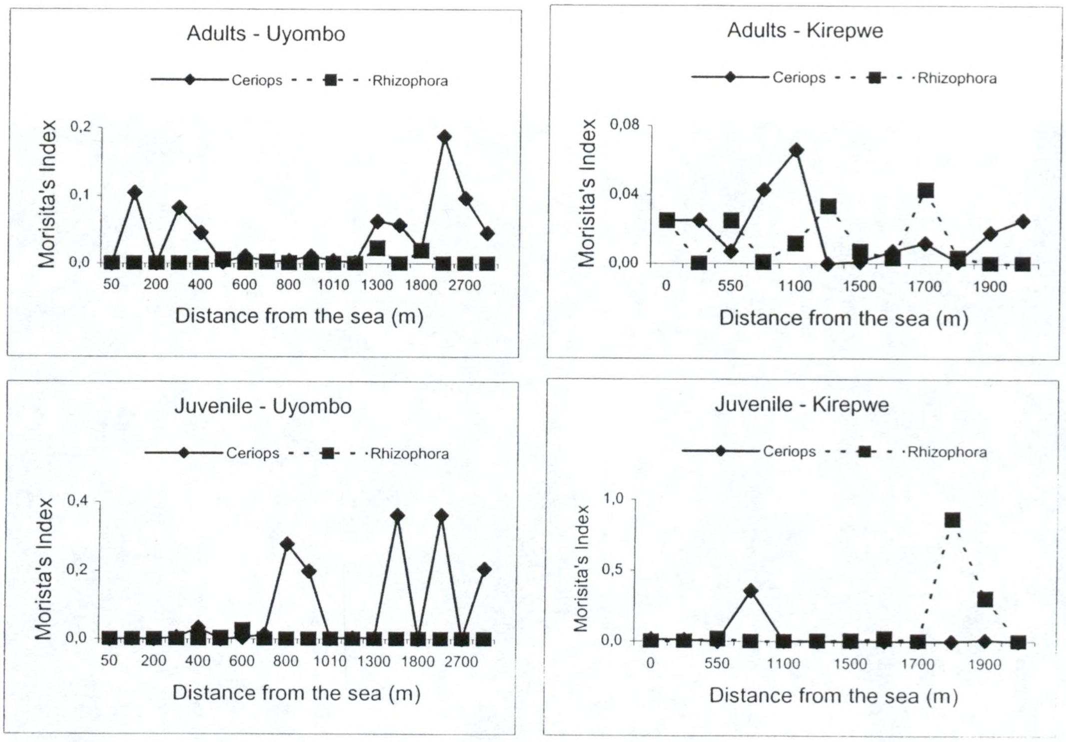


Fig. 3.6. Values of Morisita's Indices along transects for the commercial mangrove species in Mida creek. Both the adult trees and juveniles are evenly dispersed, $I_o < 0$.

3.6 References

See List of References

CHAPTER 4

MANGROVES OF KIUNGA MARINE PROTECTED AREA

Application of remote sensing and Geographic Information Systems to the management of mangrove forests within and adjacent to Kiunga Marine National Reserve, Lamu, Kenya.

How many trees are in the forest...

Mangrove of KMNR (Lamu) with *Rhizophora mucronata*

Major output of chapter 4

Kairo, J. G. and B. Kivyatu, 2000. *Mangrove management survey within and adjacent to Kiunga Marine National Reserve*. WWF/KE: 0089/01, Final Technical Project. World Wildlife Fund for Nature East Africa Regional Program Office (WWF-EARPO), Nairobi. 113p.

Kairo, J. G., B. Kivyatu and N. Koedam. Applications of remote sensing and GIS to the management of mangrove forests within and adjacent to Kiunga Marine Protected Area, Lamu, In: "*Remote Sensing and GIS in the Sustainable Management of Tropical Coastal Ecosystems*". Special Issues: KLUWER ACADEMIC PUBLISHERS – (accepted).

Application of remote sensing and Geographic Information Systems to the management of mangrove forests within and adjacent to Kiunga Marine National Reserve, Lamu, Kenya.

4.0 ABSTRACT
The status of mangrove forests within and adjacent to Kiunga Marine National Reserve (KMNR) was assessed by means of aerial photographs and intensive ground truthing. Vegetation maps (1:25,000) were produced in a GIS environment making it possible to retrieve various types of information from them and making this information available as required. GIS in addition to providing efficient data storage and retrieval facilities also offers a tool of monitoring forest conditions over time.

The present inventory revealed that the existing mangrove forests within and adjacent to KMNR had a net standing volume of 2,354,004.85 m^3 in 16,035.94 ha. There are eight species of mangrove trees, of which *Rhizophora mucronata* and *Ceriops tagal* are dominant. The standing volume ranged from 6.85 m^3/ha to 710.0 m^3/ha for stem diameter above 5.0 cm. The average volume of the entire study area was 145.88 m^3/ha, which corresponds to a stocking rate of 1736 stems/ha. Given its high potential productivity and regeneration, mangrove forests within and adjacent to KMNR have excellent prospects for sustainable exploitation.

Key words: GIS, remote sensing, management, mangroves, Kiunga, Kenya.

4.1 Background information

Since the colonial period, there were serious problems facing sustainability of mangrove forest resources in Kenya (Rawlins, 1957). As early as 1947, the colonial government took strict control of mangrove exploitation by granting concessions to private firms whose activities could easily be monitored. This was a highly unpopular move among the cutters/*nahodha* because of the general belief that mangroves were inexhaustible, and the long established custom of freedom from any sort of control. Not only did the cutters and dhow crews resent such interference, but also the middlemen, the traders, many of who had never been inside a mangrove swamp and who therefore could not appreciate the situation.

These restrictions were of a temporary nature until trained forest officers could be spared to make a thorough investigation of the swamps and prepare a work plan for the future. The survey was carried in 1949 and early parts of 1950 when trained forest officers were made available. In 1950, the government issued a statement to the effect that mangroves were significantly degraded, and in 1951 introduced the first working plans for Kenya's mangroves. The idea behind these Working Plans were, *firstly*, to keep up the supply of firewood to Mombasa, *secondly*, to sustain the supply of domestic building materials to urban areas along the coast, and of *boriti* sized poles to Lamu for export overseas, and *thirdly* to keep alive the mangrove trade. The Lamu Felling Series introduced in 1951 constituted an annual cut of one-twentieth of the total 40,000 ha available in Lamu. This 20 years rotation cycle started at Mkunumbi in 1951 (*see* Fig. 3), the annual plot shifting northwards to Kiunga.

Soon after Kenya's independence in 1964, the Spartan Air Services of Canada conducted an exhaustive survey for the mangroves of Lamu district (Roberts and Ruara, 1967). This was followed by another inventory by the Forest Department in 1981 (FD, 1983). From these two inventories, it became clear that the growing stock of mangroves in many coastal areas of Kenya had been depleted significantly. This happened primarily because of the over-exploitation of two principal species i.e., *Rhizophora mucronata* Lam and *Ceriops tagal* (Perr.) C. B. Robinson. To stop further forest degradation, a Presidential ban on mangrove export was placed in 1982. Even with the ban on pole exportation, mangrove deforestation in Kenya has intensified to meet the growing local demand (FAO, 1993; Kairo & Kivyatu, 2000). In most mangrove stands today, emergent trees of 'inferior' quality have replaced the original forest cover (Kairo & Gwada, 1998). The less desirable *Ceriops* trees whose poles are hard but short have replaced the desirable *Rhizophora* trees, whose poles are tall and straight. Therefore, the degradation of mangroves in Kenya is more in terms of a reduced quality of the forest, which is not necessarily reflected by the area under trees in the forest (Kairo *et al.,* (accepted).

The major problem facing the management of mangrove forests in Kenya is the lack of a management plan. Owing to lack of reliable and up-to-date comprehensive vegetation maps, mangrove managers do not have access to information on the present forest condition and also on the changes that have occurred in the forest cover over period of time. Accurate vegetation maps with details of mangrove distribution and abundance are essential for monitoring changes in forest conditions over time, and for investigating linkages with other ecological systems that rely on mangroves either directly or indirectly. A comprehensive database, including the information on distribution and extent of mangrove areas and forest structure is a prerequisite for the preparation of a mangrove management plan.

This chapter deals with the application of remote sensing and GIS technology in mapping the mangrove forests within and adjacent to the Marine Protected Area (MPA) of Kiunga in Kenya. Remote sensing and GIS are increasingly used in mangrove forestry worldwide to assist in gathering and analysing images acquired from aircrafts, satellites and even balloons (Ahmad & Neil, 1994; Blasco *et al.*, 1998; Spalding *et al.*, 1997; Dahdouh-Guebas *et al.*, 2000a). The notable advantages of using GIS include the ability to update the information rapidly, to undertake comparative analytical work and making this information available as required (Silapathong & Blasco, 1992; Long & Skewes, 1994). GIS in addition to providing efficient data storage and retrieval facilities also offers an important tool of monitoring forest conditions over time (Aschbancher, 1995; Long & Skewes, 1996; Ramachandran *et al.*, 1998). The application of GIS in mangrove forestry in Kenya is almost nil, because of lack of resources and trained personnel to do the work (Ferguson, 1993; Kairo *et al.*, (accepted). Results generated from this study could therefore provide an additional opportunity for a better understanding of mangrove forests geared towards their sustainable management. On the technical side, this could serve as a guideline in choosing the appropriate tools in the development of management plans for the mangrove forests in Kenya.

4.2 Objectives of the study

There were four objectives in this study:

1) To prepare vegetation maps of mangrove forests within and adjacent to KMNR.
2) To estimate the stocking rates and the standing volume of mangroves forests in KMNR,
3) To provide information on the size/class distribution of mangrove species in KMNR,
4) To provide information on the regeneration potential of the mangrove forest in KMNR.

4.3 Study site descriptions

Kiunga Marine National Reserve (KMNR) extends approximately 100 km along the northern coast of Lamu, from Ndau Island in the south (1°37'S, 41°13' E) to the Kenya-Somali border at Ishakani in the north (1°45'S', 41°35'E) – Fig. 4.1. The marine parts of the reserve are shallow, and are underlain by limestone of Pleistocene age, which surface in some areas as islands (Oostrome, 1988).

Kiunga was designated as a Marine Protected Area (MPA) in 1979 and covers an area of 25,000 ha of the continental shelf of Kenya (Fig. 4.1). The unique environment of KMNR and its high biodiversity is recognized worldwide, and this led to its designation as a Biosphere Reserve in 1980 (WWF, 1996). The reserve contains mangrove forests, coral reefs, seagrass beds, mudflats, shorebird population and turtles (UNEP/IUCN, 1998). Destruction of mangroves would have negative consequences for the reserve.

Biogeographically, KMNR is located in zone 3 (coastal mosaic) of land classification in Kenya (White, 1983). Out of the five geographical regions described by Roberts and Ruara (1967) for Lamu mangroves (Box, 4.1), KMNR is located in the Northern and North Central Swamp forests (Fig. 4.1). The Kenya Forest Department has used these geographical regions for practical management of mangroves in Kenya (FD, 1983).

In the Northern Swamp forests, most mangrove cutting has been to meet the subsistence needs of traditional people within the reserve; as such the effects of harvesting are apparently limited (Kairo & Kivyatu, 2000). However, adjacent the reserve in the North Central Swamps (e.g. in

Ndau), exploitation is high. Over-exploitation of mangroves outside the reserve will obviously lead to poaching of trees within the reserve.

The El Niño floods that befell Kenyans in 1998 did considerable damage to the riverine and creek mangrove along the coast, but very little documentation was made. The most affected areas in Lamu were along Dodori creek, adjacent to KMNR (Kairo & Kivyatu, 2000). Large numbers of trees, mostly *R. mucronata,* died probably as a result of increased sedimentation and prolonged inundation by fresh water. It cannot be said whether this was a simple case of drowning, or whether it was fresh water that had the bearing on the cause of death. The cause of death as a result of prolonged inundation by fresh water is complicated by the fact that mangroves are facultative halophytes (Walsh, 1974), thus able to survive on both fresh and saline waters. Silting may have led to closure of lenticels on the prop roots of mangroves thus resulting to choking of trees and eventually death (Tomlinson, 1986). It can also be argued that the effect of sudden changes in ambient conditions did not allow acclimatization of the plants, but this need to be investigated. It was noticeable as well that *C. tagal* scarcely suffered either immersion or siltation.

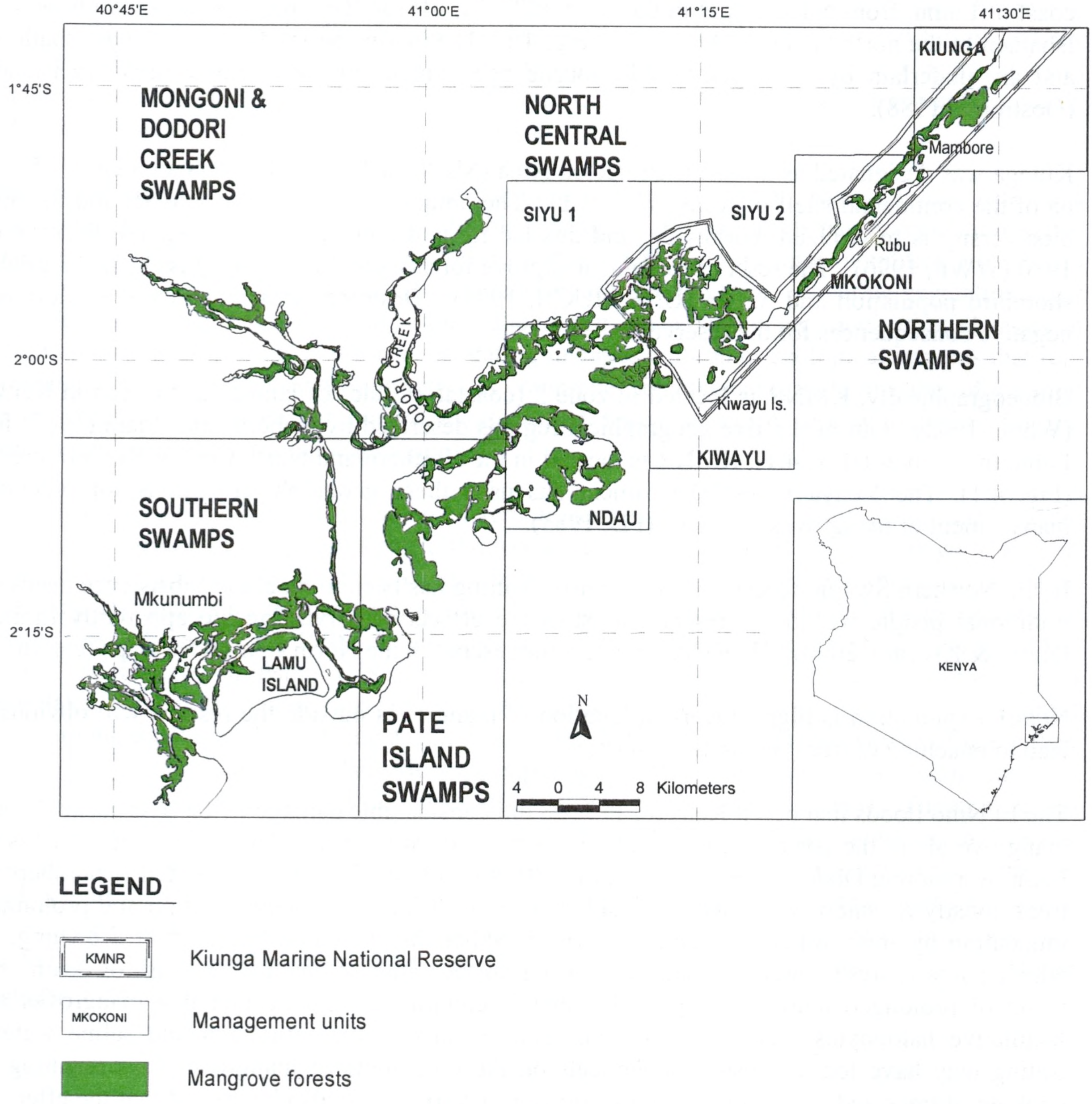


Fig. 4.1. Mangroves of Lamu district showing KMNR pilot area. The five geographical regions described by Robers and Ruura (1967) are shown. In the present study mangrove survey was carried out in the Northern and North Central Swamp forests

Geographical regions	Description
Northern swamps	Extend from Mlango wa Chano to Kiunga Dominated by pure blocks of *Rhizophora* stands
North Central Swamps	Extend from Mlango wa Chano to the mouth of Dodori creek. Include as well Uvondo and Ndau islands. Highly stocked with *Ceriops* and *Rhizophora.*
Mongoni and Dodori Creek Swamps	Comprises the mangrove found on the banks of Mongoni, Dodori creek and Manda bay. Stocked with *Ceriops* stands.
Pate Island Swamps	Includes the mangroves surrounding Pate Island, Shindabwe, Kizingitini and Chongoni.
Southern Swamps	Largest of the five mangrove regions of Lamu. Include mangroves of Mkunubi and Kimbo creeks.

Box 4.1. Description of the geographical regions of mangroves in Lamu district as applied in this study (*after* Roberts and Ruara, 1967) - *see* also Fig. 4.1.

4.4 Study approach and methodology

4.4.1 Photo-interpretation

Medium scale (1:25,000) black and white panchromatic aerial photographs procured from the Department of Resource Survey and Remote Sensing, Nairobi, were used to derive vegetation maps of mangrove forests within and adjacent to KMNR. The aerial photographs included a pair of 180 photos taken by FAO in 1992 for the whole of the study area.

Preliminary photo interpretation was carried out in the field to correlate image characteristics and ground features. A final interpretation was done using Wild APT® Mirror Stereoscope and applying a classification key developed for the purpose (Table 4.1). Tonality (contrast), crown texture, structure, and tree height and relative position on the ground easily distinguish different species of mangroves. Species of *A. marina* have a gray tone and a coarser texture compared to species of *Rhizophora mucronata* that appears dark. *R. mucronata* has a small crown diameter than *A. marina* and *S. alba*. On horizontal distribution, *S. alba* mostly occupy the seaward side of the intertidal area, while *A. marina* prefers the landward side (Fig. 1.3).

The low water line, road network, forest boundary and village location were transferred from the Survey of Kenya topographical map sheets (1:50,000 in UTM) for Lamu were used as base maps. Use was also made of the mangrove database sourced from marine dataset of the Kenya Marine and Fisheries Institute (Mombasa). The data included GIS Arc-Info coverages of mangrove areas of the entire Kenyan coast (Ferguson, 1993).

	Tonality	Texture	Structure	Other image attributes e.g. horizontal location	Species type
1	Dark grey	Fine grain, blurred	Continuous canopy Crown not separately visible	Landward, shorter than the rest	*Ceriops tagal*
2	Grey	Coarse	Discontinues canopy, large crown that is hard to distinguish	Dwarf on the landward, and tall seaward.	*Avicennia marina*
3	Dark	Fine or coarser	Continuous canopy, narrow crown not separately visible	Wide horizontal spatial range from the seaward, and along creeks	*Rhizophora mucronata*
4	Dark grey	Coarse	Discontinuous canopy mostly	Always on the water side	*Sonneratia tagal*

Table 4.1. Interpretation key used in the study

Stratification was undertaken at two levels:

- *Land use level*: The whole reserve was stratified into forested and non-forested areas. The non-forested areas contained open water, but also included agricultural area, rangeland and saline bare areas inside mangroves.

- *Operational planning level*: The mangrove-forested areas were further stratified into productive and non-productive forest types supplemented by intensive ground truthing. Each forest type was described by its species composition and was named after the dominant species. Details of different forest types recognized in the study are briefly described below.

4.4.2 Forest type classification used in the survey

1. *Ceriops* type forest

The outstanding characteristic of this forest type is its scrubby structure. *Ceriops tagal* form medium sized trees chiefly distinguishable by their buttress base, knee-like pneumatophores and small, obvate leaves. The propagules are narrow long and sharply pointed with ridges. These forest types occur in thin mud, in the inundation classes 3, 4 and 5 of Watson (1928).

