Inventory and Modelling Mangrove Forest Stand Dynamics Following Different Levels of Wood Exploitation Pressures in the Douala-Edea Atlantic Coast of Cameroon, Central Africa

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DEDICATION

To:
My family
And
All working towards:
Environmental conservation,
Rural development
&
Social justice

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ABBREVIATIONS AND ACRONYMNS

ABG:	Above Ground Biomass
AMD:	Arithmetic Mean Diameter
ANOVA:	Analysis of Variance
BA:	Basal Area
BEF	Biomass Expansion/conversion Factor
BGB	Below Ground Biomass
CAI	Current Annual Increment
CDM	Clean Development Mechanism
CS	Cluster Sampling
CWCS:	Cameroon Wildlife Conservation Society
D	Diameter
Dbh:	Diameter at breast height
DEWR:	Douala-Edea Wildlife Reserve
D_{dom}:	Dominant Diameter
D_q	Quadratic diameter
FAO:	Food and Agriculture Organisation
G:	Stand Basal Area
GIS	Geographic Information System
GPS	Geographical Position System
g:	Tree Basal Area
H:	Stand Height
HE	Heavily wood exploitation regime
Hsr/st	Stilt root height or stump
H(sr-st)	Total height above stilt root or stump
h:	Tree Height
ha:	hectare
$H_{dom:}$	Dominant height
IUCN:	International Union for the Conservation of Nature
ME	Moderate wood exploitation regime
MINEF:	Ministry of Environment and Forests (Cameroon)
MS	Multiple/multi- stemmed tree
MTNR:	Ministry of Tourism and Natural Resources (Tanzania)

NGO:	Non Governmental Organisation
Nr	Number of
OLS	Ordinary Least Squares
PAI:	Periodic Annual Increment
PI:	Periodic increment
Pom:	Point of measurment
PSP:	Permanent Sample Plot
QMD	Quadratic mean diameter
REDD	Reduced Emission from Deforestation and Degradation
rm	Red Mangrove
SCS	Stratified Cluster Sampling
SD:	Stand Density
SE	Standard Error of the mean
SF:	Site Form
SI:	Site Index
SS	Single-stemmed tree
SR	Simple Random Sampling
SRS	Stratified Random Sampling
TF:	Tree Factor
TSP:	Temporal Sample Plot
UND	Undisturbed forest
UNEP	United Nations Environment Programme
V:	Stand Volume
v:	Tree Volume
VEF	Volume Expansion/conversion Factor
wm	White mangrove
WRM:	World Rainforest Movement
WWF:	World Wide Fund for Nature
WCMC	World Conservation Monitoring Centre
Yr:	Year

ABSTRACT

Mangrove forests existing at the interface between the sea and land in inter-tidal zones in tropical and subtropical areas playing quite significant ecological, socioeconomic and climate amelioration functions across the globe have been badly degraded over the years due mainly to human factors. Efforts to manage these forests have been widely demonstrated and documented. While mainly undisturbed states of these forests have been studied, relevant information especially on stock and ecosystem responses to human driven factors is often lacking for management applications. Systems of forest assessments and monitoring often applied to upland forests appear inappropriate to these systems with varied multi-stemmed and diverse eco-morphological structure of tree forms. The main objective of the study was to develop appropriate models to facilitate the assessment, monitoring and sustainable management of mangrove forest resources following different wood exploitation pressures in the Central African coastal Atlantic forests of Cameroon. It is a contribution to the understanding of the recovery dynamics and resilience of mangrove systems to various disturbance systems. Results provided are based on data on temporary sample plots and four year observations with two remeasurements intervals on permanent sample plots established in heavily exploited, moderately exploited and undisturbed mangrove forests in the Douala-Edea Wildlife Reserve mangroves in Cameroon Atlantic coast. Tree diameter dependent allometric relationships were developed to guide sustainable exploitation of mangrove forest including height partitioning relationships, stand curves, tree and stand volume equations with their statistical and graphical fit tests. Tree diameter dependent biomass expansion/conversion factor equations or constants have also been developed based on ratios of tree volumes to total biomass obtained from relevant published generic biomass equations with tables prepared from the best models. These *Rhizophora* dominated (*Rhizophora* –rel freq 89.9%, *Avicennia germinans* (rel. freq. 0.25 %) estuarine mangroves attain maximum height of 59m and diameter of 131.7 cm with mean stand density, basal area and volume of 651 trees/ha, 784 stems/ha (d≥6.4cm), 88.43 m^2/ha and 1879m^3/ha respectively in well stocked stands. Stand density, basal area, volume and total tree above ground biomass in undisturbed stands varied from 400 – 20100 trees/ha (mean 5416.7, SE 1930.5), 400 - 22300 stems/ha (mean 5900.0, SE 2077.7) (d≥1.0cm); 25.23 - 49.62m^2/ha (mean 36.85, SE 3.23); 223 - 611 m^3/ha (mean 402.8 and SE 49.4); and 240.3 - 659.3 tons/ha (mean 435.03 SE 53.4) respectively. Standing biomass values are amongst the highest in the world mangroves. Diameter distribution tends to approximate the log-normal type. There were significant site differences in all of the stand parameters (nr-trees, nr-multi-stemmed trees, stand basal area), except incidence of problem trees. There was significant disturbance effect on all stand parameters. Spatial patterns of tree developmental stages and mortality was varied with clump structures dominating. Except for mortality and multi-stemmed trees, there were no significant site, forest disturbance, and census time or interaction differences in spatial patterns in all the tree developmental stages. There were only significant site differences in recruitment and forest disturbance differences in basal area increment. Mean recruitment over the period was generally above mortality. Mortality was highest in heavy exploitation. Disturbance patterns encouraged growth with moderate systems highest. Stand tree density decreases with increasing stem density per tree in an L-shape fashion. Branching intensity for principal mangrove species tend to increase with disturbance and decrease with census time whereas the probability of branching increases with diameter. All the stand parameters (stand density, basal area, volume and above ground biomass) had significant impact on tree form unlike stand growth parameters. Tree recruitment was generally higher than secondary stem recruitment but higher in mortality. Forest dynamics parameters were comparatively higher than examples from uplands forest showing higher resilence of mangroves to disturbance. Dynamics of *Avicennia* and *Rhizophora* in balanced mixed stands showed that except in the proportion of multi-stemmed trees that showed significant differences between the two species there were no other differences between species or their tree forms in other stand parameters. *Rhizophora* generally performed better than *Avicennia* in mixed balanced stands. The results also show that forest growth, mortality, recruitment and eco-morphological phenomena like probability of branching and root sprouting in *Rhizophora* can be modelled with linear and binary regression approaches with an established disturbance scale based on proportion of basal area removed with adjacent undisturbed regimes as reference base. The matrix development through multi-stemmed dynamic approach was better than through the traditional diameter distribution approach. The predictive harmony, consistency and convergence of the various models tested through stand table projection approach showed that the models generally predict diameter class distribution with varying accuracies with overestimation of lower diameter classes especially 1-7 cm. Like matrix models, the predictive accuracy of the regression models improved with decreasing forest disturbance with the undisturbed state being the best. A codification system amenable to eco-morphological structure of mangroves is proposed to facilitate field measurements, data processing and easy quantification of population dynamics parameters using spread sheet. The use of the models in setting rotations, planning harvests, yield projections/predictions, assessing impacts of wood extraction or deforestation, planning silvicultural or mangrove restoration operations, forest carbon stock assessments, research, and policy, legal and institutional frameworks for implementation are further elaborated.

1. INTRODUCTION

1.1. General background

Mangroves are the only forests situated at the confluence of land and sea in inter-tidal zones of the world’s subtropics and tropics. These only known woody halophytes are trees or shrubs that develop best where low wave energy and shelter foster deposition of fine particles enabling these woody plants to establish roots and grow. Mangrove forests are architecturally simple compared to rainforests, often lacking an under storey of ferns and scrubs, and are ordinarily less species-rich than other tropical forests. The global distribution of mangroves indicates a tropical dominance with major latitudinal limits relating best to major ocean currents and the 20^{o}C seawater isotherm in winter. The latter point underscores the paramount importance of warm temperatures for the existence of mangroves (Alongi, 2002). There are 9 orders, 20 families, 27 genera and roughly 70 species of mangroves occupying a total estimated area of 181,000 km^2 (Spalding *et al.,* 1997). The most diverse bio-geographical regions are in the Indo-West Pacific, Indonesia, Australia, Brazil and Nigeria having roughly 43 % of the world’s mangrove forests.

The standing crop of mangrove forests is, on average, greater than any other aquatic ecosystem, with a decline in above-ground biomass with increasing latitude, relatively low near the sea but increases inland (Komiyama *et al.,* 2008). Mangrove forests around the equator can be immense, rivalling the biomass of many tropical rainforests. The biomass of mangrove forests is even greater if the biomass of living root beneath the forest floor is included; below-ground biomass can equal the standing crop rising above-ground (Clough, 1992).

Mangroves possess characteristics that, in total, make them structurally and functionally unique. Morphological and eco-physiological characteristics and adaptations of mangrove trees include aerial roots, viviparous embryos, tidal dispersal of propagules, rapid rates of canopy development, frequent absence of an under storey, absence of growth rings, wood with narrow, densely distributed vessels, highly efficient nutrient retention mechanisms, and the ability to cope with muddy anaerobic conditions, salt and to maintain water and carbon balance. Mangrove often accumulate large amounts of biomass in their roots and the above – ground biomass to below-ground biomass ratio of mangrove forests is significantly low compared to that of upland forests (Komiyama *et al*., 2008). This is necessary to maintain a bottom heavy tree form or low ratio of top biomass to root biomass, a phenomenon that may produce peculiar conditions for the ecosystem processes in root zones owing to the anaerobic conditions.

Ecosystem characteristics include comparatively simple food webs containing a mixture of marine and terrestrial species; nursery grounds and breeding sites for birds, reptiles and mammals; and accumulation sites for sediment, some contaminants, carbon and nutrients. The biology and ecology of mangroves have been recently reviewed (Hogarth, 1999; Ellison and Farnsworth, 2000; Kathiresan and Bingham 2001).

Despite its limited global distribution, its global utility is enormous and has been widely documented (IUCN, 1983; Tomlinson, 1986; Akpata and Okali, 1990; Foote *et al.*, 1996; WRM, 2004). Mangroves are valuable ecological and economic resource, being important nursery grounds and breeding sites for birds, fish, crustaceans, shell fish, reptiles and mammals; accumulation sites for sediments, carbon and nutrients; offer protection against coastal erosion and economically and culturally useful for timber and non-timber forest products and services. Their approximately one-third destruction is related to development activities, unsustainable human uses and human population density (Alongi, 2002) especially urban development, aquaculture, mining and overexploitation for timber and fish.