Pure stands of *Ceriops* occur throughout KMNR, but are most extensive in Ndau and Siyu management areas. *Ceriops* are exploited mainly for building and firewood. The species does not coppice when felled.

2. *Avicennia* type forest

Pure stands of *Avicennia* are common in mangrove formations, mostly on the more elevated landward side, on the sandy substratum. The trees are slender and generally appear as scrub when growing on sandy substratum landward. Pure stands of *Avicennia* are extensive in Ndau and Siyu.

The richest *Avicennia* stands occur on the seaward side along Mhindi Channel and Dodori creek, growing to a height of 20 m with an average stem diameter of 30 cm. The forest is open and has pole-like appearance. The smooth greyish bark surface, pencil-like aerial roots (pneumatophores) and whitish foliage distinguish the species. *Avicennia* has poor quality wood and is exploited mostly for firewood, charcoal and wood for smoking fish. The trees will often coppice when felled.

3. *Rhizophora* type forest

The dominant plant, *Rhizophora mucronata*, is also the dominant floral element of Kenya's mangroves. *Rhizophora* thrives best on dark soft sandy-clay soils, on a gradual shore profile protected from sea waves. This type occurs in Watson's Inundation Classes 1, 2 and 3. *Rhizophora* requires tides over its arch-like roots everyday, but will not survive if the roots are covered all day long. Numerous stilt roots make this forest type almost impenetrable.

Except for some scattered Muia *(Bruguiera gymnorrhiza)* and Mkandaa *(Ceriops tagal)* this type is almost pure with a stocking rate of 909 to 1494 stems per hectare of *Rhizophora* trees. The spreading stilt roots, broad elliptic leaves with pointed tip, and long hypocotyls (propagules) are very distinctive of the species.

Pure stands of *Rhizophora* are extensive in Ndau, Siyu and Kiwayu. A striking feature of the forest is the uniform growth form of trees of the same age. *Rhizophora* stands in the northern swamp forests at Mambore and Mayayee are tall (max. height of 27 m), with an abundance of hanging aerial roots growing from both the upper stems and branches. Reportedly the forests at Mambore were clear-cut and replanted in the 1940's. Understorey is generally absent unless where the canopy has been opened though cutting or wind throw.

Along Dodori creek, heavy sedimentation caused by El Nino weather conditions of 1997/98 killed mature *Rhizophora* trees. No regeneration has been realized to date. In the northern swamp forests particulary around Rubu and Mambore, as yet unidentified insect pests have defoliated species of *Rhizophora*. The infested trees show numerous spots of leaf chlorosis.

Rhizophora is the most important mangrove species in Kiunga because of its abundance, good form and commercial size. The species is particularly exploited for building poles and firewood. *Rhizophora* trees do not coppice when felled.

4. *Sonneratia* type forest

Sonneratia alba colonizes newly deposited mud along sheltered coastlines and estuaries. Occurs further inland along creeks where the silty alluvium is formed. Pure *Sonneratia* stands occur throughout Kiunga Marine National reserve but not extensive. Walking in *Sonneratia* zone is made extremely difficult by the large peg-like pneumatophores and the deep fine substrate.

Sonneratia usually grows big, up to a height of 25 m and can be recognized by grey fissured bark surface, peg-like pneumatophores and the succulent obvate leaves. The tree has white flowers with many stamens. The fruit resembles spinning tops and has many small seeds. There is no regeneration under the canopy of old *Sonneratia* trees.

Except in new depositional areas, old *Sonneratia* trees are dying away in KMNR because of serious infestation by insect borers. The tree is exploited for boat building, fish floats, and poles. *Sonneratia* trees coppice readily when felled.

5. Mixture of *Ceriops* and *Rhizophora*

Forests with mixed vegetation of *Ceriops* and *Rhizophora* are found on slightly raised ground, in inundation classes 3 and 4 of Watson (1928). *Ceriops* is largely found on the landward side of *Rhizophora*. This forest type is extensive in Ndau, Siyu and Kiunga management areas.

6. Mixture of *Sonneratia* and *Rhizophora*

Further inland from the seaward side, *Sonneratia* may be found growing in mixed association with *Rhizophora* and *Avicennia*. In such associations, *Sonneratia* grow in depressions that are flooded daily by tides (inundation class 1), while the other species grow on the raised ground (in the inundation class 2). In over grown forests of Kiunga, *Rhizophora* is seen replacing old *Sonneratia* trees.

7. *Rhizophora* dominant, with occurrences of *Ceriops, Avicennia, Sonneratia* and *Bruguiera*
This type represents one of the most spread vegetation types in Kiunga. The dominant tree, *Rhizophora mucronata* forms a continous canopy cover along with the principal associate *Ceriops tagal*. The other species associated with this dominant type are *Avicennia marina* and *Bruguiera gymnorrhiza*. Trees in this type may attain height of up to 17 m but elsewhere, reach only 5 m.

8 *Ceriops dominant*, with occurrence of *Rhizophora, Avicennia* and/or *Bruguiera*
This vegetation type frequently occurs where forest exploitation is high. *Ceriops* has a high regeneration potential than *Rhizophora, Bruguiera* and *Avicennia*. Trees of *Ceriops* seed all year round compared to *Avicennia* and *Rhizophora* that fruit in April/May. *Ceriops* dominated stands are common in Ndau.

9. *Avicennia* dominant, with occurrence of *Rhizophora, Bruguiera, Ceriops* and *Xylocarpus*
Avicennia marina has a high salinity tolerance range as well as a high tolerance of flooding (Tomlinson, 1986). As a result, it is the most distributed mangrove species and it is found on the seaward, landward and mid-portions of the forest. *Avicennia* does poorly in muddy soils that are dominated by *Rhizophora* and *Ceriops*. When mixed with other species, it is most often found in association with *Ceriops, Xylocarpus* and *Lumnitzera*. *Xylocarpus* is often found in association with other species and prefers sandy clay substratum of low salinity.

In order to evaluate the growing stock and regeneration, forest types were divided into density and height classes. In the text, density has subjectively been assessed as very dense when greater than 80% or scarce when less than 40%. Height was subjectively categorised as very low when the vegetation was <5.0 m and high when greater than 20 m.

Attributes	Classification	Range	Description
Densities	a	< 40%	scarce
	b	40 – 80%	dense
	c	> 80%	very dense
Height	1	> 20	high
	2	15 – 20	medium
	3	5 – 15	low
	4	< 5	very low

Box 4.3. Density and height classes used in the study

4.4.3 Sampling procedures

4.4.3.1 Forest structure

Transects were selected (and made) to run from the sea ward or channel bank inward across the types already marked out on the aerial photographs, the length of each transect depending on the locality and the extent of the types. Sampling units were 10 x 10 m² for adults and 5 x 5 m² for juveniles, laid along the transects. Transects permitted analysis of the vegetation profile as well as partial pattern of trees in different quadrats (Greig-Smith, 1983).

Within each quadrat individual trees with a stem diameter (at 130 cm, DBH or D_{130}), greater than 5.0 cm were identified and counted. Vegetation measurements included tree height and the diameter of the stem at beast height (DBH), from which were derived; tree basal area, species density and frequency (Mueller-Dombois & Ellenberg, 1974; Cintron and Schaeffer-Novelli, 1984). The importance value (I.V) of each species was calculated by summing its relative density, relative frequency and relative dominance (Cintron & Schaeffer-Novelli, 1984), while the vegetation complexity (C.I.) for each of the study areas was obtained as the product of number of species, basal area (m^2/0.1 ha), maximum tree height (m) and number of stems/0.1 ha, times 10^{-3} in a 0.1 ha plot (Holdridge *et al.*, 1971). Tree heights were measured in meters using a Suuto clinometer, while DBH was measured in centimetres using forest calliper.

Stand tables were constructed according to species, diameter and height classes (*see* Table 4.7 - 4.9). Class width was set at 2.5 cm starting from a minimum diameter of 5.0 cm. In forest management, stand tables are useful in characterising stand structure, which is the distribution of trees by species and size class on a given forest area.

Measuring trees even for simple parameters like stem diameter in the hot and wet mangrove environment is a strenuous exercise. Wading through the forest with arch-like *Rhizophora* roots, crossing creeks and water canals, carrying sampling gear and enduring blood-sucking insects in hot humid days, all placed excessive demand on the energy of those surveying the forest, and this resulted in a low-data output per man-day input. An inventory crew of 4 men recorded 200 to 250 trees in a day. This however, is only an indication as time required varied due to field conditions.

4.4.3.2 Forest rejuvenation

Information on the composition and distribution pattern of natural regeneration was obtained using the method of Linear Regeneration Sampling (LRS). This method has been used in studying natural regeneration of mangroves in Malaysia (Srivastava & Khamis, 1978), and Sumarta (Sukardjo, 1987). Linear regeneration sampling provides data for site regeneration potential, in terms of seedling abundance, distribution, species and sizes (FAO, 1994).

Juveniles were sampled in 5 x 5 m² sub-plots within the 10 x 10 m² quadrats. Three regeneration classes were recognized during the survey (Box 4.3). Saplings above 40 cm height were further classified as 'established regeneration' while those below were referred to as "potential regeneration".

Regeneration class (RC)	Description
I	Seedlings of less than 40 cm in height;
II	Seedlings/saplings from 40 cm, but less than 1.5 m height
III	Saplings from 1.5 m, but with a DBH of less than 5.0 cm

Box 4.3. Regeneration classes

The analysis of spatial pattern of trees and juveniles in the field was carried out inside 10 x 10 m^2 plots along transects. The measure of dispersion used was Morisita's (1959) index, the application of which is described in Greig-Smith (1983). Morisita's Index is:

$$I_o = q\sum_{i=1}^{q}\frac{ni(ni-1)}{N(N-1)} \qquad (1)$$

where, q is number of quadrats, n_i is the number of individual per species in the ith plot, and N is total number of individuals in all q quadrats; $I_o > 1$, population is clustered; $I_o = 1$, population is randomly dispersed; $I_o < 1$, population is evenly dispersed.

4.4.3.3 Volume estimation

Estimates of volume of different forest types, qualities, and sub-samples of stands are essential for effective forest production management. These estimates will assist in the determination of potential product harvests, but may also be useful for estimating the amount locked up in the forests. Estimates of stand volume integrate information on forest structure, DBH, stocking rate (tree density), basal area, trees height, and form factor. In the present study the following function was used to estimate standing volume of mangroves:

$$V = (\pi d^2/4) \times h \times f \qquad (2)$$

where, V= volume (m^3), $\pi = 3.141$, d = DBH (cm), h = tree height (m) and f = form factor.

In forestry, form factor is determined by the way the stem tapers i.e. by the decrease in diameter from base to tip (Clutter *et al.*, 1983). In general terms, the form factor of a tree is the ratio of its volume to the volume of a specified geometric solid of similar basal area and height. Most commonly, the form factor of a tree is based on a cylinder (Clutter *et al.*, 1983). Thus the product of tree basal area, tree height and cylindrical form factor should give tree volume (*see* equation 2). Very scanty information is available on the form factor of forests in Kenya because of a gross lack of data (Wass, 1995). In this study I have used a general form factor of 0.7 that was earlier estimated for *Rhizophora* by Roberts and Ruara (1967). This value can only be regarded as a crude guide, and further research work to establish and refine the validity of estimates would be highly desirable.

4.4.4 Data treatment

The area of mangrove areas in KMNR was marked out from the Survey of Kenya toposheet. ArcInfo coverages of the entire mangroves of Kenya were loaded and the exact study area displayed on GIS ArcView 3.1 software. The polygon dimensions were checked for their accuracy and using union option of ArcView software, it was possible to reduce the forest classification from 97 types (Ferguson, 1993) to 9 without loss of important details (*see* Section 4.4.2). The error analysis showed that the overall degitisation was accurate and the boundary between marked polygons (stand compartments) coincided with the ground-truth data, at least 95% of the time. Trees in similar compartments were pooled to obtain net stock of the stands in the forest (table 4.5).

Stand table data (Table 4.8 and Table 4.9) were presented graphically as frequency diagrams (Fig. 4.7). The stand densities were harmonized using De Liocourt's negative exponential model (Clutter *et al.*, 1983).). According to the model, the ratio between the numbers of trees in successive diameter classes of uneven-aged stand is roughly constant for a particular forest, but varies from one forest to another. The observation has been confirmed in a number of uneven-aged forests throughout the world (*see* e.g. Clutter *et al.,* 1983 and the literature therein). De Liocourt's model applies particularly in mixed forests where the age classes and recruitment by natural regeneration are continuous.

Supposing we take this ratio to be 'q', then the number of trees in successive diameter classes is represented by a descending geometric sequence of the form:

$$aq^{n-1}, aq^{n-2}, aq^{n-3},\ldots\ldots\ldots\ldots aq^3, aq^2, aq^1, a \qquad (1)$$

where 'a' is the number of trees in the largest size class of interest and 'n' is the number of classes.

For such a geometric series, if the logarithm of the frequency in successive classes is plotted against size class, the distribution can be represented as exponential curve of the form:

$$y = ke^{-ax} \qquad (2)$$

where; y = number of trees in diameter class x; e = base of natural log (2.718) while k and a are constants.

The constant 'k' and 'a' in the equation above vary between forests and with site. 'k' reflects the occurrence of seedling regeneration and tend to be large in forests containing prolific seed-bearing tree species while 'a' determine the relative frequencies of successive diameter classes . A high 'a' is associated with high mortality between classes and is likely to occur in stands comprising light demanding (shade intolerant) tree species.

The constant 'k' and 'a' in the equation above vary between forests and site. 'k' reflects the occurrence of seedling regeneration and tends to be large in forests containing seed-bearing tree species while 'a' determines the relative frequencies of successive diameter classes (*see* Fig. 4.7).

A high 'a' is associated with high mortality between classes and is likely to occur in stands comprising light demanding (shade intolerance) tree species.

Basically the class interval was set at 2.5 cm commencing with class 5 – 7.5 cm. For simplicity, diameter classes have been condensed and only the upper limit in each class is entered. Thus the first class is not entered into x-axis as 5 – 7.5 cm but simply as 7.5 cm, and trees less than 5.0 cm diameter are classified under juveniles (Box 4.3). Mangrove use in Kenya is restricted to poles of diameter 5 cm and over (*see* Table 2.1).

Differentiation was made between young juveniles that could not guarantee regeneration of a stand and old juveniles that would be used to estimate the success of natural regeneration after logging. Usually these were trees overlooked during the recording of adults with DBH greater than 5.0 cm. A chi-square test was used to analyse differences in juvenile densities among the study sites.

4.4.5 Interpretation of the data

In the interpretation of the data, use was made of the following variables:

- height – diameter distributions of the principal species;
- basal areas of principal species;
- stand volume of the species, if and when available.

4.5 Results and Discussion

4.5.1 Vegetation maps

The vegetation maps of mangrove forests within and adjacent to KMNR were derived from aerial photographs (*see* e.g., Fig. 4.2 and Fig. 4.3). The detailed description of the mapped community is presented in Table 4.2 and 4.3. Large concentrations of mangroves occur in Ndau and Siyu management areas. A forested area of 16,035.94 ha includes all stands classified as falling in one of the forest type outlined in section 4.4.1. Pure stands of *Rhizophora* forest occupied 24.14% of the entire forest in KMNR (Table 4.2). The non-forested areas were mainly mudflats, but also included rangelands and agricultural fields, sand beaches and water-spread areas within and adjacent to the reserve. There were 31 million stems of mangroves in KMNR with a net standing volume of 2.4 millions m^3 (Table 4.3).

Table 4.2. Area (in ha) occupied by different mangrove vegetation types and non-mangroves within and adjacent to KMNR

Forest Type Classification	Kiwayu	Ndau	Siyu1	Siyu2	Mkokoni	Kiunga	Total	% area
Ceriops type forests	4.43	951.64	805.43	561.29	117.83	25.15	**2 465.77**	**15.38**
Mixed *Ceriops* types	0.36	228.26	56.14	99.75	55.26	5.28	**445.05**	**2.78**
Ceriops - Rhizophora type	0	377.83	229.79	232.10	144.81	280.19	**1 264.22**	**7.88**
Avicennia type	3.43	590.80	926.78	887.49	200.71	63.95	**2 673.17**	**16.67**
Mixed *Avicennia* type	0	219.77	115.67	199.73	0	25.80	**560.97**	**3.50**
Rhizophora type	209.19	1 463.54	433.28	642.82	273.43	848.85	**3 871.11**	**24.14**
Mixed *Rhizophora* type	13.87	709.59	1 107.54	1 052.04	517.00	246.41	**3 646.45**	**22.74**
Sonneratia- Rhizophora type	19.49	79.02	88.70	87.86	27.53	205.38	**507.98**	**3.17**
Sonneratia type	74.22	151.55	77.08	170.66	44.31	83.40	**601.22**	**3.75**
TOTAL MANGROVES	**324.99**	**4 772.00**	**3 839.92**	**3 933.74**	**1 440.88**	**1 784.41**	**16 035.94**	**100%**
Saline bare areas and herblands	12.86	219.50	3 405.29	1 023.71	73.43	19.53	**4 754.32**	**6.82**
Non-mangrove forests inside mangroves	0	408.92	388.80	193.19	204.05	53.51	**1 248.47**	**1.79**
Agricultural and rangeland within/adjacent mangroves	201.23	4 543.86	7 153.62	8 012.35	1 413.40	1 413.40	**24 951.81**	**35.81**
Sand-flats and beaches	44.93	49.84	48.80	100.74	57.34	115.16	**416.81**	**0.60**
Mudflats and shallow waters	1 177.62	3 414.25	311.40	3 548.09	557.53	3 071.50	**12 180.39**	**17.48**
Water spread areas (creeks, channel, ocean)	10 230.84	8 900.21	249.12	2 779.86	2 232.87	1 742.81	**26 135.71**	**37.50**
TOTAL NON-FORESTED AREAS	**11 676.48**	**17 636.58**	**11 557.03**	**15 657.94**	**6 743.57**	**6 415.91**	**69 687.51**	**100%**

Table 4.3. Detailed characteristics of mangrove vegetation types within and adjacent KMNR

Forest types	Number of compartment (polygons)	Area (ha)	Average Canopy height (m)	Crown cover (%)	Tree density (Trees/ha)	Standing volume (m³/ha)	Net Stocking	Net volume (m³)
Mixed Avicennia	53	560.97	12.5	69	2148	106.78	1,167,570	65,142.73
Avicennia	632	2673.17	10.0	66	2064	45.39	5,448,090	67,730.05
Ceriops-Rhizophora	249	1264.22	12.5	75	2072	106.58	2,635,091	132,146.50
Ceriops	548	2465.77	1.5	80	2291	50.08	5,694,540	100,193.11
Rhizophora	189	3871.11	15.0	78	1532	334.36	5,910,449	1,281,517.25
Sonneratia-Rhizophora	97	507.98	12.5	80	2141	102.41	1,045,622	59,480.01
Sonneratia	335	601.22	12.5	73	1962	78.30	1,216,612	49,742.12
Mixed Ceriops	180	445.05	7.5	80	2306	41.36	987,889	21,597.79
Mixed Rhizophora	268	3646.45	12.5	79	1938	159.44	7,082,465	576,455.29
TOTAL	**2,551**	**16,035.94**	-	-	-	-	**31,188,328**	**2,354,004.85**

Mangrove forests within and adjacent to KMNR have been under uneven cutting pressures and the accessible areas adjacent to the reserve have now been largely over-exploited, particularly in Ndau and Siyu 1 management areas (Fig. 4.1). In areas where commercial harvesting is still going on such as Uvondo and Yowea most of market-sized *boriti* poles (butt diameter: 11.5 – 14.0 cm) have been cleared. *Rhizophora mucronata* and *Ceriops tagal* are the most affected species. Only very large trees, the majority *Avicennia marina* and *Sonneratia alba* are left behind. This selective logging greatly affects the quality and stability of the remaining future forest.