1.2. Statement of the problem

Like the tropical forests, mangroves are being degraded and destroyed globally (Spalding, 1997; Choubhury, 1994). Over 50 % of mangrove worldwide has been lost over the last 50 years with an annual depletion rate of 1% (Rodriguez, 2001; FAO, 2002). FAO (2003) further puts the mangrove forest cover at 146,530 km^2 of the tropical shorelines of the world representing a decline from 198,000km^2 of mangrove in 1980 and 157,632km^2 in 1990. These loses represent about 2% per year between 1980 and 1990 and 1% per year between 1990 and 2000 (Lewis, 2005). In a recently published report by UNEP World Conservation Monitoring Centre (UNEP, 2007) on the mangroves of West and Central Africa (available online at http://www.unep-wcmc.org/resources/publications/UNEP_WCMC_bio_series/26.htm), mangrove forests in the zone have declined by a quarter between 1980 and 2006 to a current estimate of 20,144 km^2. The major threat to this ecosystem especially in SE Asia and the Americas is shrimp farming (WRM, 2001). This activity, which until the nineties was on a low level in Africa, now threatens the African mangroves with 29 countries already involved in it (WRM, 2004). In most other areas in Africa, mangrove formations are harvested unsustainably and used extensively as fuel wood, charcoal making, thatching material, construction, canoe building, poles etc (Hamilton and Snedaker, 1984; FAO, 1994). Cutting of mangroves for fuel wood, charcoal, construction etc. is probably the second most pervasive and intrusive threat on the resource (Olsen *et al*, 1997; UNEP, 2007). As depletion of this ecosystem proceeds, most of its unique fauna and flora disappear, processes are altered and consequences of these events become evident in an ecosystem whose functional mechanism is still yet not fully understood (Maltby, 1985). Basic empirical data on mangrove management is lacking in most African countries; this is especially true of Cameroon mangroves (Din and Ngollo, 2003). The level of exploitation of any product from forest stands should be based on growth and regeneration data which can be used in determining rotation or cutting cycles (Usher, 1969; Osho, 1991). However in Cameroon, rotation cycles for forest concessions are purely speculative. In Nigeria, the rotation time of 50 years set by the forest administration is speculative (Enabor, 1981).

In Cameroon, these mangroves cover about than 3,000km^2 and distributed along major bays, creeks, and estuaries along the more than 400 km coast dominated by three species: *Rhizophora mangle*, *R. harrisonii* and *R. racemosa* (Letouzey, 1968) and to a lesser extent *Avicennia germinans.* Current mangrove estimate according to UNEP (2007) stands at 1,957 km$^{2.}$ They have remained forgotten in the past, undervalued by government, destroyed by encroachers and neglected by scientists. They have also been facing a lot of threats from surrounding agro-industrial companies, petroleum exploitation activities, urbanisation and fuelwood extraction for fish smoking especially in the Douala-Edea reserve portion constituting over 160 km^2 of mangroves (Ajonina and Usongo, 2001). Cameroon Wildlife Conservation Society (CWCS), a national research and conservation NGO (www.cwcs-cameroon.org) working in the Douala-Edea Reserve since 1997 within the framework of developing a community based conservation management plan for the reserve, puts annual mangrove fuelwood harvests of over 180,000 m^3 for an annual turnover of between 500 – 1,000 tonnes of smoked fish (CWCS, 2001) supplying most of Cameroon towns.

Most of these threats have been identified, are well known but not properly quantified and documented for management applications. There is an apparent lack of data particularly on the stock and regenerative or recovery capacity of mangrove forest following human and other disturbance systems and especially fuelwood harvests on which to set sustainable harvest levels. This study sets to contribute to this regard.

1.3. Study Objectives

The main objective of the study therefore, is to develop appropriate models to facilitate the assessment, monitoring and sustainable management of mangrove forest resources following different wood exploitation pressures in the coastal Atlantic forests of Cameroon, Central Africa.

Specific objectives include to:

i) Develop a harmonised mensuration and codification system as well as assessing the relative efficiency of some sampling methods to improve the inventorying and monitoring of mangrove forest resources;

ii) Establish allometric equations for volume, yield and biomass estimation to facilitate sustainable wood harvesting in the mangrove forest;

iii) Investigate the impact of different wood exploitation pressures on mangrove stand dynamics;

iv) Model mangrove stand structure and dynamics following different wood exploitaiton regimes;

v) Evaluate implications for mangrove forest management

1.4. Study Hypotheses and Research Questions

Are mangrove forests resilient/vulnerable to various disturbance systems? That is, do various disturbance systems through wood exploitation levels (heavy, moderate and zero levels) have any impacts on stand composition (tree species composition including invasive species), stand structure (tree diameter distribution, tree spatial patterns, and stand density) and stand dynamics (recruitment, growth, mortality)? Can they be modelled following disturbance?

Other Questions:

i) Can the present mensuration and codification system be improved and harmonised for rapid assessment and monitoring of mangrove wood resources?

ii) What is the natural stock and structure of the mangrove forests of Douala-Edea Atlantic coast of Cameroon?

iii) How does disturbance affect tree and stand parameters spatially and temporally?

iv) How can mangrove forests in the region be managed sustainably for wood production?

1.5. Study Justification

1.5.1. Research

The unique features endowed, their fragile nature coupled with the immense tangible and intangible services the mangroves provide are beginning to foster scientific understanding of mangrove ecosystems (RAMSAR, 1987; Rivera, 1997; Babier *et al.,* 1999). The economic role of mangroves cannot be fully realised without taking into consideration its ecological aspects. Studies must be conducted to improve understanding of the relationship between exploitation and biodiversity conservation in order to avoid ecological disasters (Liyanage, 1995; Rabarisoa, 2001). Regardless of the economic benefits, mangroves deserve a thoughtful management scheme because of the environmental services they offer. Management systems should be devised to safeguard these benefits and optimise resource use. Mangroves have been extensively studied but no empirical scientific data exists on the mangroves of Cameroon (Ajonina and Usongo, 2001). Data is being collected world wide on the distribution of mangrove habitats, species composition, traditional and potential utilisation and the socio-economic structure of people dependent on mangroves, but, there is very limited understanding of the values and functions of mangroves and how this is affected by human use (Hamilton and Snedaker, 1984; Tomlinson, 1986; Liyanage 1995; Alongi, 2002; Nganje, 2004). This study is expected to contribute to our current understanding of mangrove forest structure and dynamics and especially as this is affected by human disturbance. It will also provide an insight for the estimation of the carrying capacities of this important but fragile ecosystem.

1.5.2. Sustainable management of mangrove forests

There is growing concern of the involvement of local communities in forest management with the evolution of the sustainable use concept that stipulates that forest resources be used for the benefit of the present and future generations without compromising ecological integrity. Often the operationalisation of the concept in the field is compounded by lack of data on the dynamic nature of the resources especially the ability of the resource to regenerate or recover naturally when disturbed on which to base exploitation (Ajonina and Usongo, 2001; Alongi, 2002; Din and Ngollo, 2003; Ajonina *et al.*, 2005). This further stems from the fact that forest dynamics plots have been established in major forest types world wide (Condit, 1998; Newbery *et al.*, 2004; Su *et al.,* 2007) usually in undisturbed forest conditions and presents difficulties in understanding how the forest behaves under various perturbed conditions.

Mangrove regeneration processes are unique because of vivipary and dispersal by water only (Zuleiku *et al.*, 2003; Clarke, 2004) hence lack of regeneration data may result in poor assessment of harvesting regimes, poor intervention and stand degradation. There is need to correlate mangrove regeneration, growth and yield rates with the current patterns of wood off-take (Osho and Akinsanmi, 1990). The acute lack of knowledge on the growth and yield of forest stands is unfortunate because knowledge on growth is necessary for the management of forests under the sustained yield concept (Osho, 1991). This makes forest management in Africa and in Cameroon in particular difficult as rotation cycles for forest concessions are purely speculative not based on reliable growth and yield data.

Results from this study will be very useful to mangrove stand managers and government officials in understanding stand dynamics and forecasting yields for the ecosystem and hence fuel wood off-takes especially at the time where there is increased awareness on mangrove ecosystem value, functions and the need to conserve it. Moreover, the outcomes of the study may contribute in the development of a management plan for the Douala-Edea Reserve recently transformed into a national park to involve the participation of surrounding local communities whose livelihoods can only be sustained under a healthy ecosystem through the determination of realistic fuel wood harvesting quotas and putting in place efficient system of control and compliance.

1.5.3. Forest Policy development

Many African countries lack clear-cut forest policies, legislations and institutions that response to current realities of collaborative natural resources management and some countries are in the process of policy review to adapt to current context. In some countries good policies suffer from lack of implementation. There is general consensus in forest and environmental debates that the mangroves due to their fragile nature and biological, ecological and socioeconomic values be given a greater policy attention separate from the terrestrial forest system. The development of such a policy must necessarily take into consideration key issues like collaborative management and ecological monitoring issues that embrace the sustainable use concept. The result of this study can provide insights into the operationalisation of this concept in the field.

1.6. Scope and Methodology

The study is limited to the mangrove forests of the Douala-Edea Reserve, Cameroon covering over 160 km^2 using data from temporary sample plots (TSP) (Loetsch *et al.*, 1973; Husch *et al.*, 2003) from natural undisturbed stands and permanent sample plots (PSP) (Condit, 1998) established on three human fuelwood harvesting regimes (Zero, moderate and heavy exploitation). Data analysis ranges from the establishment of tree and stand allometric relationships with attempts to develop biomass conversion expansion/conversion factors; the assessment of human impacts on mangrove forest structure (stem diameter distribution, stem characteristics and stand density) (Cintron *et al.*, 1984; Moeur, 1993; Fromard *et al.*, 1998; Berger and Hildenbrandt, 2000) and dynamics (mortality, growth and recruitment) based on two to four years observation on PSP; using mortality, growth and regeneration (Vanclay, 1994) as well as transitory matrix models to characterize stand dynamics (Usher, 1966; Osho and Ajonina, 1998); and determination of sustainable wood exploitation levels for mangrove forests of the reserve. The conceptual framework for the study is summarised in Figure 1.1.