Near pristine mangrove forests with stand densities of over 80% and mean stand height greater than 10 m still occur in many parts of KMNR (Table 4.4 and Table 4.5). The analysis of different stand compartments show that there is no significance difference ($F_{(1,46)} = 4.052$, $p = 0.259$) in compartment sizes between the Northern and North Central Swamps. There are 8,975.52 ha (55.97%) of high density forests (c-3) in the entire KMNR with a net stock of 16.4 million stems (equivalent to $1.5 \times 10^6 m^3$ of wood). The high concentration of a-4 and c-4 stands in the North Central forests indicate most probably human pressure though we cannot rule out completely the role of environmental factors in determining dwarf stands in this region. Salinity levels on the landward areas of North Central Swamps recorded 72 ‰ on Atago refractometer during low spring tide (Kairo & Kivyatu, 2000).

Table: 4.4 Area (in ha) of stands compartments in the mangrove forests within and adjacent to KMNR

Height and density classes*	Kiwayu	Ndau	Siyu1	Siyu2	Mkokoni	Kiunga	Total	%
a-3	3.02	416.81	-	3.29	2.35	14.49	484.96	**3.02**
a-4	1.34	376.72	239.65	447.27	84.77	47.05	1196.80	**7.46**
b-3	8.90	121.66	2.9	11.56	13.70	88.09	246.81	**1.54**
b-4	-	223.18	404.53	328.90	34.12	6.79	997.52	**6.22**
c-1	0.80	92.35	2.24	27.15	197.00	206.5	526.04	**3.28**
c-3	305.04	2270.70	1955.56	2196.16	870.83	1377.23	8975.52	**55.97**
c-4	5.89	1225.58	1235.04	919.41	178.11	44.26	3608.29	**22.50**
TOTAL	**324.99**	**4772.00**	**3839.92**	**3933.74**	**1380.88**	**1784.41**	**16,035.94**	

*Density classes are as follows:
a = <40% ,
b= 40 – 80% ,
c = >80%.

Height classes are given as
1 = > 20m,
2 = 15 – 20m,
3 = 5 – 15m,
4 = <5m.

Table 4.5. Detailed characteristics of stand compartments within and adjacent to KMNR

Height and density classes[1]	Number of compartments	Area (ha)	Average tree density (stems/ha)	Average standing volume (m^3/ha)	Net Stock	Net standing Volume (m^3)
a-3	33	484.96	1,597	30.51	915,491	48,496.88
a-4	170	1197.80	1,540	6.85	1,939,510	8,533.21
b-3	41	246.81	1,510	58.56	427,311	28,403.50
b-4	261	997.52	2,156	38.57	2,261,795	38,414.70
c-1	32	526.04	1,013	710.00	936,488	632,560.30
c-3	1,023	8,975.52	2,022	137.64	16,354,951	1,456,663.11
c-4	991	3,608.29	2,313	39.01	8,352,782	140,933.15
Total	**2,551**	**16,035.94**	-	-	**31,188,328**	**2,354,004.85**

[1]Density and height classes as follows:

Density
a = <40% ,
b = 40 – 80%
c = > 80% ,

Height
1 = > 20m,
2 = 15 – 20m,
3 = 5 – 15m
4 = <5m

4.5.2 Community characteristics

Structural attributes like tree height, basal area, density and species composition that were recorded from sample plots were used to characterize mangrove community of KMNR (Table 4.6). There are eight mangrove species that occur in the area. Based on the highest importance values, the principal species are *Rhizophora mucronata* (I.V. = 162.73%), *Ceriops tagal* (I.V. = 64.44%) and *Sonneratia alba* (I.V. = 29.58%). Others are *Avicennia marina*, *Bruguiera gymnorrhiza*, *Xylocarpus granatum, X. moluccensis* and *Lumnitzera racemosa*. The high value of the Complexity Index in the Northern Swamps C.I. = 62.81%) indicate especially the high basal area and canopy height of the stands in the Northern Swamps region as compared to the North Central Swamps.

Table 4.6. Structural characteristics of the mangrove forests within and adjacent to KMNR. All trees with DBH > 5.0 inside 100m^2 were measured.

Management Unit	Species	Density (stems/ha	Mean height (x ± s.d.)	Basal area (m²/ha)	Relative values (%) Frequency	Dominance	Density	I.V.%[1]	Complexity Index[2]
Northern Swamps *(Kiunga and Mkokoni)*	*A. marina*	103	7.40 ± 4.16 (1 - 10)	2.63	7.22	7.50	4.39	19.11	**62.81**
	R. mucronata	1613	11.40 ± 5.00 (2 - 27.5)	36.53	63.40	77.78	68.87	210.05	
	C. tagal	443	5.10 ± 2.67 (1.2 - 14)	2.70	15.98	5.74	18.92	40.64	
	S. alba	174	8.90 ± 3.96 (6 - 18)	4.97	9.28	10.59	7.43	27.30	
	B. gymnorrhiza	10	6.50 ± 3.00 (3 - 10)	0.14	4.12	0.30	0.43	4.85	
North Central Swamps *(Siyu, Ndau, Kiwayu)*	*A. marina*	132	3.60 ± 1.94 (1.5 - 13)	1.15	6.37	4.77	6.68	17.82	**25.14**
	R. mucronata	920	8.80 ±3.20 (2 - 18)	14.20	49.98	58.97	46.47	115.41	
	C. tagal	799	4.50±1.94 (1 - 17.5)	4.18	30.49	17.38	40.37	88.24	
	S. alba	110	9.06 ± 3.27 (2 - 17)	4.28	8.49	17.81	5.54	31.85	
	B. gymnorrhiza	17	8.2 ± 2.42 (4 - 13.5)	0.24	4.25	0.98	0.84	6.06	
	X. granatum	2	2.67±0.577 (2- 3)	0.004	0.43	0.02	0.11	0.56	

[1]The Importance Value (I.V.) of a given species is the sum of relative frequency, dominance and density.

[2]Complexity index (C.I.) of a stand is calculated as: number of species x basal area (m²/0.1ha) x maximum tree height(m) x number of stem/0.1 ha x 10^{-3} in 0.1 ha.

Sample size: Northern Swamps = 3138 stems (in 134 quadrat); North Central Swamps = 2633 stems (in 133 quadrat). Number in parenthesis indicates the range.

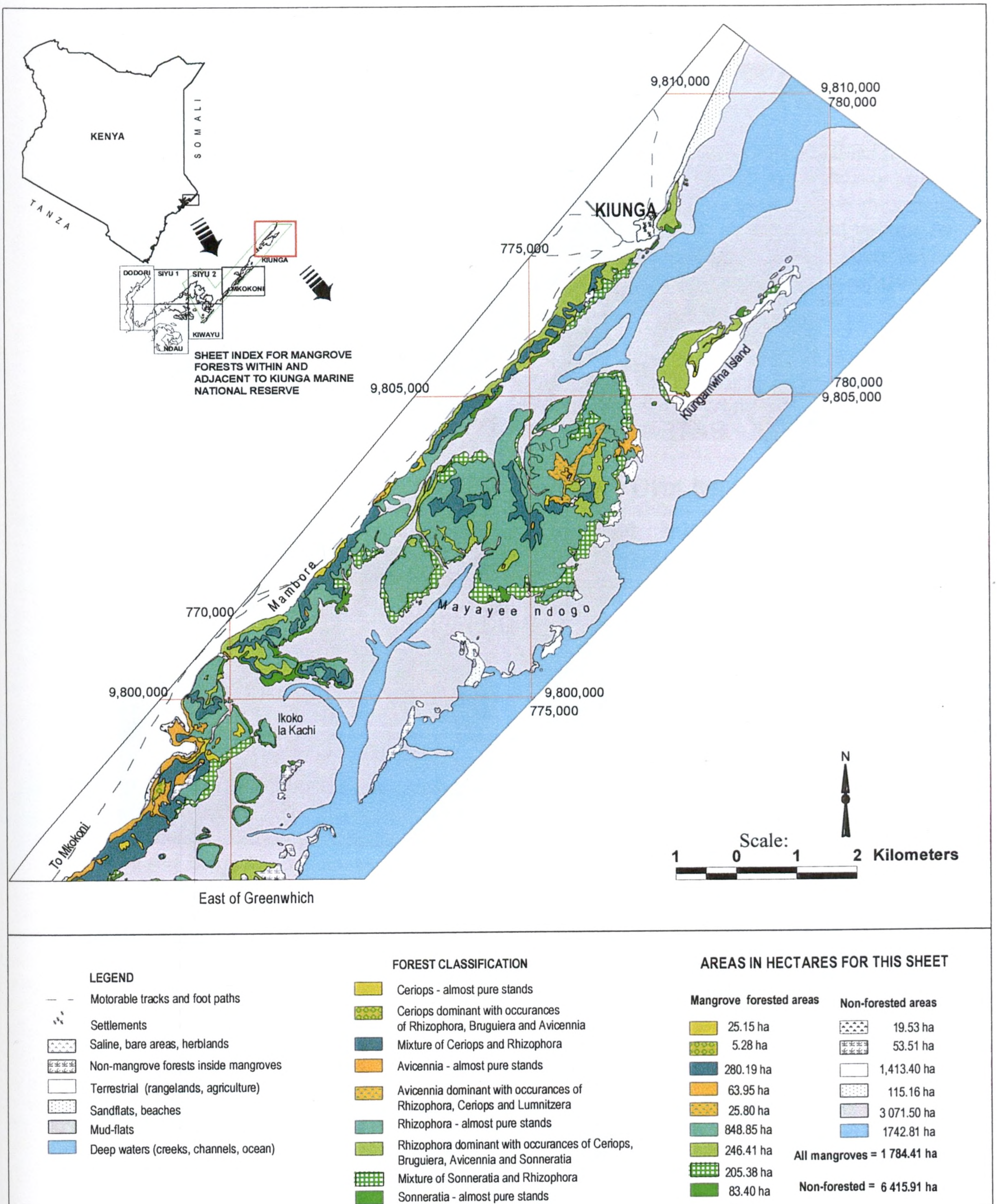


Fig. 4.1. Vegetation map: Kiunga management unit. The final map is printed on A-0 paper (85 x 59 cm) to indicate detailed characteristics of stand compartments.

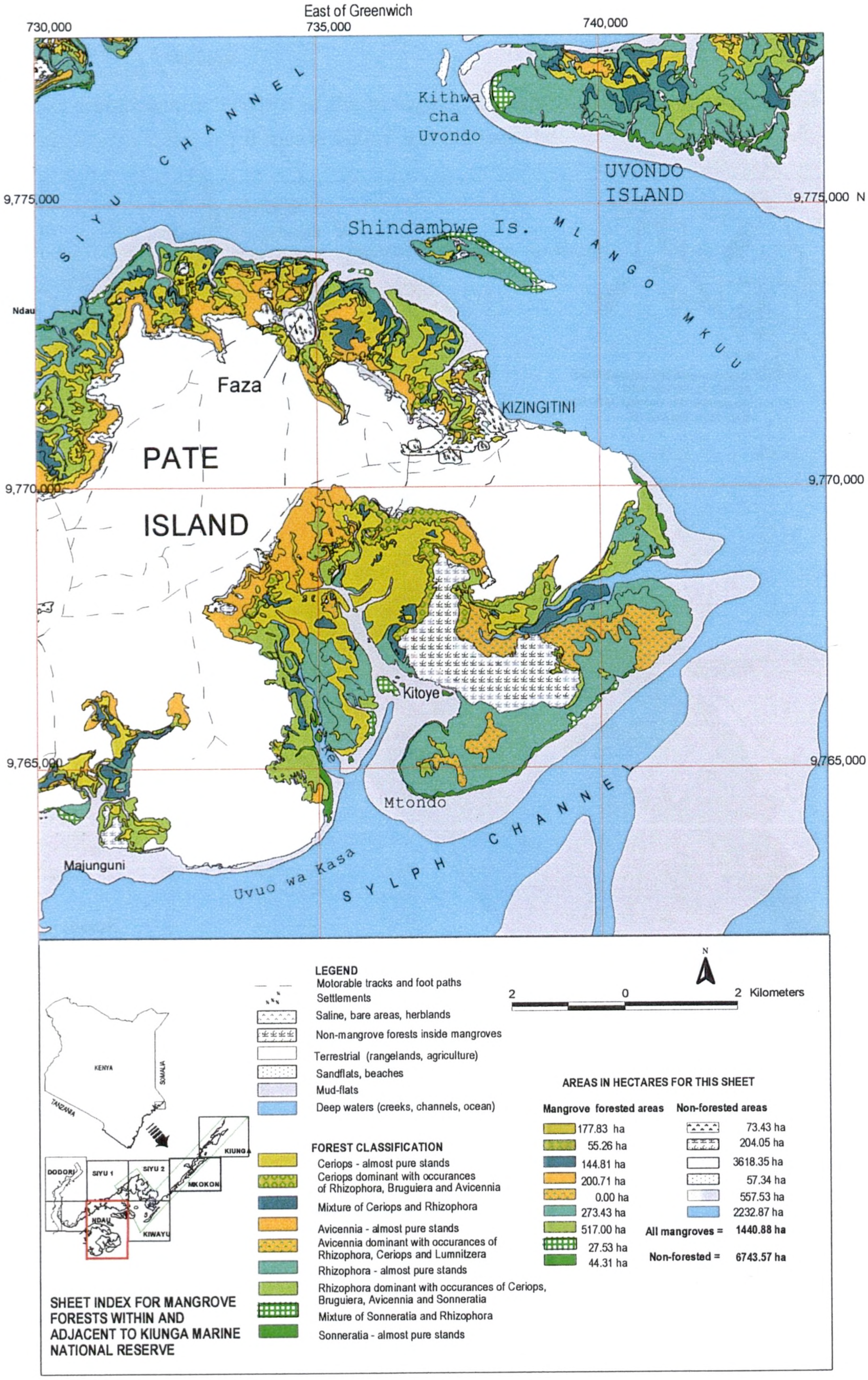


Fig. 4.2. Vegetation map: Ndau management unit. The final map is printed on A-0 paper (85 x 59 cm) to indicate detailed characteristics of stand compartments.

4.5.3 Stand tables

The vegetation attributes of stand compartments were pooled to construct stand tables for each mangrove management area within and adjacent to KMNR. The average stand density ranged from 2207stems per hectare in Mkokoni to1967 stems/ha in Siyu 1. Kiunga had the highest stand volume of the six management areas: 465.70 m^3/ha (Table 4.7). The average stand volume for plots outside the reserve was 172.62 m^3/ha (Siyu 1) and 176.22 m^3/ha (for Ndau). These values are likely to differ from what is recorded in the vegetation maps since individual compartments were treated separately while preparing the maps (*see* Table 4.5).

Figure 4.4 shows the height – diameter scattergrams of *Rhizophora mucronata* in the North and North Central forests. In the Northern Swamps, 50% of *Rhizophora* had stem diameter of between 15.5 – 26.5 cm and heights of 10.0 – 17.5 m (Fig. 4.4). While in the North Central Swamps, 50% of the trees had a diameter of 6.0 – 16.0 cm and heights of 9.0 – 14.0 cm.

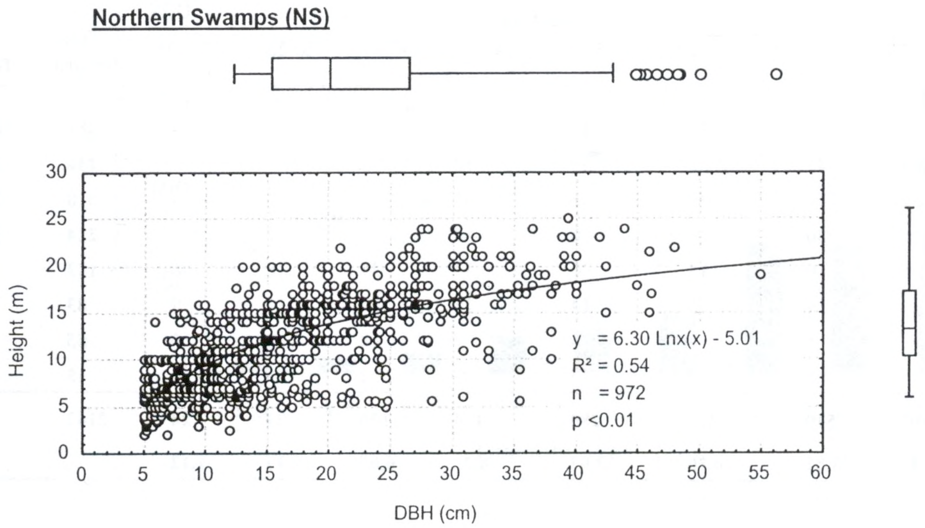
The frequency distributions of diameter and height classes for mangrove trees in the two geographical areas of KMNR are shown in Table 4.8 and Table 4.9. In the Northern Swamps (Kiunga), 881 trees (41.13%) had a diameter of between 5.0 – 10.0 cm and 153 trees (7.14%) had a diameter above 30 cm (Table 4.8). In the North Central Swamps (Ndau), 1187 trees (or 57.20%) had a diameter of 5.0 –10.0 cm, while only 45 trees (or 2.16%) had a diameter above 30 cm (Table 4.9).

Figure 4.5 show plots of the standing volume against diameter classes for *Rhizophora* in the Northern and North Central Swamps. There was a significant difference ($p < 0.05$) in the volumes of different diameter classes between the Northern and North Central Swamp forests (Table 4.10). Because of physical barriers, insecurity and low human population the Northern Swamp forests still harbour some pristine to semi-pristine mangrove stands compared to the North Central forests. The standing wood volume (m^3/ha) of the forests in the Northern Swamps increased with increasing diameter classes. There was also strong correlation ($R^2 > 0.95$) between tree heights and diameter classes. Trees of diameter greater than 30 cm in the Northern Swamp forests had a standing volume of more than 150 m^3/ha and an average height of 18.0 m (Fig. 4.5a). In the North Central Swamps, stand volume increased initially with increasing diameter classes, but drops after 25 cm class. Large trees with diameter greater than 30 cm diameter had a standing volume of less than 30 m^3/ha (Fig. 4.5b). This could arise because of a long history of cutting that has taken place in the North Central forests particularly in Ndau, Siyu and Kiwayu, thus reducing the forest stature in the region (Roberts and Ruara, 1967; Kairo *et al.*, (accepted); Fig. 4.1).

In order to evaluate the market quality standing poles in the forest, a tree was arbitrarily assigned Quality Class 1 (Qc1) if the main stem of the tree was 'straight and long' enough for the building market; Qc2 if the poles/stem needed slight modification, and Qc 3 if the poles was unsuitable for building. Using this 'quality analysis technique' it was clear that the Northern Swamps forests had significantly higher quality poles (Qc1 and Qc 2) than the North Central forests ($\chi^2_{(0.05,\ 2df)}$ = 160.15, $p < 0.001$). More than 40% by volume of *Rhizophora* forests in NS were of Qc1 (Table 4.11).

Table 4.7. Stand tables (stems/ha) of mangrove forests within and adjacent to KMNR

Management Unit	Dimeter class / Species	<7.5	7.5 - 10	10 - 12.5	12.5 - 15	15-17.5	17.5 - 20	20 - 25	25 - 30	>30	Total stems/ha	Volume (m^3/ha)
Kiunga	*Avicennia*	6	11	12	8	9	18	9	8	3	**84**	15.23
	Bruguiera	2	2	3	-	2	-	2	-	-	**11**	0.83
	Ceriops	218	112	50	14	11	9	9	-	-	**423**	13.98
	Rhizophora	320	192	159	167	136	121	176	100	123	**1494**	400.26
	Sonneratia	17	14	18	11	12	15	14	11	18	**130**	35.40
	TOTAL	**563**	**331**	**242**	**200**	**170**	**163**	**210**	**119**	**144**	**2142**	**465.70**
Mkokoni	*Avicennia*	35	29	11	3	6	8	3	-	-	**95**	2.98
	Bruguiera	29	9	8	5	6	6	2	5	3	**73**	9.83
	Ceriops	438	174	98	34	15	3	2	-	-	**764**	15.13
	Rhizophora	358	197	118	162	111	102	114	54	75	**1291**	263.92
	Sonneratia	9	22	9	14	6	5	12	5	2	**84**	8.00
	TOTAL	**869**	**431**	**244**	**218**	**144**	**124**	**133**	**64**	**80**	**2307**	**299.86**
Ndau	*Avicennia*	72	46	17	4	-	-	-	-	2	**141**	2.20
	Bruguiera	7	9	7		2	-	-	-	-	**25**	0.60
	Ceriops	359	54	20	17	20	9	9	-	-	**488**	14.50
	Rhizophora	507	202	185	124	104	98	130	54	17	**1421**	158.92
	TOTAL	**945**	**311**	**229**	**145**	**126**	**107**	**139**	**54**	**19**	**2075**	**176.22**
Siyu 1	*Avicennia*	68	66	22	8	15	5	3	-	-	**187**	3.21
	Bruguiera	7	5	8	3	3		2	-	-	**28**	2.09
	Ceriops	332	90	53	24	15	17	3	-	-	**534**	14.35
	Rhizophora	322	215	136	80	81	41	73	39	15	**1002**	116.33
	Sonneratia	19	41	31	29	29	17	20	22	15	**223**	36.64
	TOTAL	**748**	**417**	**250**	**144**	**143**	**80**	**101**	**61**	**30**	**1974**	**172.62**
Siyu 2	*Avicennia*	57	38	18	13	6	4	1	1	1	**139**	3.40
	Bruguiera	3	2	2	2	1	2	2	1	-	**15**	1.83
	Ceriops	498	170	75	24	19	6	1	-	1	**794**	16.68
	Rhizophora	269	174	107	81	72	56	88	33	29	**909**	128.52
	Sonneratia	16	7	8	13	17	12	16	8	13	**110**	27.60
	TOTAL	**843**	**391**	**210**	**133**	**115**	**80**	**108**	**43**	**44**	**1967**	**178.03**
Kiwayu	*Rhizophora*	640	340	190	120	110	160	270	80	40	**1950**	244.51
	Sonneratia	-	-	-	10	-	20	10	-	10	**50**	18.97
	TOTAL	**640**	**340**	**190**	**130**	**110**	**180**	**280**	**80**	**50**	**2000**	**263.48**
Global average/ha		**768**	**370**	**228**	**162**	**135**	**122**	**162**	**70**	**61**	**2077**	**261.99**
% of global total		**37**	**18**	**11**	**8**	**6**	**6**	**8**	**3**	**3**		



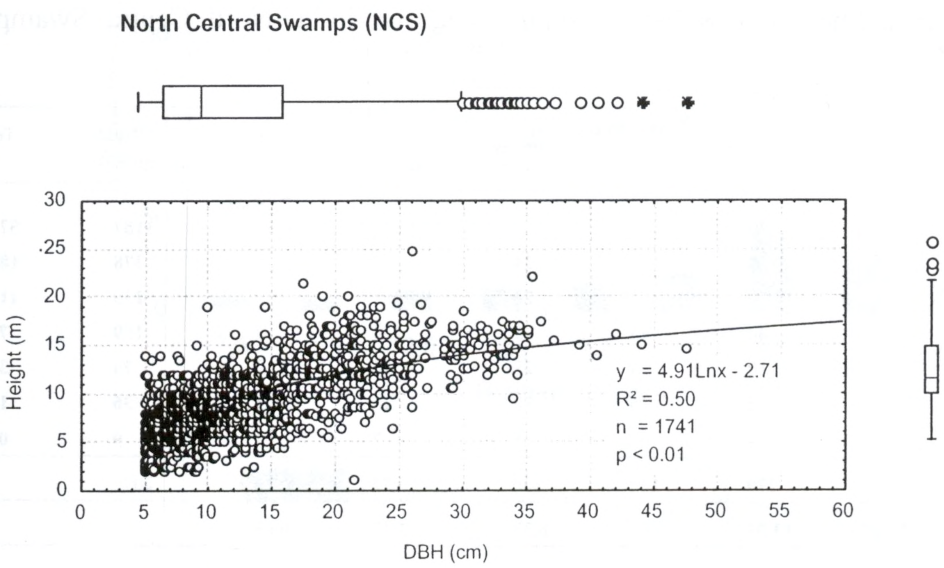


Fig. 4.4. Height/Diameter distribution of *Rhizophora mucronata* in the Northern and North Central Swamps of KMNR. Linear equations, correlation coefficients (R^2), the *p*-values and sample size (n) are given in each case. The box-plots display percentile distribution in each case. The extremities of the plot correspond to the maximum and minimum observations in the data set. The ends of the box are positioned at the 25% and 75% percentiles of the data set.

Table 4.8. Diameter and height class distribution of mangroves in the Northern Swamps of KMNR.

Diameter Class (cm)	Height class (m									Total (stems/ha	Total %
	< 5	5 - 7.5	7.5 - 10	10 - 12.5	12.5 - 15	15 - 17.5	17,5-20	20-22,5	22,5-25		
5 – 10	162	414	247	35	18	5	-	-	-	**881**	**41,13**
10 – 15	15	109	141	98	53	12	6	-	-	**434**	**20,26**
15 – 20	1	50	57	40	92	52	26	-	-	**318**	**14,85**
20 – 25	-	19	30	23	70	50	29	3	-	**224**	**10,46**
25 – 30	-	5	10	15	20	33	35	8	6	**132**	**6,16**
30 – 35	-	-	14	6	14	15	14	11	9	**83**	**3,87**
35 – 40	-		8	3	8	9	18	3	6	**55**	**2,57**
40 – 45	-	-	3	2	5	-	2	-	3	**15**	**0,70**
Total	**178**	**597**	**510**	**222**	**280**	**176**	**130**	**24**	**24**	**2142**	
% of Total	**8,31**	**27,87**	**23,81**	**10,36**	**13,07**	**8,22**	**6,07**	**1,17**	**1,12**		

Table 4.9. Diameter and height class distribution of mangroves in the North Central Swamps of KMNR.

Diameter Class (cm)	Height class (m)							Total (stems/ha)	Total %
	< 5	5 - 7.5	7.5 - 10	10 - 12.5	12.5 - 15	15 - 17.5	17,5-20		
5 – 10	652	513	20	2	-	-	-	**1187**	**57.20**
10 – 15	71	107	128	41	24	7	-	**378**	**18.22**
5 – 20	2	37	70	80	26	15	-	**230**	**11.08**
20 – 25	-	15	40	45	35	22	2	**159**	**7.76**
25 – 30	-	9	10	9	28	11	9	**76**	**3.36**
30 – 35	-	-	2	5	12	15	2	**36**	**1.73**
35 – 40	-	2	-	-	5	2	-	**9**	**0.43**
Total	**725**	**683**	**270**	**182**	**130**	**72**	**13**	**2075**	
% of Total	**34.94**	**32.92**	**13.01**	**8.77**	**6.27**	**3.47**	**0.63**		

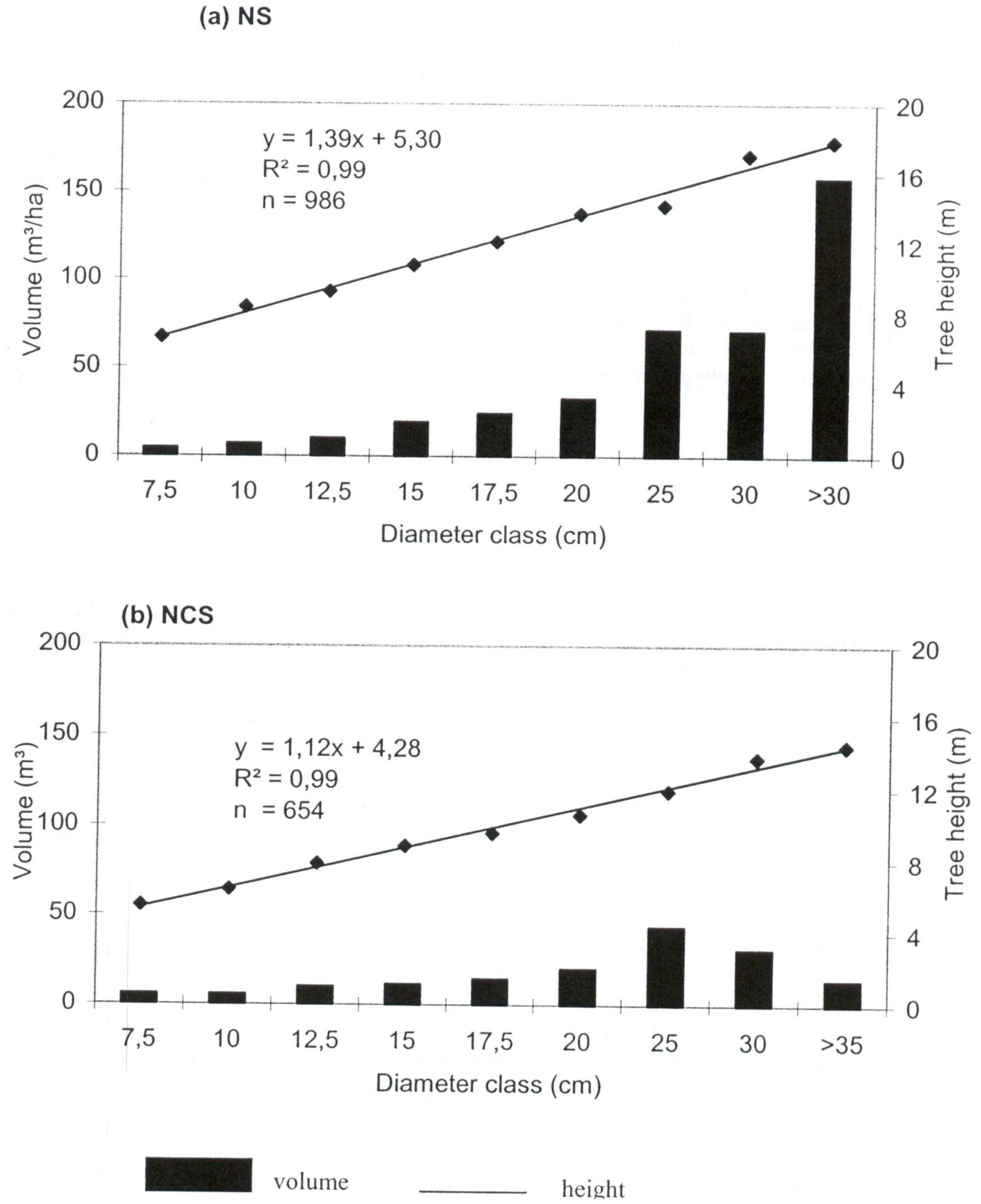


Fig. 4.5 Volume in m³/ha (*first y-axis*) and height in meters (*second y-axis*) of *Rhizophora mucronata* in the (a) Northern swamps and (b) North Central Swamps forests.

Table 4.10. Single classification ANOVA with unequal stand volume of *R. mucronata* in the Northern and North Central regions of KMNR

Source of Variation	*Df*	*SS*	*MS*	$F_{calc.}$	*P-value*	$F_{crit.}$
Between Groups	1	9.794	9.795	92.063	0.000	3.847
Within Groups	1617	172.035	0.106			
Total	1618	181.830				

$F_{calc} >> F_{crit}$, highly significant ($p < 0.001$). This means that mangroves in the two regions are significantly different in height.,diameter and basal area which is reflected in the stand volume. There was also a significant difference in the wood quality between NS (Kiunga) and NCS (Ndau) region ($\chi^2_{(0.05, 2df)} = 160.15$, $p < 0.001$). *See also* Table 4.11.

Table 4.11. Characteristics of Quality Class 1 *R. mucronata* in KMNR. Lamu

Geographical region	Management unit	DBH(cm)	Height (m)	Quality 1 wood volume (m^3/ha)	Total stand volume (m^3/ha)
Northern Swamps	Mkokoni	13.38 ± 8.26[a] (5.0 – 48.0)[b]	11.0 ± 4.20 (4.0 – 26.0)	103.15	263.92
	Kiunga	17.03 ± 9.98 (5.0 – 48.0)	13.26 ± 5.02 (3.0 – 25.0)	193.85	400.26
North Central Swamps	Ndau	9.60 ± 6.30 (5.0 – 28.9)	7.90 ± 3.70 (3.7 – 17.5)	17.18	151.90
	Siyu1	11.30 ± 6.70 (5.0 – 32.0)	8.93 ± 3.81 (3.5 – 22.50)	29.52	116.33
	Siyu2	14.93 ± 8.36 (5.0 – 47.5)	10.76 ± 3.76 2.5 – 24.7)	48.48	128.52
	Kiwayu	11.80 ± 8.30 (5.1 – 40.0)	9.10 ± 3.00 (5.0 – 17.5)	77.67	244.51

[a](mean ± s.d.) [b]range

4.5.4 Forest rejuvenation

The density, composition and distribution patterns of mangrove juveniles in the Northern and North Central swamps are shown in Table 4.12 and Fig. 4.6. Analysis of juvenile composition in respect to density in the two regions indicated the understorey being dominated by *Ceriops* and *Rhizophora* saplings of less than 40.0 cm in height (RC I). Northern Swamp forests had a stocking rate of 7646 juveniles/ha of which 5145, 1208 and 1293 juveniles were of RCI, RCII and RCIII respectively. In the North Central Swamps densities of RCI, RCII and RCIII were 6118, 3344 and 2019 juveniles per hectare respectively. The parent trees were evenly distributed in both the Northern and North Central swamps as indicated by Morisita's Index of less than 1 (Fig. 4.6). The juveniles of *C. tagal* in the North Central Swamps were clustered ($I_0 > 1$) around the parent trees as well as in areas where the forest had been opened through cutting (Fig. 4.6b).

Table 4.12. Juvenile densities in KMNR. There was a significant difference ($\chi^2_{(0.05,\ 2df)}$ = 512.55, p< 0.001) between the regeneration ratios of NCS and NS forests.

Geographical area	Species	Regeneration classes I	II	III	Total/ha
North Central Swamps *(Ndau)*	*A. marina*	255	66	23	344
	B. gymnorrhiza	23	2	3	28
	C. tagal	3862	2297	1352	7511
	R. mucronata	1967	970	639	3576
	S. alba	11	9	2	22
	TOTAL	**6118**	**3344**	**2019**	**11481**
Northern Swamps *(Kiunga)*	*A. marina*	24	17	12	53
	B. gymnorrhiza	16	4	16	36
	C. tagal	1227	414	530	2171
	R. mucronata	3873	771	733	5377
	S. alba	5	2	2	9
	TOTAL	**5145**	**1208**	**1293**	**7646**

4.6. Conclusions and recommendations

4.6.1 Production

The stratification of the aerial photographs, the ground-truthing and the use of GIS made it possible to locate stands within and adjacent to KMNR that were productive and those that were unproductive, either because of edaphic factors or because of human pressure. The highly productive stands (classified in this study as b-1, b-2, b-3, c-1, c-2 and c-3) occupied 9,745.47 ha of KMNR (Table 4.4), and an average volume of 302.07 m^3/ha (Table 4.5). The area of less productive category (classified in this study as; a-2, a-3, b-4 and c-4) was 6,290.47 ha. with an average volume of 28.73 m^3/ha. The net standing volume of mangroves within and adjacent to KMNR was 2.4 million m^3. This is considered to be a conservative estimate as measured compartment volumes exceeding 700 m^3/ha were recorded, particularly in the Northern Swamp forests (Table 4.5).

The stand curves for principal mangrove species in KMNR are shown in Fig. 4.7. The graphs display typical reversed J-shaped distribution patterns, characteristics of uneven-aged forest structure. Given such positive stand curves ($R^2 > 0.9$); the evidence for continuous recruitment below 7.5 cm DBH may be taken to be sufficient (Dawkins; 1958; Clutter *et al.*, 1983). The graphs also show higher seedling regeneration in North Central Swamps than in the Northern

Swamp forests as indicated by large k-values (Equation – 3). A high 'a' in the Northern Swamps is associated with a high mortality between classes which is most likely to occur in stands comprising shade intolerant species (Dawkins,1958). Field observations in KMNR indicated that *R. mucronata* is less tolerant to shade than *C. tagal*. More than 80% of the forest in the Northern Swamps had a crown closure greater than 80% (Table 4.4). These findings further support field observation that North Central forests particularly in Ndau, are opened by human encroachment. However a good natural regeneration is already taking place.

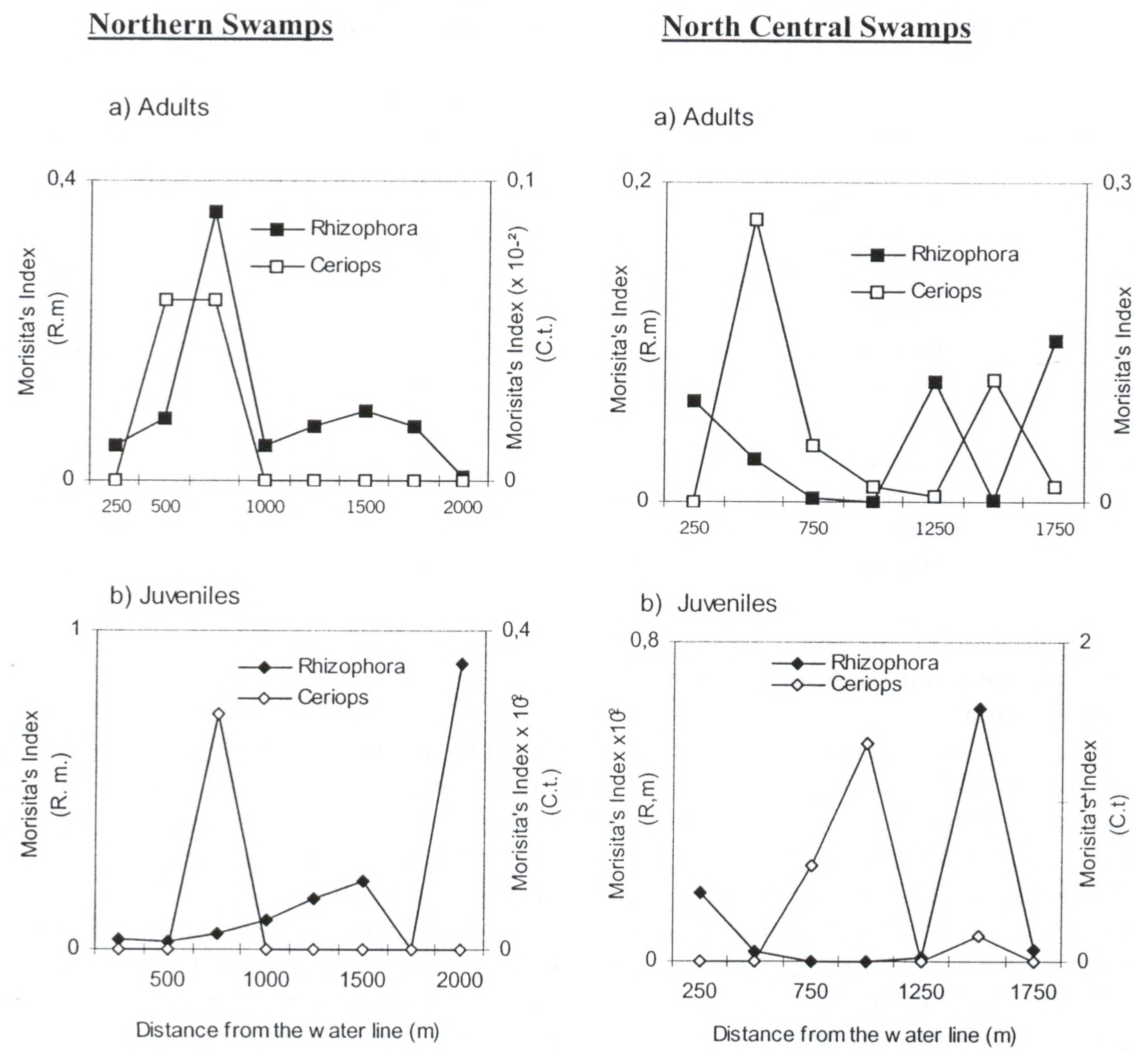


Fig. 4.6. Values of Morisita's Indices along transects for the principal species in KMNR. The dispersion patterns show a close to uniform distribution with the adults' trees ($I_o << 1$), but a tendency to random distribution for juveniles in Northern Swamp ($I_o = 1$), and clustered for juveniles in North Central Swamps ($I_o > 1$). Species names are abbreviated as C.t. for *C. tagal etc.*