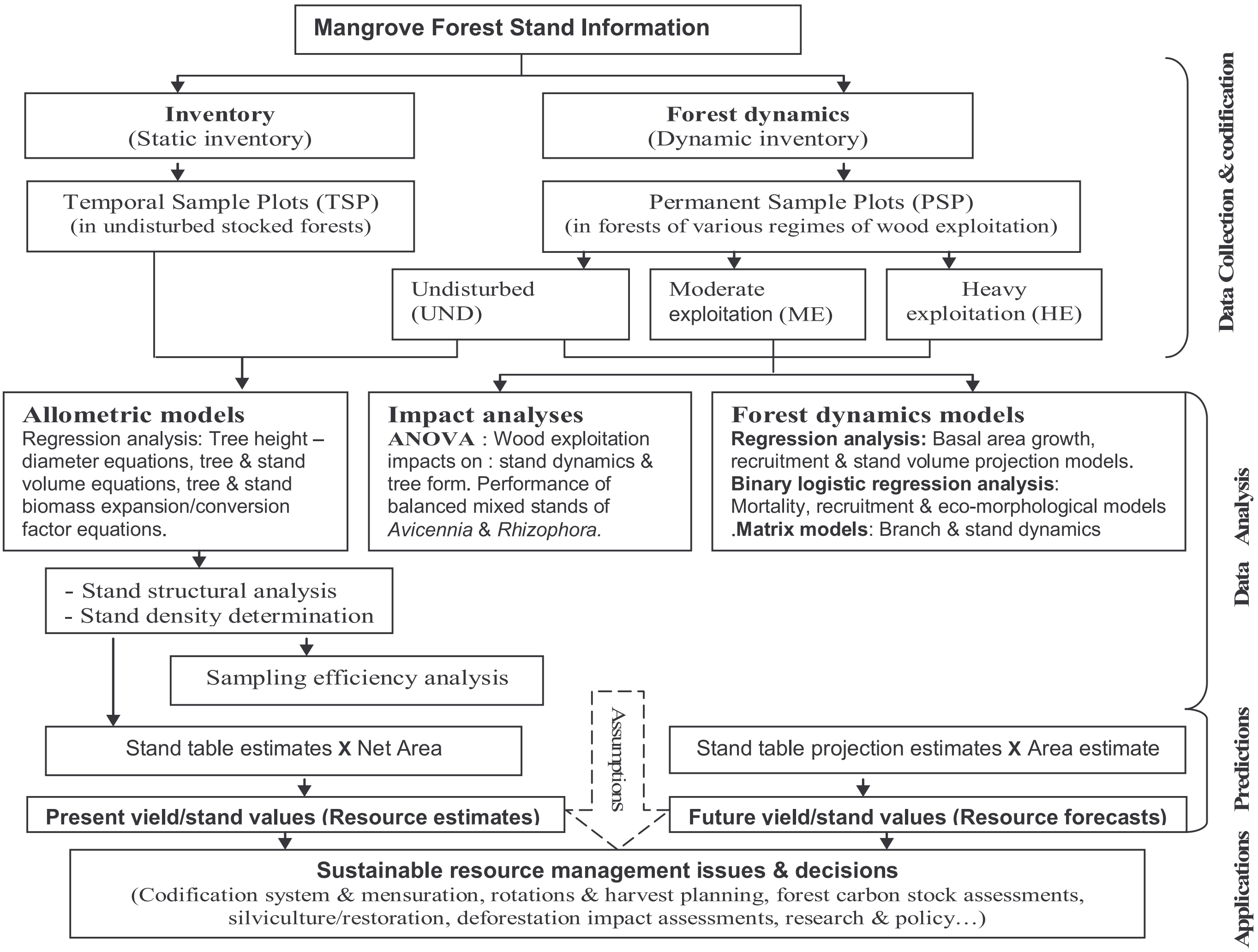


Figure 1.1: The conceptual framework of the study

2. LITERATURE REVIEW

This chapter presents summaries of work that have been done on mangroves, portraying the global distribution, species composition, taxonomy, habitat adaptation and factors favouring growth and development. A review of identified threats and services is carried out, with current mangrove management efforts around the world. A brief review on the concept of sustainable management is also presented. Finally, a brief review of some mathematical and statistical modelling approaches applied in the study of forest ecosystems is attempted giving an impetus to the present study.

2.1. General Overview on Mangroves

Mangroves have been generally described by many authors (Tomlinson, 1986; Kjerfe *et al.*, 1997; Alongi, 2002) as salt tolerant evergreen plants and often monospecific communities of the inter-tidal tropical and subtropical regions of the world. Mangroves are forested intidal wetland ecosystems classified by Ramsar Convention under the marine and coastal wetlands type (Frazier, 1996).

2.1.1. Extent and Global Distribution

Mangroves cover an estimated surface area of 181.000km^2 occurring along coastlines of tropical and subtropical regions of the world. They are limited latitudinally between 30^0N and 30^0S of the equator. Northern extensions of this limit occur in Japan (31º22’N) and Bermuda (32º20’N); Southern extensions are in New Zealand (28º30’S), Australia (32º45’S) and on the east coast of S. Africa (31º59’S). They have been found as far as South of New Zealand, North Japan, South Australia, South Africa and South Florida. These are exceptional cases that have been favoured by local conditions. A fall in temperature may limit the latitudinal distribution of some mangroves species (Tomlinson, 1986; Spalding; 1997; Kjerfve and Macintosh, 1997; Choudhury, 2002). According to FAO (2002) mangroves are distributed in 121 countries worldwide. Most of the mangroves are found in the South East Asian countries (see map Figure 2.1). Indonesia, Brazil, Australia and Nigeria have 43% of the world’s mangroves with Indonesia alone accounting for up to 23% of the world’s total.