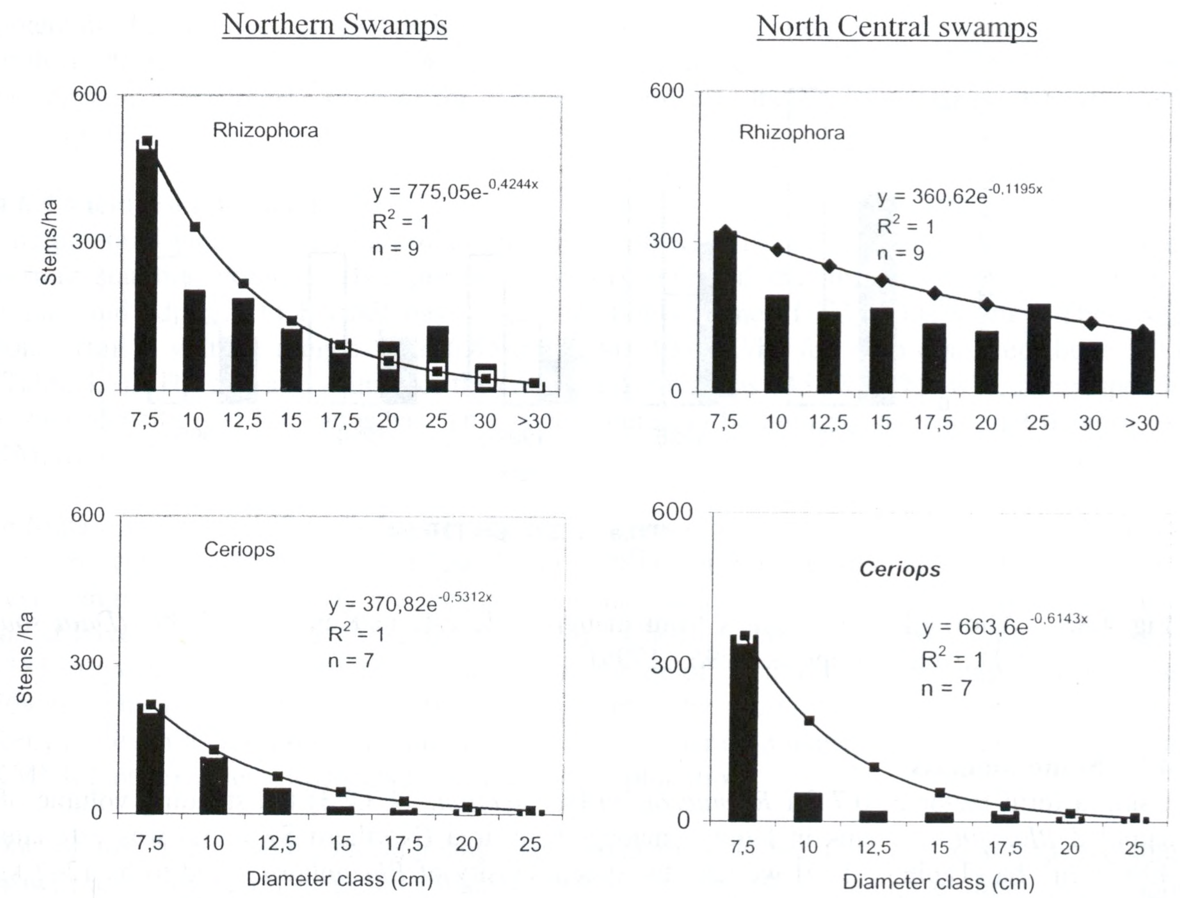


Fig. 4.7. Size class distribution of mangroves, *R. mucronata* and *C. tagal* in KMNR. The NCS stands contain sporadic regeneration in the lower diameter classes as indicated by high k-values in the equation $y = ke^{-ax}$ [*see* also section: 4.5.4]. There was no significant difference ($p > 0.05$) between the observed and adjusted densities.

The stocking of '*pau*' and '*mazio*' sized poles (see table 2.1) is relatively higher compared to *boriti* and *nguzo* sized poles in all of KMNR (Table 4.7 – 4.9). *Boriti* poles are the most desirable utilization class and until 1982 were being exported to Middle East countries (Rawlins, 1957). In the period 1967 – 1982, Kenya was producing on average 6000 and 5000 scores of *boriti* and *mazio* respectively per year (Rawlins, 1957; Roberts and Ruara, 1967; Forest Records, (1970-1999). Even with the exportation ban of 1982, the local demand for mangrove poles has escalated. In 1995 alone, the Forest Department in Kenya licensed the harvest of 31,550 scores of mangroves of which 21,200 (67.2%) were extracted from Lamu district alone (Fig. 4.8). It is very unlikely that the current mangrove stock can meet the national demand. This is in the sense that large part of mangrove growing areas in Lamu; particularly the Southern Swamp forests in Mkunubi, Milhoi and Manda (see Fig. 4.1) are already depleted. The results of this survey indicate the availability of 298,043 scores of *pau* and *mazio* and only 130,162 scores of *boriti* within and adjacent to KMNR (Kairo & Kivyatu, 2000).

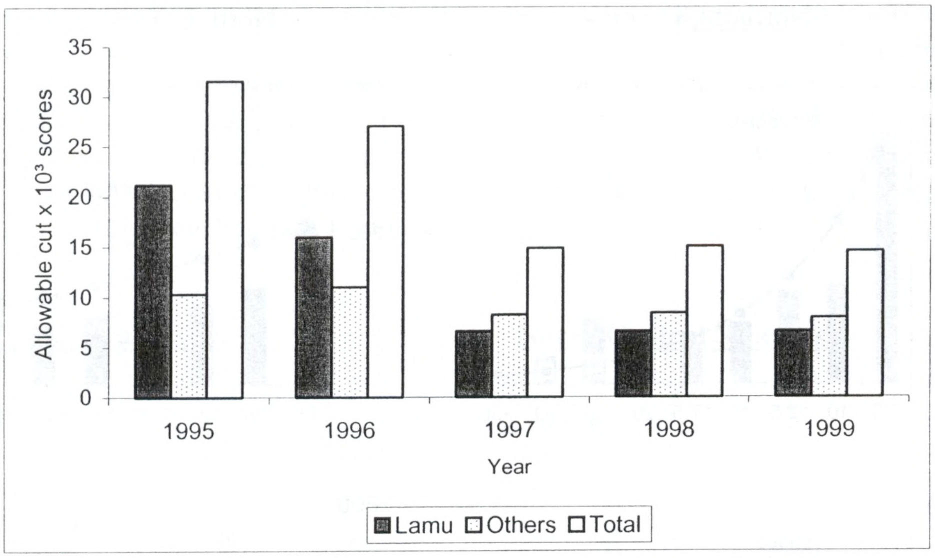


Fig. 4.8. Allowable cut of poles from mangrove forests in Kenya, 1995-99 *(Data source:* F.D. Annual Reports, 1995 - 1999).

4.6.2 Stand biomass

Using a form factor of 0.7 for *R. mucronata* (*see section:* 4.3.2.3) the standing volume of the sampled *Rhizophora* stems in Kiunga management area (Northern Swamps) was estimated at 400.26 m^3/ ha (Table 4.7). If we take the green density of *Rhizophora* wood to be 1242 kg/m^3 (Roberts and Ruara, 1967) the standing above-ground biomass of a mature *Rhizophora* stand in KMNR can be estimated as 497.1 tons/ha. The figure compares well with the highest productive stands of *Bruguiera gymnorrhiza* (406.6 t/ha) and *Rhizophora apiculata* (436.4 - 460 ton/ha) reported in Asia (Komiyama *et al.,* 1988; Putz and Chan, 1986). In the Andaman Islands, Mall *et al.,* (1991) recorded a total above-ground biomass of a mature stand of *Rhizophora mucronata* as 124.0 ton/ha.

4.6.3 Regeneration

In the Northern Swamps 752 trees/ha (35.11%) had a diameter of 10-20 cm, while 356 trees (16.62%) had a diameter of 20 –30 (Table 4.8). In North Central forests, 608 trees (29.30%) had a diameter of 10-20 cm and 112 trees (11.12%) had a diameter of 20 –30 (Table 4.9). This shows that the mangroves of Kiunga have the potential to rejuvenate themselves in terms of parental trees at least *within* the marine protected area. The principal mangrove species (*Rhizophora mucronata*) attained a height of over 10 m (70 %) and a diameter greater than 20 cm (50%; Fig. 4.4). KMNR had an average stem density of 1736 per hectare (Table 4.5). The adults were distributed evenly as indicated by a Morisita's Index of less than 1 (Fig. 4.6). Juvenile densities were 7,647 and 11,481 saplings/ha in Northern and North Central Swamps respectively. Empirical studies carried out in Malaysia show that sapling densities of 5,000 to 10,000 per hectare were sufficient for a good regeneration (UNDP/UNESCO, 1991). In Costa Rica Chong (1988) estimated a minimum of 2,500 saplings per hectare with a spacing of 6.25 m^2/saplings as being sufficient for adequate regeneration. In view of these considerations, the regeneration potential of mangroves of KMNR is good. Examination of dispersion patterns showed a close to uniform distribution ($I_0 < 1$) for *Rhizophora* juveniles in the Northern and North Central Swamps but clustered distribution ($I_0 > 1$) for *Ceriops* juveniles in the exploited areas of North Central Swamps (Fig. 4.6).

4.6.4 Yield from future forest

The potential yield of the future mangrove forest in KMNR can be gauged by an evaluation of current standing volume. The present inventory revealed that the existing mangrove forests within and adjacent to KMNR have a net standing volume of 2,354,004.85 m^3. The average compartment volume ranged from 6.85 m^3/ha to 710.0 m^3/ha for stem diameter above 5.0 cm (Table 4.5). The average volume of the entire study area was 145.88 m^3/ha, which corresponds to a stand density of 1736 stems/ha. This is considered to be high considering that mangroves of KMNR are not virgin forests.

In Matang, Malaysia, the average density for 30 years old stand of *R. apiculata* is 1,343 trees/ha with an average volume of 153 m^3/ha (Haron, 1981). In Ranong, Indonesia, where some of the best mangroves in the world are located an average density of 812 trees/ha and volume of 226 m^3/ha have been reported (Aksornkoae, 1993). Chong (1988) estimated an annual harvest of 1185 m^3/yr in a 25 years rotation from Terraba-Sierpe of Costa Rica that contained a stocking of 769 trees/ha (or 281 m^3/ha), KMNR has probably the most productive mangrove forests in Kenya. Given its high potential productivity and regeneration mangroves within and adjacent to KMNR have excellent prospects for sustainable exploitation.

One of the firm conclusions in mangrove management is the thinning to improve diameter growth and natural regeneration (Watson, 1928; Noakes, 1955) though optimal and temporal distribution of thinning are debatable (Devoe & Cole, 1997). If a strip clear-cut exploitation is to be used in mangrove management in Kenya as in Asia since the 1840's (Hamilton & Snedaker, 1984) thinnings should be part of the cycle. Otherwise, much of the potential site productivity is unused. Fuelwood and small dimension poles (*fito & pau*) can be harvested from the same stands much sooner than the *boriti* poles that are so important in house-building at the coast (Kairo *et al*., 2001); Dahdouh-Guebas *et al*., 2000b), and this sooner than the *nguzo* (Table 2.1). Because all mangrove wood products are used (though generally *boriti* is preferred pole size) in Kenya, the early thinnings (*fito & pau*) that are silviculturally desirable in naturally regenerated stands might be economic. The value of thinned *vs*. unthinned stands can be expected to exceed thinning costs but without controlled studies of growth and labour costs it is impossible to project by how much at this stage.

Rotation age is difficult to fix for mangroves of Kenya because of inadequate growth and yield data as well as differences in the commercial sizes of poles. The current uses of mangrove in Kenya differ significantly from those reported from other parts of the world (FAO, 1993). In Kenya mangroves are not commercially exploited for charcoal or pulp production one finds in Asian countries like the Philippines and Malaysia (FAO, 1994). *S. alba* is used mostly in boat repair and fish floats in Kenya whereas in other countries like Bangladesh the species is harvested for match-sticks low-grade utility timber and flooring timber. *Xylocarpus granatum* is highly priced wood in Asia and Pacific for interior panelling and cabinetry (Hamilton & Snedaker, 1984). In Kenya the species is sometimes used for carving but mostly as building and fencing poles (Dahdouh-Guebas *et al.*, 2000b). *Heritiera sp.* is sawn in S. E. Asia (Hussein, 1995), but in Kenya the use of *Heritiera littoralis* is restricted to building and as boat mast. Worldwide, the development of mangrove saw timber production is still low (Clough, 1993).

This survey has established the presence of 31 million stems (equivalent to 2.4 x 10^6 m^3 of wood) of mangroves within and adjacent to KMNR (Table 4.3, Table 4.5). Not all of these trees are harvestable, either because of over-size or poor quality or are located in the preservation zones of the forest. Kairo & Kivyatu (2000) have estimated the presence of 130,162 scores of *boriti* and 298,043 scores of *mazio* within and adjacent to KMNR. Almost 40% of the *boriti* and *mazio* are locked up in the protection zone, thus unavailable to cutters. It takes approximately 30 years for a mangrove tree in Kenya to reach *mazio* size (8.0 – 11.0 cm) and 37 years to reach *boriti* (11.5 – 13.5 cm) – (Roberts and Ruara, 1967). Based on these estimations, the final crop in KMNR can sustainably yield at least 3,500 scores of *boriti* (Table 2.2) on a 20 year rotation, and an approximately 1,000 scores of *mazio*.

5.0 Literature cited

See List of References

CHAPTER 5

RESTORATION OF MANGROVES

Above ground biomass of restored mangrove forests at Gazi bay, Kenya

..... and let there be forest

A re-afforested *Rhizophora mucronata* stand: 1996, 8-month-old stand.

Major output of Chapter 5

Kairo, J.G., 1995a. *Artificial regeneration and sustainable yield management of mangrove forests at Gazi Bay, Kenya.* Unpublished M.Sc. Thesis, University of Nairobi, Botany, Nairobi, Kenya: p116

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Above ground biomass of restored mangrove forests at Gazi bay, Kenya

5.0 ABSTRACT

Above ground biomass was determined for 5 and 8 years old mangrove plantations at Gazi bay, Kenya. Trees with a stem diameter greater than 5.0 cm inside 100 m^2 were harvested, and then separated into stems (trunks), branches, leaves and prop roots. Mean above ground biomass was calculated at 20.25 t dry matter ha^{-1} for *Rhizophora mucronata* Lam. 11.7 t dry matter ha^{-1} for *Avicennia marina* (Forsk.) Vierh. 6.7 t dry matter ha^{-1} for *Sonneratia alba* Sm. and 3.7 t dry matter ha^{-1} for *Ceriops tagal* (Perr.) C. B. Robinson. In *A. marina* and *R. mucronata*, stems (52.19%) and prop-roots (30.28%) respectively accounted for the highest proportion of the above-ground dry weight. While in *S. alba* and *C. tagal,* branch biomass represented the highest percentage of biomass, 48.20% and 43.62% respectively. The total above-ground biomass of *R. mucronata* was best estimated from regression equations using a combination of height and diameter above stilt root as the independent variables. For *A. marina, C. tagal* and *S. alba,* there was no simple correlation found between the above-ground biomass and tree height or stem diameter. The regression models developed by previous workers for natural mangrove stands in Asia and Pacific did not give satisfactory estimation of biomass in our plantation plots.

Key words: Mangrove regeneration, above-ground biomass, Gazi bay, Kenya.

5.1 Introduction

As terrestrial forest resources become further depleted in many tropical countries, mangrove forest management is likely to pick up. Already mangroves are being managed for timber in a number of Indo-Pacific regions, notably Bangladesh (Chowdhury & Ahmed, 1994), Malaysia (Noakes, 1955; Tang *et al.*, 1984) and Thailand (Aksornkoae, 1987). Reliable estimates of biomass and growth rates of mangroves are essential for assessing the yield of commercial products from forests, and for the development of sound silvicultural practices. Non-destructive allometric relations are used widely to estimate tree biomass in tropical and temperate forests (Brown *et al.*, 1989; Rondeux, 1993). In mangrove forests, biomass above ground is normally estimated indirectly from measurements of stem diameter at a height of 1.3 m (usually abbreviated to DBH or D_{130}, diameter at breast height) and tree height. Allometric relationship between DBH alone, or in combination with height (h), as the independent variables and the dry weights of different parts of the tree as dependent variables are then used to estimate biomass from measurements of DBH and height (Boto *et al.*, 1984; Cintron & Scheffer-Novelli, 1984; Ong *et al.*, 1985; Putz & Chan, 1986; Saenger & Snedaker, 1993).

In this way, Suzuki & Tagawa (1983) established a regression of the type $y = b(DBH^2.h)a$ for *Rhizophora mucronata* (n = 9) and *Bruguiera gymnorrhiza* (n = 8) in Japanese mangroves of dwarf trees. Woodroffe (1985) reported the relationship $y = (a - bx)^{-3}$ for *Avicennia marina* in New Zealand, where x is the diameter, the height of the trunk or the diameter of the crown (n = 12, h < 4 m, DBH < 10 cm).

Amarasinghe & Balasubramaniam (1992) established a relationship between DBH and biomass for *R. mucronata* and *A. marina* in Sri Lanka of the form $\log y = a\log dbh + b$ (n = 30, dbh < 12 cm). Mackey (1993) working with a single population of *A. marina* in Australia used linear regression with circumference as the predictive variable (n = 6, dbh < 5.0 cm), and logarithmic with height as the predictive variable (n = 13, h < 2 m). It appears from these data that most of the published information on allometric relations in mangroves relied on natural mangrove stands and that these studies were mostly carried out in Asia and Australia. Few data are available from the America and African regions. We can however mention

Puerto Rico (Golley *et al*., 1962); Panama (Golley *et al*., 1975); Florida (Lugo & Snedaker, 1974); French Guyana (Fromard *et al*., 1998) and South Africa (Steinke *et al*., 1995). Until now, however, no biomass data have been available for the East African region.

The biomass values presented in this chapter are to my knowledge the first information ever presented for re-planted mangroves in the African region. They can be discussed in comparison to similar data for other regions, particularly the managed mangroves forests of Asia (e.g. Ong *et al*., 1985; Putz & Chan, 1986), and hence contribute to our understanding of the mitigation pathways of the restored mangrove systems.

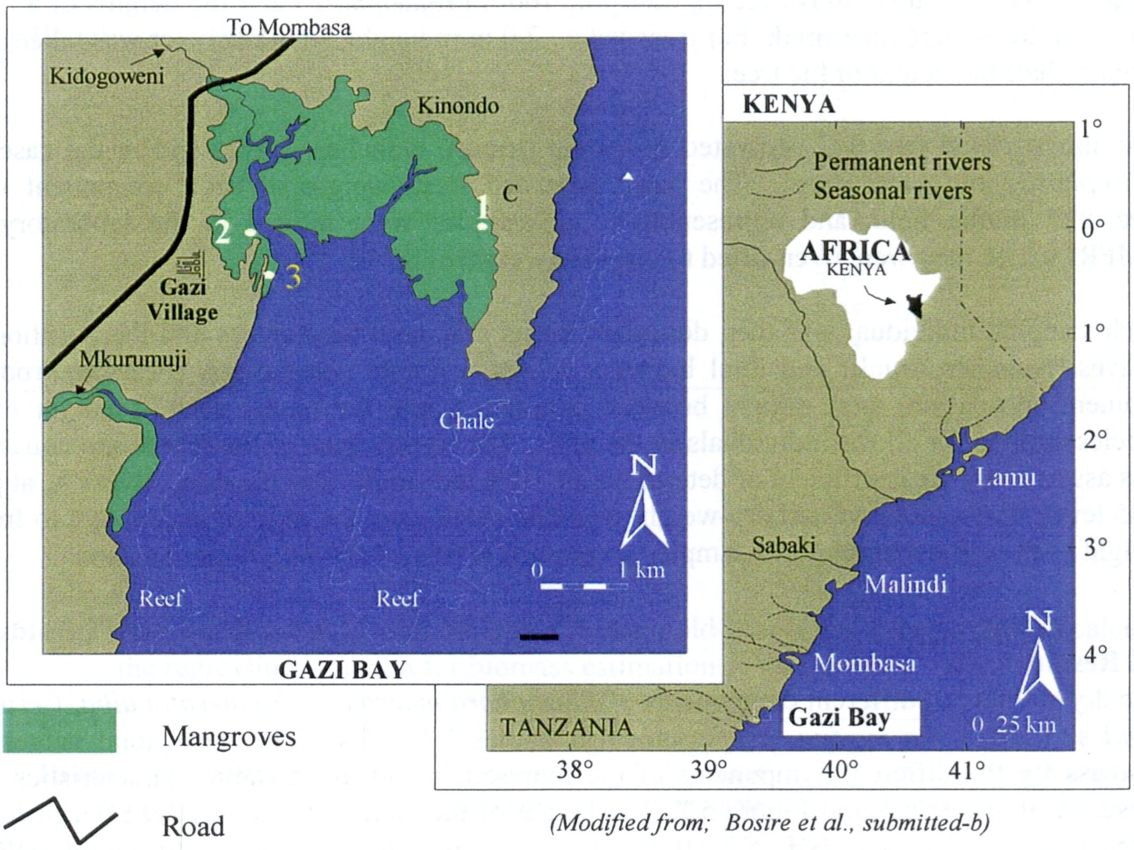
5.2 Study site

Gazi (4°25'S and 39°50'E) is an 18km² bay in the south coast of Kenya (Fig. 5.1). The bay is sheltered from strong waves by the presence of Chale Peninsula to the east and a fringing coral reef to the south. Mangroves of Gazi cover 615 ha (Doute *et al*., 1981). There are two major tidal creeks penetrating the mangrove forests. The western creek is the mouth of the river Kidogoweni, a seasonal river. The eastern creek, Kinondo, is a tidal creek. A total of 9 mangrove species occur in Gazi bay, although most publications (e.g. Gallin *et al*., 1989) mention 8 and even 7. *Rhizophora mucronata* and *Ceriops tagal* are the dominant species. The average heights of these two dominant species are 10 – 12 meters with vertical stratification. Regeneration is abundant in areas where the canopy has been opened through selective logging; otherwise it is very low in clear-felled areas and under closed-canopy. Other species are *Avicennia marina*, *Sonneratia alba* and *Bruguiera gymnorrhiza*. At the edge of the forest landward, *Heritiera littoralis, Lumnitzera racemosa* and *Xylocarpus moluccensis* occur. The fringing mangroves on the seaward side are inundated by incoming tides twice a day, and the highest tidal range, at high spring tide, is about 4.0 m (Brakel, 1982). The water is poor in nutrients, especially nitrates and phosphates and has an average salinity of 34.5‰ (Ohowa, *et al*., 1997).

There has been extensive exploitation of Gazi mangroves for various purposes over many years. The mangrove forests have been affected most noticeably by wood extraction for industrial fuel and building poles. Wood extraction for fuel has declined following the near depletion of the big trees and inaccessibility of the remaining resource. The forest areas are however still allocated to concessionaires for building poles and there is also widespread small-scale woodcutting to meet the needs of the local community. Gazi village has a resident population of 800 people, mostly dependent on marine resources in one way or another (Kairo, 1995b).

A pilot reforestation project to rehabilitate degraded mangrove areas, restock denuded mudflats and transform disturbed forests into uniform stands of higher productivity was launched at Gazi bay in October, 1991. Planting was carried out in 1 x 1 m² and 2 x 2 m² matrices for propagules and saplings respectively. By 1995, more than 200,000 trees of mainly *Rhizophora mucronata, Ceriops tagal, Avicennia marina* and *Sonneratia alba* had been planted as monocultures in a total of 12.47 ha (Kairo, 1995a, Kairo, 1995b; Kairo, 1997).

Subsequent development of the restored areas has been monitored by comparing height and diameter increment of the planted trees (Kairo, 1995a, 1995b), and by studying floral and faunal secondary succession of the restored areas (Bosire, 1999; Bosire *et al.* (submitted-a); Bosire *et al.* (submitted - b)). This chapter estimates the above-ground tree biomass for mangrove plantations established at Gazi bay since 1991.



(Modified from; Bosire et al., submitted-b)

Fig. 5.1. Map of Gazi bay showing the location of plantation areas. Because of the presence of neat zonation pattern in Gazi mangroves (*see* Fig. 1.4), majority of the artificial plantations were established as monocultures of the dominant species in the neighbourhood. **1**. *Rhizophora mucronata,* **2**. *Sonneratia alba,* **3**. *Avicennia marina* and *Ceriops tagal.* Site 1 receives water every high neap, approximately twice every week (Inundation class 3). Site 2 receives water every day (Inundation class 1) while site 3 is a mixture of Inundation class 3 and 4. For detailed physico-chemical characteristics of the plantation areas refer to Kairo (1995a), (1995b).

5.3 Materials and methods

Artificial plantations of *R. mucronata*, *S. alba*, *C. tagal* and *A. marina* that were established since 1991 at Gazi bay were sampled. Trees with stem diameter greater than 5.0 cm inside 10 x 10 m^2 sample plots were harvested at ground-level using handsaws. The diameter of the stems, DBH (measured above the highest prop root in *Rhizophora*) and the heights of all the harvested trees were measured. For trees below 2.0 m in height, stem diameter was taken at a distance half the height of the tree.

The aboveground part was separated into stem (trunk), branches, leaves and in the case of *Rhizophora,* into prop roots. The total harvested fresh weight of each component was measured in the field, and representative sub-samples were moved to the laboratory at KMFRI where they were oven-dried to constant weight at 85°C.

Each sampled individual was then described by its structural parameters and the partitioned (leaves, branches, trunk) and total biomass values. Simple correlations (Pearson Product Moment correlation) were sought between parameters and the model established for each species applied for all the individuals in the plots. The significance of the regression equation was assessed by the coefficient of determination (R^2) and single classification ANOVA, at $p =$ 0.05 level. The total harvested dry-weight was calculated from the ratio of dry-weight to fresh weight of the corresponding sub-samples, expressed in tonnes dry weight per hectare.

5.4 Results

The dry weights of different components of *Rhizophora mucronata*, *Sonneratia alba, Ceriops tagal* and *Avicennia marina* are presented in Tables 5.1 – 5.4. The mean total values of biomass for the different components of the four stands and mean stand characteristics are presented in Table 5.5 and Figure 5.2. The height of the canopy trees was 3.9 ± 0.6 m for 5 years old *Rhizophora* (DBH: 5.3 ± 0.8 cm), 5.3 ± 0.7 m for 8 years *Avicennia* (DBH: 7.5 ± 1.4 cm), 4.5 ± 0.3 m for 5 year old *Sonneratia* (DBH: 8.9 ± 1.7 cm) and 2.3 ± 0.2 m for 8 year old *Ceriops* (DBH: 5.1 ± 0.2 cm). In *Sonneratia* and *Ceriops*, branch biomass represented the highest proportion of the total above-ground dry weight, 48.20% and 43.62% respectively. In *Avicennia* and *Rhizophora* trees, stems (52.19%) and prop roots (30.28%) respectively, accounted for the greatest percentage of the biomass (Fig. 5.2). Mean total above ground biomass for trees with DBH > 5.0 cm amounted to 20.25 t dry matter ha^{-1} for *Rhizophora*, 11.7 t dry matter ha^{-1} for *Avicennia,* 6.7 t dry matter ha^{-1} for *Sonneratia* and 3.7 t dry matter ha^{-1} for *Ceriops* (Table 5.5).

Table 5.1. Harvest data for 11 individuals of 5 years old *Rhizophora mucronata* used to calculate the regression equation for biomass estimation.

		Above-ground dry biomass (kg)				
Ht (m)	**DBH (cm)**	**Prop root biomass**	**Branch biomass**	**Leaf biomass**	**Stem biomass**	**Total aerial biomass**
	3.00	0.37	0.44	0.61	1.63	**3.06**
3.33	4.50	3.24	0.93	3.42	1.63	**9.22**
3.46	5.50	2.75	3.05	2.78	2.40	**10.98**
3.49	4.00	2.75	2.27	2.36	1.92	**9.30**
3.85	5.00	3.27	2.83	2.15	2.33	**10.58**
3.90	6.50	4.62	5.82	1.12	4.00	**15.56**
4.14	6.00	3.35	2.70	1.87	3.17	**11.10**
4.20	5.20	2.04	1.61	3.37	2.50	**9.53**
4.24	7.00	4.88	2.73	3.05	3.16	**13.82**
4.50	6.20	3.42	2.51	4.44	5.25	**15.62**
5.06	5.30	2.18	1.79	4.46	3.04	**11.47**

Table 5.2. Harvest data for 10 individuals of 8 years old *Avicennia marina* used to calculate the regression equation for biomass estimation.

		Above-ground dry biomass (kg)			
Ht (m)	**DBH (cm)**	**Branch biomass**	**Leaf biomass**	**Stem biomass**	**Total aerial biomass**
5.5	5.2	4.40	1.17	5.11	**10.69**
5.6	6.9	2.87	1.29	6.54	**10.69**
5.7	8.4	2.64	0.40	8.33	**11.38**
5.7	7.8	4.32	1.42	6.90	**12.64**
6.0	10.2	6.99	2.25	13.30	**22.54**
5.4	7.7	3.28	0.88	2.66	**6.81**
5.8	9.0	4.06	1.49	6.72	**12.27**
4.0	6.3	4.07	1.06	3.39	**8.52**
4.3	6.8	6.12	2.76	3.41	**12.28**
4.5	6.8	3.41	1.12	4.75	**9.27**

Table 5.3. Harvest data for 10 individuals of 5 years old *Sonneratia alba* used to calculate the regression equation for biomass estimation.

		Above-ground dry biomass (kg)			
Ht (m)	**DBH (m)**	**Branch biomass**	**Leaf Biomass**	**Stem biomass**	**Total aerial biomass**
5.0	10.2	5.20	1.01	2.24	**8.45**
4.8	7.8	6.01	1.80	1.64	**9.46**
4.8	8.0	1.45	0.22	2.21	**3.88**
4.8	11.3	2.62	0.31	2.17	**5.11**
4.0	10.4	2.84	0.74	3.03	**6.61**
4.7	9.1	3.72	0.69	3.82	**8.23**
4.5	5.3	2.55	0.98	3.04	**6.57**
4.1	9.3	3.23	0.98	2.20	**6.41**
4.2	9.9	3.13	1.54	3.27	**7.95**
4.4	7.7	1.56	0.44	2.38	**4.37**

Table 5.4. Harvest data for 10 individuals of 8 years old, *Ceriops tagal* used to calculate the regression equation for biomass estimation.

		Above-ground dry biomass (kg)			
Ht (m)	**DBH (cm)**	**Branch biomass**	**Leaf biomass**	**Stem biomass**	**Total aerial biomass**
1.8	5.0	1.35	1.06	1.25	**3.66**
2.2	5.0	3.05	1.54	1.54	**6.13**
2.3	5.0	1.46	0.96	1.27	**3.69**
2.3	5.0	2.09	0.91	1.60	**4.60**
2.3	5.1	2.52	0.95	1.92	**5.39**
2.4	5.0	1.15	0.82	0.51	**2.48**
2.2	5.0	0.60	0.38	0.56	**1.54**
2.2	5.0	0.88	0.60	0.61	**2.09**
2.6	5.5	1.66	0.81	1.14	**3.62**
2.3	5.5	1.24	0.79	1.43	**3.47**

Table 5.5. Biomass partitioning in four mangrove species of different ages. DBH is the diameter at breast height (or half-height for trees less than 2 m height), *n* is the sample size. Number in parenthesis indicates the % of total biomass.

Species	**Tree height (m)**	**DBH (cm)**	**Branch biomass (kg dry wt)**	**Leaf biomass (kg dry wt)**	**Trunk biomass (kg dry wt)**	**Prop root biomass (kg dry wt)**	**Actual above-ground biomass (kg dry wt)**	**Estimated stand biomass (t/ha)**
Rhizophora mucronata (5 years old) $n = 56$	3.9 ± 0.6	5.3 ± 0.8	149.6 ± 2.7 (24.62%)	128.8 ± 1.4 (21.19%)	145.3 ± 1.0 (23.91%)	184.0 ± 1.0 (30.28%)	607.6 ± 4.3	**20.25**
Avicennia marina (8 years old), $n = 10$	5.3 ± 0.7	7.5 ± 1.4	42.2 ± 1.4 (36.00%)	13.8 ± 0.7 (11.82%)	61.1 ± 3.1 (52.19%)	-	117.10 ± 4.2	**11.7**
Sonneratia alba (5 years old) $n = 10$	4.5 ± 0.3	8.9 ± 1.7	32.3 ± 1.5 (48.20%)	8.7 ± 0.5 (13.00%)	26.0 ± 0.7 (38.79%)	-	67.0 ± 1.8	**6.7**
Ceriops tagal (8 years old) $n = 10$	2.3 ± 0.2	5.1 ± 0.2	16.0 ± 0.8 (43.62%)	8.8 ± 0.3 (24.07%)	11.8 ± 0.5 (32.31%)	-	36.7 ± 1.4	**3.7**

The dry weights of the trees were estimated by power functions, and their linear transformation, using DBH as the independent variable (logy= **a** + **b**logx), *where*, y = biomass, x = DBH and, **a** and **b** are the regression constants). Figure 5.3 shows linear relationships obtained when dry weight biomasses of different components of *Rhizophora mucronata* were plotted against DBH. The regression equation used for predicting the total above-ground biomass for *R. mucronata* was: $\log_{10}$Biomass = -0.1811 + 0.6590logDBH, $R^2 = 0.8347$, $p < 0.05$. In the case of *S. alba*, *C. tagal* and *A. marina* regression values listed in Table 5.6 were found to be less significant, and the R^2 values were less than 40%.. This indicates that plant biomasses in these species had no simple relationship with their stem diameters.

The best estimate of biomass in *Rhizophora* was obtained when DBH was substituted with the square of the diameter multiplied by height ($y = ax^b$ where y = biomass and $x = DBH^2h$). This way, the R^2 values for the total biomass estimate improved slightly ($p > 0.05$) from 0.8347 to 0.8402 (Table 5.7).

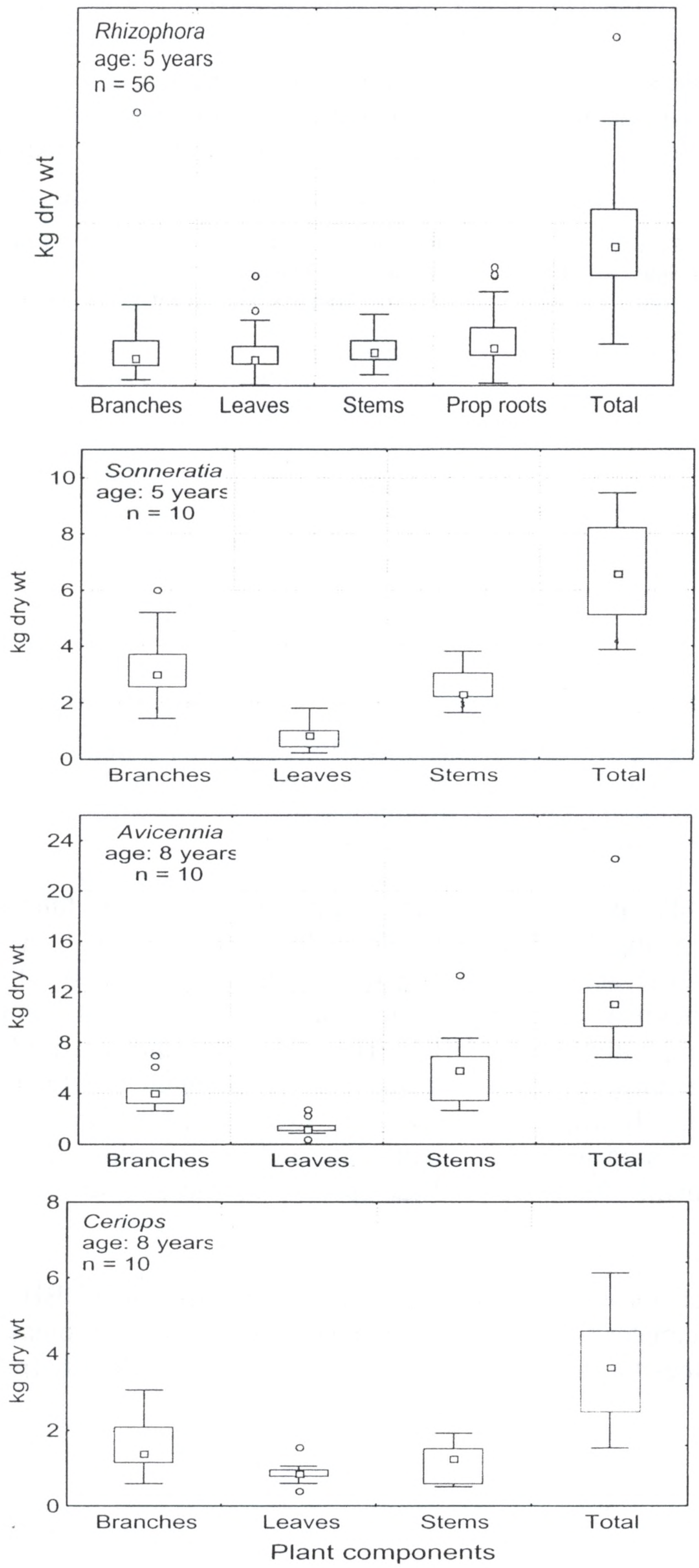


Fig. 5.2. Distribution of above-ground biomass amongst different plant components for mangrove plantation of different species.

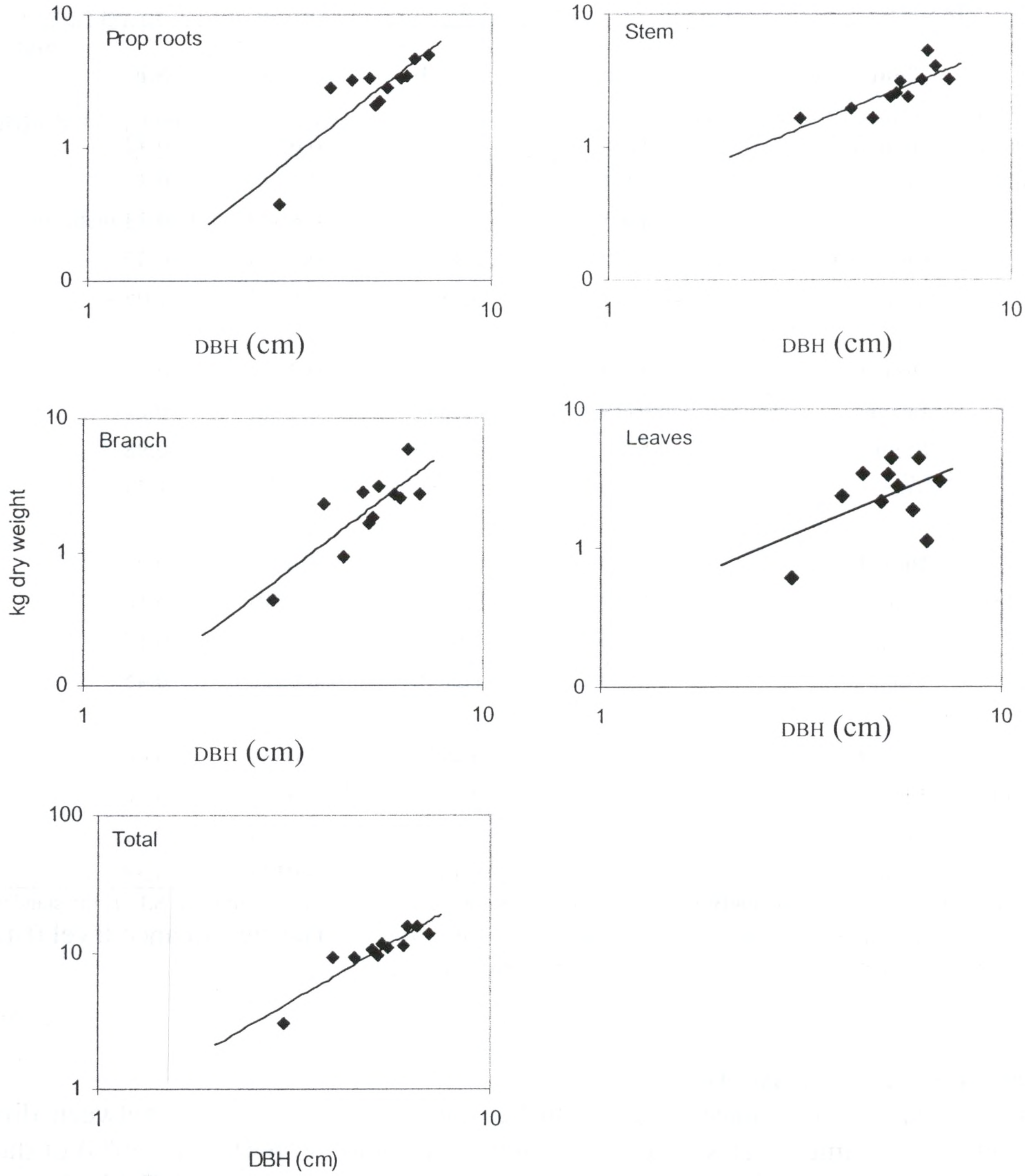


Fig. 5.3. log-log plots of dry weight against DBH for different components of a 5 year old *Rhizophora mucronata* stand at Gazi bay. The corresponding regression coefficients are given in Table 5.6.