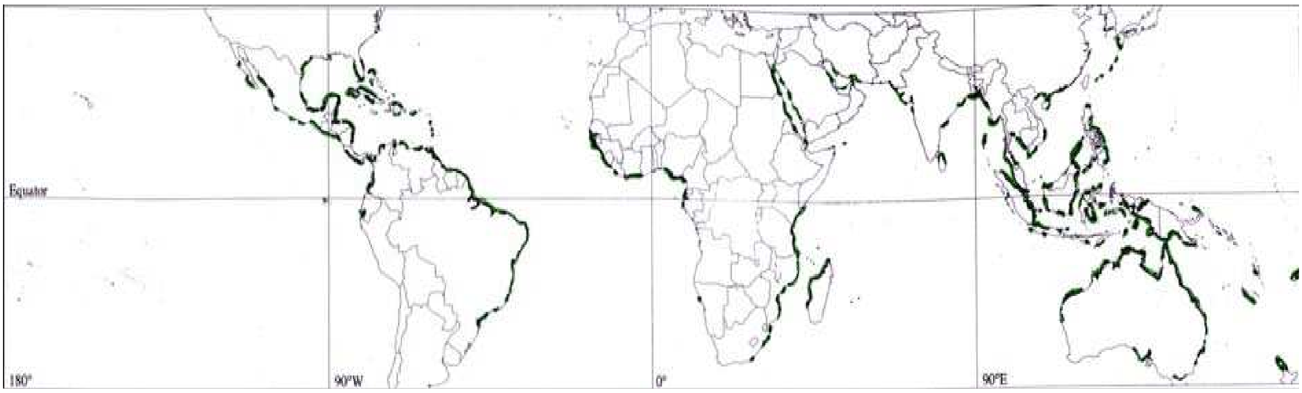


Figure 2.1: World distribution of Mangrove forests (after Spalding *et al.*, 1997)

2.1.2. Distribution of Mangroves in Africa

Mangrove forests cover most of the African sub regions in the Atlantic, Indian and Mediterranean coasts and Red Sea in Africa. In the Atlantic coastal section of Africa, mangroves stretch from Mauritania in the north western section of the Atlantic coast to Senegal in the Saloum Delta, Lower Casamance through Guinea Bissau, South Guinea, to the Gulf of Guinea flanking the coastlines of West and Central Africa from Liberia to Angola. The Niger delta in Nigeria supports up to 10,000km^2 of mangrove stands in this area and plays a critical role in supporting the regions rich wildlife. Climatic conditions are predominantly humid and tropical but changes to more temperate conditions towards Angola. In the Indian Ocean section in East Africa mangrove forests thrive in Mozambique, Tanzania within Rufji delta, Kenya in Tana and Sabaki Rivers and a greater part of Madagascar. Within the African section of the Mediterranean Coast few mangroves strive in Alexendria Egypt and more or less irregular manner in Somalia and Djibouti in the Red Sea. Estimates in Africa vary but according to the International Society for the Mangrove Ecosystems (ISME) and International Tropical Timber Organisation (IITO, 1993), they vary from 3.4 to 3.9 million ha for the continent and 2.1 million ha in West Africa and 1.1 million ha in Central Africa. Present estimates about 19% of global mangrove coverage is given by UNEP (2007) are 3.20 million ha found in Sub- Saharan Africa comprising 26 countries with regional distribution as follows: 1.58 million ha (49%) in West Africa (Mauritania to Nigeria-12 countries), 0.43 million ha (14%) in Central Africa (Cameroon to Angola-7 countries) and 1.18 million ha (37%) in Eastern Africa/Southern Africa (Kenya, Madagascar, Mozambique, Seychelles, Somalia, South Africa and Tanzania-7 countries).

2.1.3. Distribution of Mangroves in Cameroon

Cameroon (8-16° E; 2-13° N see Figure 3.4), is a west/central African country with population of about 16 million people over a total surface area of 475,000 km^2 having a coast situated in the extreme north eastern corner of the Gulf of Guinea measuring more than 400 km from the Equatorial Guinea border to the Nigeria borders. An equatorial climate type, greatly influenced by the equator, characterizes this coastal area. The Cameroon coastal extent and mangrove morphology have been extensively described (ITTO, 1993; Din and Ngollo, 2003). Cameroon mangroves stretch from the South West, through the Littoral to the South provinces. According to Letouzey (1968), they extend inland from the coast for up to 30 km and are largely riverine establishing along coasts and creeks. Mangrove areas in Cameroon are commonly grouped into three main zones: Rel Del Rey estuary mangroves (54%) from the mouth of Rivers Akpa Yafe and Ndian from the border with Nigeria, Lokele and Meme right up to the West of Mount Cameroon; Cameroon estuary mangroves (45%) stretching from the bay of River Bimbia, the islands formed by the tributaries of River(s) Mungo, Wouri and Dibamba and around the cities of Limbe, Tiko and Douala to River Sanaga estuary; and Ntem estuary mangroves (1%) from the south of River Sanaga, the Nyong estuary, Lokounje to Ntem River on the border with Equatorial Guinea. Cameroon mangroves area cover is not certain, estimates of 250,000ha (MINEF, 1995) and 227,500ha (FAO, 2002) have been given with much recent estimates of 195,700 ha by UNEP (2007) representing a decline of 28% from the 1980 estimate. The mangroves of the Douala-Edea Reserve (see Figure 3.4) are situated mostly within the Cameroon estuary mangroves and partly in Ntem estuary mangroves. These mangroves extend from the mouth of River Nyong through Mbiako, Yoyo I and II to the South West of the reserve and Youme (in the Sanaga Maritime Division) to Manoka (Wouri Division). They occupy more than 10% of the reserve covering more than 16,000 ha of mangroves and about 40% of the Cameroon coastline (Ajonina and Eyabi, 2002).