Table 5.6. Allometric regressions of above-ground biomass on DBH for four mangrove species

Species	Plant component	a	b	R^2	S.E.	Significant level
R. mucronata	Branch	-1.3116	2.2731	0.6546	0.42	**
(5 years old)	Leaves	-0.4811	1.1982	0.2338	0.37	ns
n = 56	Stem	-0.4465	1.2206	0.6579	0.33	**
	prop root	-1.3010	2.4044	0.7026	0.37	***
	Total	-0.1811	0.6590	0.8347	1.05	***
A. marina	Branch	0.3703	0.2708	0.0284	0.44	ns
(8 years old)	Leaves	-0.0719	0.1887	0.0048	0.21	ns
n = 10	Stem	-0.5781	1.5175	0.3647	0.98	ns
	Total	0.2540	0.9140	0.3135	1.34	ns
C. tagal	Branch	-0.3627	0.7372	0.0036	0.24	ns
(8 years old)	Leaves	0.1862	-0.3740	0.0016	0.10	ns
n = 10	Stem	-2.1549	3.0864	0.0658	0.15	ns
	Total	-0.3209	1.2036	0.0125	0.45	ns
S. alba	Branch	0.0083	0.4910	0.0559	0.46	ns
(5 years old)	Leaves	0.1616	-0.3179	0.0107	0.16	ns
n = 10	Stem	0.4256	-0.0245	0.0004	0.21	ns
	Total	0.6715	0.1473	0.0118	0.58	ns

a and **b** are constants in the equation logBiomass = **a** + **b**logDBH. R^2 is the correlation coefficient, S.E. is the standard error of the biomass estimate and *n* is the sample size. Biomass is in kg and DBH in cm. The significance level (t-test) is given as , *: $p < 0.05$; **: $p < 0.01$; ***: $p < 0.001$; ns = not significant

5.5 Discussion and conclusions

There was variation in biomass distribution between species as well as between different components of the same species. Stems accounted for a high proportion (> 50%) of the total above ground biomass in *A. marina* compared to other species (Fig. 5.3 Table 5.5). In *R. mucronata*, a high proportion of above-ground biomass (30.88%) is invested in the prop-roots (Fig. 5.2). As the size of the tree increases (Fig. 5.4), there is an increasing allocation to above-ground prop roots at the expense of that of the stem and leaves. This presumably reflects the greater support requirements of larger trees, since the prop roots are the major support structures of *Rhizophora* species (Tomlinson, 1986). Since stems and prop roots in *Rhizophora* are relatively long-lived stable structures, the accumulation of biomass in each, provides at least some idea on how carbon is partitioned between them as the tree grows. By contrast leaves and twigs (or small branches) are shed as litter throughout the year.

In this study, the biomass of different components of *Rhizophora mucronata* were best estimated by power curves, and their linear transformation, using DBH as the independent variables (Fig. 5.3). The best estimate of total above-ground biomass ($R^2 > 0.8$) was obtained using a combination of tree height and diameter at breast height (DBH^2*h) as the independent variables (Table 5.7). There was no close relationship between height (and/or stem diameter) and biomass of *S. alba*, *C. tagal* or *A. marina* (Table 5.6), and none of the regression models suggested by previous workers (*cited above*) were successful.

Table 5.7. Allometric relations of above-ground biomass for 5 years old *Rhizophora mucronata* based on different independent variables

Independent variable (x)	Dependent variable (y)	a	b	R^2	Significant level
DBH	Prop Roots	-1.3010	2.4044	0.7026	***
	Branch	-1.3116	2.2731	0.6546	**
	Stems	-0.4465	1.2206	0.6579	**
	Leaves	-0.4811	1.1982	0.2338	ns
	Total	-0.1811	0.6590	0.8347	***
h	Prop Roots	-0.9905	2.3918	0.3142	ns
	Branch	-0.9897	2.2131	0.2804	ns
	Stems	-0.5567	1.6710	0.5573	**
	Leaves	-1.0899	2.4937	0.4578	*
	Total	-0.1722	2.0124	0.5486	**
DBH*h	Prop Roots	-1.4413	1.4267	0.6043	**
	Branch	-1.4330	1.3398	0.5556	**
	Stems	-0.6275	0.8088	0.7056	***
	Leaves	-0.8639	0.9518	0.3605	*
	Total	-0.3630	1.0554	0.8155	***
DBH^2h	Prop Roots	-1.4295	0.9154	0.6553	**
	Branch	-1.4260	0.8620	0.6057	**
	Stems	-0.5761	0.4968	0.7012	***
	Leaves	-0.7289	0.5476	0.3143	ns
	Total	-0.3198	0.6601	0.8402	***

a and **b** are constants in the equation log y = **a** + **b**log x. R^2 is the correlation coefficient. Biomass is in kg. height in m and DBH in cm. Sample size is 56 trees. The significance level (t-test) is given as , *: $p < 0.05$; **: $p < 0.01$; ***: $p < 0.001$; ns = not significant.

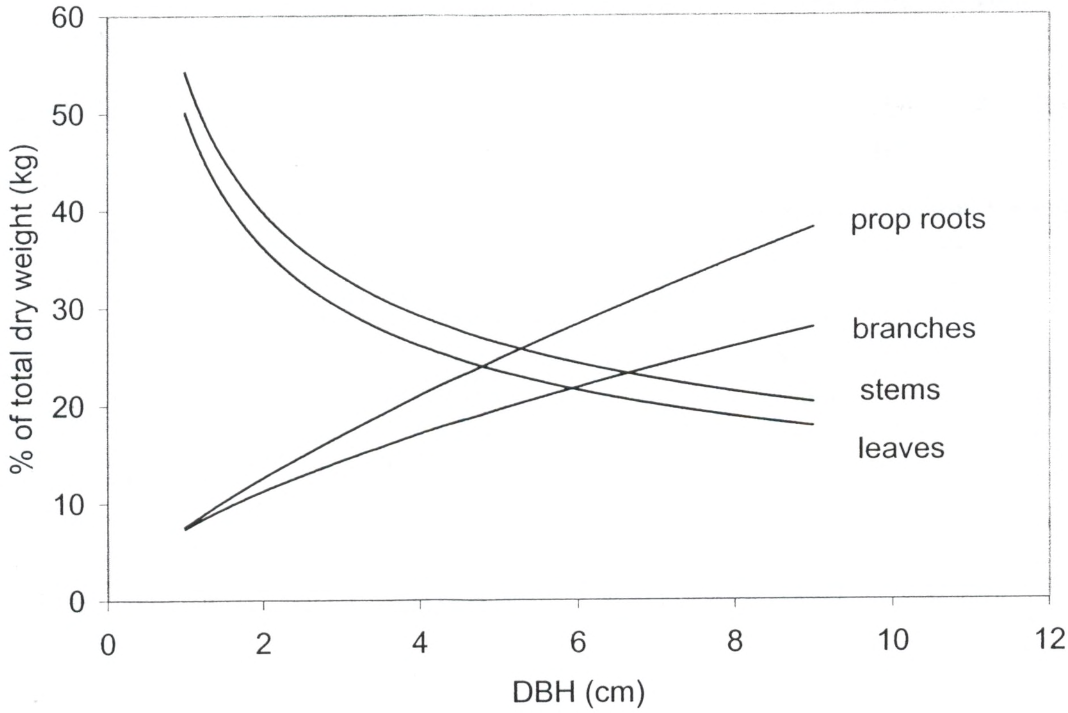


Fig. 5.4. Partitioning of aboveground biomass in a 5-year old *Rhizophora mucronata* plantation at Gazi bay Kenya. The curves are for the best fit line and may thus fail to add to 100% when extrapolated below 2 cm. Individual data points have been omitted for clarity. The corresponding regression coefficients are given in Table 5.8.

Table 5.8. Allometric regressions of resource partitioning on DBH for 5 years old *Rhizophora mucronata* trees at Gazi bay (*see* also Fig. 5.4).

Components	a	b	R^2	S.E.	Significant level*
Branch	7.4024	0.6042	0.1550	2.35	ns
Leaf	50.1180	-0.4707	0.0582	2.86	ns
Stem	54.2710	-0.4482	0.1358	2.92	ns
Prop root	7.5794	0.7356	0.3172	2.16	ns

a and **b** are constants in the power equation, Biomass = $aDBH^b$. R^2 is the correlation coefficient. S.E is the standard error of biomass estimate. Biomass is in kg and DBH in cm. Sample size is 56. * ns: $p > 0.05$, therefore not significant.

These results imply that regression models developed for estimating biomass of natural mangrove stands in Asia and Pacific could not be applied directly without modification for artificial plantations in Kenya. Other parameters such as canopy diameter and width, which provides better description on the growth form of *A. marina,* might need to be explored. The method developed by Briggs (1977), which calculated the mean tree biomass of *A. marina* from the mean volume and mean wood density per unit area, and the photosynthetic biomass from the regression equation using stem diameter and non-photosynthetic biomass as the independent variables might be worth considering for the planted mangroves. Regression models vary between species (Clough, 1992). Even within the same species, regression models will vary at different localities, depending on site-specific factors such as tree density, location on the ground, whether there is a monoculture or mixed forest, and management practices (Christensen, 1978; Woodroffe, 1985).

In production forestry, the stem yields most of the commercially useful timber. The proportion of stem biomass to total above ground biomass was highest in *Avicennia*, whereas *Rhizophora* had significantly lower fraction of stem biomass to the total above-ground biomass (Table 5.5). Although differences in growth rate between species may be the main criterion of selecting species for production forest in a particular area, the results shown in Table 5.5 provide information that might be useful in selecting the species for production forestry, depending on whether the product of interest is building poles, firewood or even a protective function. In a fast growing species, planned thinning and pruning would help meet the subsistence demand of small wood requirement particularly firewood and building.

The reliability and limitations of allometric relationships for estimating tree biomass, and their application to forestry management have been reviewed by Whittaker & Marks (1975) and Causton (1985). In the present study, sampling was done in a relatively dense even aged artificial mangrove plantation. Tree harvesting was restricted to trees whose stem diameter (DBH) was greater or equal to 5.0 cm. In a few occasion, the tallest tree in a stand that could be cut for *fito* (DBH < 5.0 cm) were used. This may account for the relatively low correlation coefficients (R^2) obtained in the study (Table 5.6) that occurs due to multicollinearity of individual sampling points. Multicollinearity causes no special problems when inferences on Y are made within the region of sample observations on the independent variables (Neter *et al*, 1988). The regression equations derived in this study for the artificial plantations may not be appropriate for open natural plantations, where horizontal expansion of the crown of individual trees is less restricted by the crown of their neighbours. The effects of tree population density on the allometric relationship between stem biomass and DBH are not clear (Clough, 1989), but it seems likely be less affected by stand structure than those for the branches and leaves. Furthermore, prospective users of the allometric relations derived should be careful when extrapolating the relationship to trees outside the range of DBH used to obtain the relationship. A wise thing to do will be to survey several trees in a plot and check whether they conform to the allometric relationship for the species.

5.6 Literature cited

See List of References

CHAPTER 6

SYNOPSIS

A comparative analysis of mangrove forests along the Kenyan coast

6.0 Introduction

In Kenya, products from mangrove ecosystems, particularly wood, have been used and traded for centuries. Early historical records indicate that as early as 200 BC mangrove poles were an important item of commerce between East Africa and the desert countries of Arabia (*see* Rawlins, 1957). By the 1970's (AD) Kenya was exporting some 34,000 scores of mangrove poles to Somalia, Iran, Iraq, Kuwait and Saudi Arabia (Kairo, 1992; FAO, 1993). Despite this rich and long history, issues of mangrove management have not received serious attention until recently (Ferguson, 1993; FD&KWS, 1993; Wass, 1995; Kairo, 1996).

Mangrove wood is hard, heavy and resistant to termite attack; it also has the highest heating value among the known woods used for charcoal production. These characteristics make mangrove wood suitable in the construction and production industries. Further, mangroves serve as spawning grounds for fish and for endangered fauna such as sea turtles. They protect the shore of estuaries and lagoons against erosion and control floods. Not only are mangroves the '*restaurants*' and '*runways*' of numerous migratory birds, the detritus from mangrove forests to the offshore waters can form an important source of food for microscopic organism in the food chain (Odum & Heald, 1975; Robertson *et al*., 1992).

Kenya has over 54,000 ha of mangrove forests along her 574 km coastline (Doute *et al*., 1981). The highest concentration of these forests occurs in the area north of the Tana river delta in Lamu district. Threatening the mangroves of Kenya is the indiscriminate removal of wood products and the conversion to other land uses, such as fishponds and solar salt works (Kairo, 1992). Degradation of mangroves is directly reflected in the increased coastal erosion (Kairo *et al.*, 2001), shortage of building material and firewood (Dahdouh-Guebas *et al.,* 2000b), and reduction in fishery (Tiensongrusmee, 1991). Recent surveys indicate considerable loss of mangrove resources through over-exploitation in Lamu (FD, 1983; Kairo & Kivyatu, 2000), Mida creek (Gang and Agatsiva, 1992; Kairo *et al*., *submitted*) as well as the south coast area at Gazi bay (Ferguson, 1993). Losses of mangrove through oil pollution (Abuodha & Kairo, 2001) and aquaculture (Yap and Landoy, 1986) have also been witnessed.

This study was carried out in three sites, containing all together five distinctive mangrove populations. The sites span the entire Kenyan coastline from the northern limit at Kiunga (1°45'S, 41°30'E) to the southern limit at Gazi bay (4°25'S, 39°32'E). As pointed out in the introductory pages of my thesis, these two observations prompted the present study. Firstly, the existence of significant differences in mangrove forest structure between the area north and south of the Tana river delta. Secondly, there was a need to assess the recovery processes of the mangrove plantations established at Gazi bay since 1991, this type of data was not available before in the country. Based on these observations, a research agenda was formulated and results presented in Chapter 3 - 5. The present Chapter is a synthesis of the preceding Chapters, and sets the ground for the future work.

Mangrove forestry in Kenya suffers from the inadequate knowledge of; silviculture of species, of multiple-use potential of resources, and of the techniques and economics of natural regeneration and reforestation. Consequently, this thesis serves several purposes:

- It provides the state of knowledge of how mangrove forest in Kenya develop, so future silvicultural practices can be done with a higher level of expertise,
- It synthesizes knowledge on mangrove forest management in Kenya, to allow future research efforts to build on this knowledge,
- It puts a scientific perspective on future mangrove forestry in Kenya in the context of the growing human population in the coastal areas, on the one hand, and of potential threats to the mangroves (both biotic and abiotic) in the next century, on the other.

The work was constrained by lack of adequate reference data from the region that could be used to model patterns of stand development. Occasionally, we made use of the published information on growth rate, stocking densities and wood biomass from the mangroves of South East Asia. Care should be taken when extrapolating such information since mangrove of Asia are growing under tropical and sub-tropical conditions as compared to the mangroves of the Eastern Africa that are basically tropical.

6.1 Why mangroves north of the Tana river delta are structurally complex and different from those in the south

The variation in mangrove forest structure and productivity in a given environment is related primarily to the characteristics of the landforms colonized by the trees. The particular mix of fluvial, tidal, and wave energies acting in a region creates a landscape the geomorphology whereof is a function of the energy signature of that region (Lugo & Snedaker, 1974). The size, type and frequency of occurrence of these different geomorphic structures will vary from site to site. These structures are sites in which mangrove forests develop. Thom (1982) defined five types of environmental settings (structures) based upon the relative influence of rivers, rainfall, tidal amplitude, turbidity, and wave energies on coastal processes. To this list, Twilley (1995) added the reef environmental setting that includes chemical processes. These settings are not discrete categories, but integrate in such a way that many particular coastlines might fall between two or more environmental settings. The sites are colonized by different species of mangroves in a pattern that depends on each individual species' adaptations to growth at different tidal or flood water elevations, and to edaphic differences such as particle size, salinity, redox potential etc. To better understand the pattern of mangrove forest distribution, size range and extent in Kenya, it is necessary to understand the environmental settings under which these forests are growing. This information is indispensable for a rational management of a mangrove ecosystem and its resources.

The northern Kenyan coast is characterized by strong, seasonal fluctuations of biological productivity caused by wind-induced upwellings. These upwellings have long been known to enhance biological productivity particularly in phytoplankton (Kromkamp *et al.,* 1997) and fisheries (Smith, 1992). The effects of coastal currents and waves on mangrove forest structure and productivity have not been studied yet. Such effects may be 'positive': imports of nutrients through upwellings may increase mangrove productivity, but little is known about this. Schaeffer-Novelli & Cintron-Molero (1993) attributed the occurrence of highly developed forest stands (canopy height > 20 m) in the extremely arid coast of Ecuador and Southern Peru to non-climatic forcing functions such as tidal, wave and current energy.

Another characteristic feature in the northern Kenyan coast is the remnant topography associated with the geological shifting of Tana river mouth between Mambrui (40°10' E, 3°10'S) and Lamu (1°45'S, 41°30'E). It is believed that this is related to the barrier island system observed between Mambrui and Somali border. Offshore, there is evidence of major rivers draining into the Indian ocean in the Lamu area which are now separated by fossil underwater deltaic features (Caswell, 1953; Schloeder, 1974).

There are two permanent rivers that drain into the Indian Ocean in Kenya, the Tana and the Sabaki (Fig. 1.2). The river Tana has an annual discharge of 4.7 x 10^9 m^3 while the Sabaki has a discharge of 1.3 x 10^9 m^3 per year (Angwenji, 1980). During the SE monsoons, the long rains increase the discharges of the Tana and Sabaki rivers nearly four fold (Angwenji, 1980). This pulse of water and sediments is transported to northern Kenya by monsoon winds and the East Africa Coastal Currents (EACC) both of which are blowing from the south to the north (Fig. 2.3). Although there are no large rivers that drain into the mangroves north of Lamu, it is highly likely that terrigenous materials discharged by the River Tana, Sabaki and Dodori are transported northwards and deposited into the mangroves during the SE monsoons. There is also a possibility that mangroves of Lamu receive copious ground water outflow originating from Lorian Swamps in the northeastern Kenya. Exactly how much of this river discharge and the groundwater outflow influences the mangroves in Lamu are unknown; consequently the sedimentology and hydrology of the Kenyan coastal zone is largely unknown as well.

While it is essentially true that mangroves develop better in brackish water environments (Tomlinson, 1986), there are areas in Kenya where fresh water influx is minimal e.g. Mida creek. It is also difficult to imagine that the sea fringing *Sonneratia alba* in Mida will be dependent on fresh water other than rainfall for their growth, since they occur in areas flooded by seawater twice every day, Inundation class 1 of Watson (1928). Taking into account the highly developed mangrove forest structure in Mida creek (Table 3.2), the overruling factor responsible for a high complexity index seems to be groundwater seepage as well as wave and tidal dominated input of terrigenous materials into the forest. The presence of groundwater outflow into Mida creek and its possible influence to mangrove ecosystems has recently been confirmed by Kitheka *et al.* (1998) and Tack & Polk (1999).

Table 6.1 compares the structural characteristics of the four mangrove sites considered in this study using (1) the environmental settings of Thom (1982), (2) the functional types of Lugo & Snedaker (1994), and (3) the forcing functions of rivers, tides, waves and rain. Gazi bay, which has Type II and III environmental settings has riverine, fringe and basin forests due to the interactions of rivers and tides with the local topography. As 'energy signatures' (as defined by Odum, 1968) of coastal regions increase, there will be evidently greater biomass productivity, higher forest regeneration rates, and greater exchange of nutrients and organic matter with coastal waters (Lugo & Snedaker, 1974, Twilley, 1995). The high complexity indices (C.I.) recorded in the mangrove forests north of River Tana indicate especially the high basal area and canopy height in the Northern Swamp (C.I. = 62.81) and North Central Swamp (25.14) forests, as compared to the southern mangroves in Mida creek (6.97) and Gazi bay (0.35). The variation in complexity indices between the sites can also be argued in the light of human pressure. Although there is limited access to the mangroves of Kiunga and Mida, increased logging is observed in sites closer to human settlement. This is well demonstrated in KMNR whereby the areas adjacent

Table 6.1. Description of the environmental settings, 'energy signatures' and structural properties of 4 pilot areas compared in this study

Region	Site	Environmental settings[1]	Mangrove Type[2]	Major Forcing functions[3]				Structural properties[4]				
				River	Tide	Wave	Rain	Basal area (m^2/ha)	Stand density (ha^{-1}).	Canopy height (m)	Standing biomass (ton/ha)	Complexity index
North of the Tana river	Northern Swamps (KMNR)	III	Basin Fringe	N	H	H	L	46.97	2142	26.5	497.1	62.81
	North Central Swamps (KMNR)	II III	Riverine Basin Fringe	M	H	H	L	24.05	2075	16.0	197.38	25.14
South of the Tana river	Mida creek	II III	Basin Fringe	N	H	M	M	23.62	1197	12.1	104.73	6.97
	Gazi bay[5]	II III	Fringe Riverine	M	H	L	M	3.91	678	8.3	43.15	0.35

[1]Environmental settings (Thom, 1982)
I River-dominated (allochthonous) coasts of low tidal range that tend to form a delta
II Tide-dominated (allochthonous) coasts with terrigenous materials resulting in mudflats
III Coasts with minor river influence and autochthonous materials resulting in the formation of bays and lagoons dominated by higher wave energy.
IV Mixture of Settings I and III
V Drowned river valley complex.
[2]Lugo & Snedaker (1974)
[3]High (H), Medium (M), Low (L), Nil (N)
[4] Complexity index (C.I.) of a stand is calculated as: number of species x basal area (m^2/0.1ha) x maximum tree height (m) x number of stem/0.1 ha x 10^{-3} in 0.1 ha., standing biomass (ton/ha) is estimated for *R. mucronata* in each case.
[5]The complexity index for Gazi bay is according to Bosire *et al.* (submitted- a)

to the reserve in Ndau and Siyu (North Central Swamp) have less merchantable poles left compared to areas within the reserves (Table 4.4). Using a similar argument, we find the open access forest of Gazi bay nearly depleted of quality poles that could be used for building.

Mangroves with greater tidal activity and water turnover have generally been shown to exhibit greater litter fall than those in areas with stagnant water (Pool *et al*., 1975). In a recent study, Gwada & Kairo (2001) estimated litter productivity values of Mida mangroves as 16.42, 22.63 and 8.40 ton dry wt $ha^{-1}yr^{-1}$ for *Rhizophora mucronata, Ceriops tagal* and *Avicennia marina* respectively. The observed litter production in *R. mucronata* and *C. tagal* in Mida is significantly higher than the values reported for Gazi bay and other parts of the world (Table 6.2). The underlying factors influencing mangrove litter fall appear to be complex. Only a few reports focus on the relationship between environmental factors and litter fall. Rainfall (Woodroffe *et al*., 1988), soil salinity (Duke, 1988), temperature and wind speed (Saifullah *et al.,* 1989) have been shown to influence mangrove forest structure and hence litter fall. No data yet are available on the effects of non-climatic forcing functions (e.g. tides, waves and current energies) on mangrove forest structure and litter-fall in Kenya.

The variation in litter fall between Mida and Gazi bay may be a function of a combination of several forcing factors such as site-specific environmental differences, spatial and temporal differences in community structure and productivity, or just chance events. Gazi bay and Mida creek are known to have different hydrographic forcing factors (Kitheka, 1998, Table 6.1) and nutrient regimes (Woitchik *et al.*, 1997; Kitheka *et al.*, 1999; Ohowa *et al.*, 1997), which may partly explain their differences in litter productivity.

Table 6.2. Estimates of annual litter production (ton dry wt ha^{-1} yr^{-1}) for Mida and Gazi bay (Kenya) compared with highly productive mangrove forests in the world

Location	Species	Litter fall (ton dry wt ha^{-1})	Reference
Mida creek (Kenya)	*Rhizophora mucronata*	**16.42**	*This study*
	Ceriops tagal	**22.63**	*This study*
	Avicennia marina	**8.40**	*This study*
Gazi bay (Kenya)	*R. mucronata*	9.16	Slim *et al.* (1996)
	C. tagal	1.79	Slim *et al.* (1996)
Adaman Islands	*R. apiculata*	17.3	Singh *et al.* (1987)
USA	*R. mangle*	10.70	Teas (1979)
	R. mangle	4.75	Golley *et al.* (1962)
	R. mangle	8.80	Heald (1969)
	R. mangle	8.18	Pool *et al.* (1975)
New Zealand	*Avicennia marina*	7.61	Woodroffe (1985)
USA	*Rhizophora* sp.	16.31	Lahmann (1988)
Australia	*Bruguiera gymnorrhiza*	9.96	Duke *et al.* (1981)
	A. marina	15.98	Bunt (1995).
	C. tagal	12.90	Bunt (1995)
	C. tagal	5.39	Conacher *et al.* (1996)
	A. marina	6.28	Conacher *et al.* (1996)
New Guinea	Mixed forest	14	Twilley *et al.* (1997)
Matang (Malaysia)	Mixed forest	3.90	Gong and Ong (1990)
South Africa	Mixed forest	4.50	Steinke and Ward (1990)

6.2 Stem density, height and volume data

The forest structures in Mida and KMNR are given in Table 3.2 and Table 4.7. One observation that could be deduced from the stand table data is that stem density is lower for large trees, which is expected. However, the relation is not straightforward and when put into size-frequency diagrams it is not possible to obtain a simple correlation between the factors (Fig. 3.4 and Fig. 4.7). This is an indication of man induced pressure in the forest. Theoretically in an uneven aged forest there is a normal series of age-gradations, depicted by the reversed J-curve. The fact that such a relationship was not obvious in some stands of KMNR and Mida means that the forest is human influenced and the normal relationship disturbed. It also indicates that the disturbance of the forest is according to direct needs by the people without a particular harvesting plan and therefore the distribution of different size classes becomes haphazard. On the general assumption that the sizes of trees express age, we can use the density curves obtained in this study (Fig. 3.4

and Fig. 4.7) to predict the composition of the future managed forest. This can be done through two approaches. Firstly, we must harmonize the irregularities in the size-class distribution, and the second step will be to reduce density per class (i.e. stems/ha) by allowing multiple use of mangrove wood e.g. for charcoal or fuelwood production.

Another factor to be deduced from this study is that mangrove forests can actually produce enormous wood volumes. Trees higher than 20 m are observed in mangroves of Mida and KMNR. This combined with considerable stand diameter (30 cm and above) in a forest whose stem density is greater than 1000 stems/ha results in a very high wood volume. Mangroves of KMNR have an average stocking rate of 2077 stems/ha and a standing volume of 261.99 m^3/ha (Table 4.7)

In agreement with the general model established for all terrestrial ecosystems, Saenger and Snedaker (1993) hypothesized for mangroves a decrease in biomass values at high latitudes: 'in the absence of any particular ecological constraint, a mature stand of mangroves in an equatorial region develops a significantly greater biomass than at the northern or southern limits of its range'. They established an allometric equation of the form:

Biomass ($t.ha^{-1}$) = 244.994 - 5.470 x Latitude (°)
($r = -0.689$, $F_{(1,41)} = 36.47$, $p < 0.0001$)

The above equation is not specific to particular species, and can therefore be criticized on the ground that different mangrove types growing in similar latitudes attain different biomass values. For instance, a riverine mangrove stand is structurally more complex than the landward fringing stand, although the two may occur in similar latitudes. Using the above equation the predicted above ground biomasses for mangroves in KMNR (1°45' S); Mida creek (3°20' S) and Gazi bay (4°25' S) are 236.92, 227.17 and 221.32 ton/ha respectively. The observed biomasses for *Rhizophora mucronata* in KMNR, Mida and Gazi bay are 497.1, 104 and 43.15 ton/ha respectively (Table 6.1). Reasons for the differences between the observed and the expected biomass values are difficult to explain although human pressure and site conditions appear to be most likely contributing factors. Mangroves of KMNR are influenced by alluvial deposition from the river Tana and suffer less logging pressure, compared to the tidal dominated mangroves of Mida creek that are under constant harvesting pressure.

6.3 Diameter increment

Information on diameter increment of natural mangrove stands in Kenya is almost totally unavailable. The only reference made to-date is on a *Rhizophora* stand in Kiunga that was clear cut and replanted after the First World War by the Smith & Mackenzie Company. In 1950 it was recorded that the regeneration had reached *boriti*-sized poles, 11.5 - 13.5 cm (Roberts and Ruara, 1967). In the present study the plantation area was traced at Mambore in Kiunga. The mean stand diameter of the stems was 15.78 ± 8.96 cm (range: 5.0 - 55.0 cm) with a height of 11.38 ± 4.89 m (range: 2.0 - 25.0 m). The mean annual diameter increment was estimated as 0.20 ± 0.11 cm/yr (n = 972) and the mean biomass increment was 6.06 $tonha^{-1}yr^{-1}$ over the 80 years the trees were growing. This diameter growth is comparable to those published for Malaysia and Thailand (Table 6.3). In Perak, Malaysia, Watson (1928) recorded an annual diameter increment of 0.19 cm/yr for an old growth plantation of *R. mucronata*. The 1.06 ± 0.23 cm/yr average diameter increment for a young plantation of *R. mucronata* (n = 10) that was observed at Gazi bay (Table 6.3) was higher than similar published values, 0.73 cm/yr in Malaysia (Watson, 1928). No published figures were found for the annual diameter increment in young *S. alba*, *A. marina* or *C. tagal* plantations. Young plantation of *S. alba* recorded the highest mean annual diameter increment of 1.78 ± 0.35 cm/yr (n = 10) while *C. tagal* gave the smallest increment, 0.64 ± 0.03 cm/yr (n = 10, Table 6.3)

Table 6.3. Estimates of mangrove diameter growth increment (cm/yr) in Kenya in comparison with other parts of the world

DBH (cm) range	Species	Mean annual increment (DBH) (cm/year)	Forest type	Location	Source
3.0 - 7.0	*R. mucronata*	**1.06**	5 years old plantation, monoculture	Gazi bay, Kenya	*This study*
5.3 - 11.3	*S. alba*	**1.78**	5 years old plantation, monoculture	Gazi bay, Kenya	*This study*
5.0 - 5.5	*C. tagal*	**0.64**	8 years old plantation, monoculture	Gazi bay, Kenya	*This study*
4.0 - 6.0	*A. marina*	**0.94**	8 years old plantation, monoculture	Gazi bay, Kenya	*This study*
5.0 - 55.0	*R. mucronata*	**0.20**	dominant trees, old growth	Kiunga, Kenya	*This study*
5.5	*R. apiculata*	0.42	9 years plantation	Matang, Malaysia	Saw , 1983
3.2	*R. apiculata*	0.77	6 years plantation	Matang, Malaysia	Saw , 1983
10 - 20	*B. gymnorrhiza*	0.17	old growth	Matang, Malaysia	Putz and Chan, 1986
29.1 - 34.0	*B. gymnorrhiza*	0.38	dominant trees	Selangor and Perak, Malaysia	Watson, 1928
20 - 30	*R. apiculata*	0.28	old growth	Matang, Malaysia	Putz and Chan, 1986
24.1 - 34.0	*R. mucronata*	0.36	dominant and co-dominant trees	Matang, Malaysia	Durant, 1941
11.0	*R. mucronata*	0.37	dominant	Yap, Micronesia	Devoe & Cole, 1998
48.7	*S. alba*	0.49	dominant	Pohnpeian, Micronesia	Devoe & Cole, 1998
27.0	*X. granatum*	0.31	dominant	Pohnpeian, Micronesia	Devoe & Cole, 1998

Rotation ages were difficult to fix for mangroves of the study areas because more growth and yield data were needed, and utilization classes were different. The most used mangrove pole sizes in Kenya are *mazio* and *boriti* (Table 2.1). The time it takes for a mangrove pole to reach *mazio* size in Lamu is 30 years, while it takes additional 10 years for *mazio* to reach *boriti*-sized pole (Roberts and Ruara, 1967). Based on this, the rotation age of mangroves in KMNR to produce *mazio* and *boriti* poles was estimated as 20 years. This value differs widely from what is found in literature for different mangrove wood products in the world. Mangrove fuelwood rotations have ranged from seven years in the Philippines (Hamilton & Snedaker, 1984) to 25 years in Puerto Rico (Holdridge, 1940) to 30 years for mixed *Rhizophora* forest and 40 years for mixed *Bruguiera* sp (5.0 - 9.5 cm dbh) in Malaysia (Noakes, 1955, p. 28). Charcoal coupe ranged from 15 years in Sarawak and the Philippines to 30 years in Venezuela and Perak (Hamilton and Snedaker, 1984). Only one mangrove saw-timber was found in the literature for *Heritiera* sp. in Myanmar, where 295 years were required to reach the saw-timber merchantability standard of 39 cm diameter at 2.6 m above the ground (Seth and Mathauda, 1957).

6.4 Recommendations for future mangrove management research

Mangrove forests grow under the influence of many environmental factors that vary in intensity and periodicity. Having recognized this, it becomes clear that an effective mangrove management requires good understanding of the forcing function operating in the area. Managers must recognize that no single set of rules can be used to manage a system that is subject to processes that occur over wide scale spatial and temporal dynamics. Thus there is need for a coordinated and interdisciplinary approach to mangrove management that embraces multiple spatial and temporal scales.

Although many studies have been carried out on mangroves, we still do not understand many basic processes, including what controls within-habitat distribution, survival or growth of individual mangrove tree species or the responses to disturbances, and restoration properties. So far there is no single study that has measured total primary production in any mangrove system. Thus long-term studies on the biotic and abiotic factors controlling mangrove diversity and productivity must be initiated. These studies will require intra and inter-institutional linkages and closer cooperation of the researchers. Proper coordination of the collaborators will be needed to avoid duplication of efforts and to increase efficient use of available resources.

Research priority for mangrove restoration as a tool for ecosystem management will need to focus on the extent and mechanism through which mangroves contribute to fisheries productivity, and projects which approach the restoration of mangroves from an ecosystem perspective. Such projects will require long-term monitoring to determine how quickly and close to naturally functioning ecosystems the mangroves we restore can achieve.

In the present study it was difficult to fix rotation lengths for mangroves of Kenya because of inadequate growth and yield data. Consequently research on quantitative data of the forest should be promoted in order to establish growth rate, density, volume and form factors of different mangrove species. Information is also required regarding (a) propagule production: crop size per tree in relation to tree size and crown class, flooding frequency, soil salinity; (b) causes of losses of reproduction effort: abortion, herbivory, predation; (c) dispersal: losses on dispersal viability; and (d) establishment: rates of establishment, mortality, growth.

An understanding of variability of mangrove forest structure and distribution in Kenya awaits a more complete study of geomorphological and hydrological processes and of how these create suitable substrates. We need to study the relationship between the ocean currents and nutrient rich water or nutrient poor water, the downwellings or upwellings, the sediment loads and the possible effects to mangroves. Efficient use of remote sensing technology and GIS for monitoring of mangrove degradation and sedimentation processes should be promoted.

While it is anticipated that most regions will eventually suffer adverse consequences from global climate change, the low lying coastal areas may face the most dire and immediate consequences. The best-guess 'business as usual' projections of the Intergovernmental Panel on Climate Change (IPCC) for sea-level rise, atmospheric CO_2 and global mean temperature over the next century are +60.0 cm, 840 ppmv (parts per million volume) and +3.0°C respectively (IPCC, 1990; Titus and Narayanan, 1996; Kathiresan & Bingham, 2000). As mangrove forests are among the most prominent ecosystems in the low lying coastal areas of the tropics (Spalding *et al.*, 1997), they are likely to be the first systems to be affected by global changes. Most mangroves will experience increasing temperature, changing hydrographic regimes, rising sea level, increasing CO_2 and increasing tropical storms and intensity (Stewart *et al.*, 1990; Field, 1995; Michener *et al.*, 1997). In projecting global climate change over the next century, it must be emphasized here that the impacts of expected climate change on mangroves remain fraught with uncertainty.

Small increases in air temperatures may have little effects on the mangroves (Field, 1995), but if the temperature exceeds 35°C, root structures, seedling establishment and photosynthesis will be negatively affected. The broader effect of temperature increases may be in modifying global distribution and community composition by promoting spread of mangroves into sub-tropical salt marsh environment (Ellison, 1994).

Changes in hydrological or tidal regimes will affect mangroves negatively because mangroves have narrow tolerance ranges of these forcing functions (Blasco *et al.*, 1996). Reduced rainfall and runoff would produce higher salinity and higher sulphate concentrations in the seawater. Both would decrease mangrove production (Snedaker, 1995).

Mangroves operate in the C_3 pathway of carbon fixation for photosynthesis. Research indicates that increases in atmospheric CO_2 increase the productivity and efficiency of water use by C_3 plants (Clough *et al.*, 1982). Thus, it is anticipated by some researchers that projected increases in CO_2 will enhance mangrove tree growth and litter production (Ellison and Farnsworth, 1997). The projected increase in mangrove growth will however be offset by decreased growth resulting to sea-level rise. Further, it is generally commented in the literature that other environmental constraints might limit the CO_2 enhancement effects.

A rise in sea level from the greenhouse is predicted to increase flooding of the low-lying coastal areas and drawn mangroves (Field, 1995). Where accretion of the sediments is sufficient and topography suitable, mangroves will migrate towards higher altitudes (Pernetta, 1993; Woodroffe, 1999). Human habitation in the low-lying coastal areas will however obstruct the landward migration of mangroves in many areas. Consequently, the width of mangrove systems is likely to decrease in the effect of sea-level rise (Kjerve & Macintosh, 1997). Increased salinity caused by sea-level rises may also result in decreased productivity and stunted growth in certain species (Kathiresan and Bingham, 2000).

Effects of global climate change on mangroves will affect coastal protection, agriculture, aquaculture and forestry activities. Mangrove forestry activities will for instance be affected by changes in phenology, changes in aridity, changes in salinity and direct disruption of specific sites by sea-level rise and storms. Mangrove scientists and managers should closely monitor the environment of the forest for early indication of change.

Throughout much of the world today, the coastal areas are the centres of economic development and are over-crowded. According to the United Nations (1990) nearly 60% of the world population live along the world's coastlines. If this trend continues within the next three decades (i.e. 2020), 75% of humanity will reside in coastal areas. Increased population pressure will exert pressure on marine ecosystems including mangroves. We would expect that during the next decade scientists play an active role in conserving, managing and restoring mangroves and the associated coastal ecosystems if we are to continue enjoying their supply of goods and services.

6.5. Literature cited

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