2.2. Ecology and Biology of Mangroves

The ecology and biology of mangroves have been widely studied. These plants are characterised by their common ability to grow in aggregation in pure stands (commonly called natural monocultures) and to thrive along sheltered inter-tidal coastlines on sediments that are alkaline, often anaerobic and sometimes acidic. Many have unique adaptational features such as viviparous propagule, prop root, pneumatophores and lenticels which contribute in one way or another to their survival in their relatively stressful environment.

The most important site conditions influencing the establishment and ecological succession of mangroves are the nature of the substrate, age of the swamp, inundation class, water salinity and erosive and abrasive action of the sea (Hamilton and Snedaker, 1984; Twilley, 1997; Doyle, 2003). Mangroves thrive well in and around estuaries of large rivers that run over narrow continental shelf like the Ganges, Bramaputra, Sanaga, Wouri, etc, forming major creeks and bays. They develop in such areas because of the low coastal relief, deep tidal inlets and micro-tides that create suitable landforms and transports materials and propagule (Cintron-Molero and Schaeffer-Novelli, 1992). They develop on a firm to soft unstable muddy substrate continuously built up through deposition, which produces a strong pungent hydrogen sulphite smell when disturbed, indicating the anaerobic property of the water logged soils. Their roots branch opportunistically, mostly to overcome some environmental stress. Basically, it is the geological, climatic and biological factors that determine the development of a particular type of mangrove. The geological factors have a direct relationship with the geology and sedimentation model of the area, the climatic/meteological factors equilibrate water processes like sea waves, ocean and river currents while the biological factors condition the physiological adaptation of the plants (Pool *et al*., 1977; Cantera and Anaud, 1997). However, the biogeochemical properties of mangroves are the least understood of processes along the transition from upland to coastal ecosystems (Twilley and Ronghua, 1996). Canopy height and stand structure is influenced by climate, topography and the extent of human disturbance. Mature undisturbed stands have high dense canopy with tall boles, limited aerial roots and little stratification (Plate 1-Figure 2.2). Strong competition for light causes trees on the inner forest to grow more linear with fewer stems per hectare, than those at the forest edge (Plate 2-Figure 2.2). In disturbed or impoverished stands, plants are stunted and shrubby (Plate 4-Figure 2.2) with abundant gaps, crabs, mud skippers, wasps and bee nests (Tomlinson, 1986, Spalding, 1997). Mangrove type and distribution follow topographical dynamics, tidal movements and tolerance to salinity with the most tolerant species like *Avicennia spp* thriving along the coast. Associating with mangroves are lichens, mostly abundant on the tree barks and branches, the most common being *Pyremula aurantiaca* and *Ramalina camplanata* (Jouana, 1997) climbers are absent. Because of their wide vessels, subjected to extreme water tension, only few epiphytes are associated with mangroves, usually very high up the canopy or on inland mangrove fringes (Snedaker, 1982).

According to Tomlinson (1986) mangrove zonation is influenced by propagule sorting according to size with the heavier propagules occupying the seaward habitats because they are less easily dispersed landward. However, species with lighter propagules like *Avicennia spp* and *Sonneratia spp* have been noticed on the seaside of Australasia. Mangroves are pioneer species because they are the very precursors of the climaxed stands (Clarke, 2004) and their consideration as a successional stage will imply that mangroves represents a transition stage towards a more climax terrestrial community (Tomlinson, 1986). This explanation has strongly been embedded into ecological literature because of the Clementian concept of succession (Snedaker, 1982). Other proposals for mangrove zonation like e.g. geomorphic change and ecological concepts have failed to explain the mode of action, the mechanisms through which the different geomorphic factors generate zonation patterns and also the mode of action of environmental gradient (Snedaker, 1982). According to Clarke (2004), though not yet tested, zonation of Indo-pacific mangroves may be due to environmental gradients. Mangrove species often form distinctive zones and grow in pure stands because of the differences in tree tolerance and requirements. Even in mixed stands, one species always dominates.

2.2.1. Biology of Mangroves

2.2.1.1. Mangrove habit and characteristics

Tomlinson (1986) and Spalding (1997) broadly characterised mangroves into true mangroves, minor mangroves and mangrove associates. Mangroves vary in size and species composition from the equatorial region to the savannah with a corresponding increase in temperature from 24^0C to 35^0C. Decrease in rainfall from 4000 mm to 500 mm, increase in salinity from 1 – 15% and a consequent decrease in size and increase in species composition. Reduced fresh water inflow due to limited rainfall results in low nutrient input from the land, increased salinity, creating a stressful environment that results in Stunt mangroves like the dwarf *Rhizophora* of Senegal (Pool *et al.*, 1977; Tomlinson, 1986). Mangroves develop best in tropical estuaries which receive heavy rainfalls evenly distributed throughout the year, resulting in tall trees and large diameters of up to 50m and 100cm in height and diameter respectively observed in the Douala-Edea Reserve (Ajonina and Eyabi, 2002). The basic climatic factor governing the geographical distribution of mangroves is temperature, with the number decreasing as temperature decreases from 30 species in the equatorial Indo-Malaysian countries to just one species in the African red sea coast, *Avicennia marina* (Pool *et al.*, 1977).

2.2.1.2. Habitat Adaptations

The hard to soft muddy mangrove substrate, coupled with tidal salt-water movement have lead to development of characteristic features of highly specialised mangroves. Aerial roots (Plate 3-Figure 2.2) like the stilt roots of *Rhizophora* spp. aid in support. Stilt roots are associated with lenticels for aeration. Pneumatophores in mangrove roots, aid in respiration by appendages accumulating oxygen during low tides. In some mangrove species e.g. *Nypa* palm, individual leaves function like giant pneumatophores. Development of salt secretary cells in mangroves controls salinity, but the rate of salt exclusion varies with species hence variability in salt tolerance. Loss of leaves is also an adaptation for further salt loss.

2.2.2. Taxonomy and Species Composition of Mangroves

2.2.2.1. Global mangrove species

The term Mangrove was first used as “Manguez” in the 16th century on Brazilian charts to describe the vegetation along the coast “Golfo de los Reyes”. Similar vegetation was described as “Alagados” implying “inundated” in Indonesia at the same time (Spalding, 1997). Knowledge on the floristic composition of mangroves is still limited (Choubhury, 2002, Jayatissa *et al.*, 2002). Despite their familiarity, characters that separate species are not very obvious given the impression of a young group of plants. Information as to the exact existing number of mangrove species in the world is very conflicting. In 1984, Hamilton and Snedaker reported 60 species with 20 associated species. Hong (1998) reported 68 species worldwide of which 51 are found in Vietnam. Spalding *et al.* (1997) reported 9 orders 20 families, 27 genera and roughly 70 species of mangrove worldwide. The taxonomic disparities may be due to the variance in the definition of a mangrove species. A comprehensive botanical account has been given by Tomlinson (1986). According to him mangrove plants can be put into the true and or minor mangroves or associates. True mangrove plants are characterized by their common ability to grow in aggregation in pure stands (commonly called natural monocultures) and to exclusively thrive along sheltered inter-tidal coastlines on sediments that are alkaline, often anaerobic and sometimes acidic. Many have unique adaptation features such as viviparous propagule, prop roots, pneumatophores and lenticels which contribute in one way or another to their survival in their relatively stressful environment. The minor or mangrove associates can exist in mangrove and non mangrove environments. Based on Tomlinson (1986), there are 52 mangrove species distributed worldwide grouped into 15 families (see Table 2.1). There are further grouped into two major blocks based on their supposed centres of genetic diversity into the eastern block (East Africa, Madagascar, Red Sea, India, South East Asia, Australia and the western pacific) and the western block (West Africa, Atlantic South America, Caribbean, Florida, Central America and Pacific North and South America). There is a great deal of segregation between the eastern and western block mangroves, for instance, *Rhizophora* and *Avicennia*, two primary mangrove genera contain identical species in the western and eastern worlds (Enankou *et al.,* 1997). This suggests independent speciation in each region, though the eastern block has been suggested to be the centre of origin for mangroves. Generalised reports by researchers and the lack of a clear-cut definition of the mangrove ecosystem and its constituents are at the origin of these diverse species publications (Jayatissa *et al.,* 2002).

Table 2.1. Global phytogeographical distribution of mangrove species at intervals of 15° longitude in Western area: West Africa, Atlantic South and North America, Caribbean, Central America, and Pacific South and North America. Eastern Area: East Africa, India, Indochina, the Malay Peninsula and Archipelago, Japan, Philippines, Australia and the Pacific islands (After Tomilison, 1986).

Family	Species	No Spp	Western area									Eastern area											
			W1	W2	W3	W4	W5	W6	W7	W8	W9	E1	E2	E3	E4	E5	E6	E7	E8	E9	E10	E11	E12
Avicenniaceae	*Avicennia alba*	*8*													1	1	1	1	1	1			
Avicenniaceae	*Avicennia bicolor*							1															
Avicenniaceae	*Avicennia eucalyptifolia*																		1	1			
Avicenniaceae	*Avicennia germinans*		1			1	1	1	1	1													
Avicenniaceae	*Avicennia lanata*																1						
Avicenniaceae	*Avicennia marina*												1	1	1	1	1	1	1	1	1	1	
Avicenniaceae	*Avicennia officinalis*														1	1	1	1	1	1			
Avicenniaceae	*Avicennia schaueriana*				1	1	1																
Bombacaceae	*Camptostemon philippensis*	*2*																1	1	1			
Bombacaceae	*Camptostemon schultzii*																		1	1			
Combretaceae	*Laguncularia racemosa*	*3*	1		1	1	1	1	1	1													
Combretaceae	*Lumnitzera littorea*															1	1	1	1	1	1	1	
Combretaceae	*Lumnitzera racemosa*													1	1	1	1	1	1	1			
Euphorbiaceae	*Excoecaria agallocha*	*1*													1	1	1	1	1	1	1	1	1
Lythraceae	*Pemphis acidula*	*1*											1	1	1				1	1			
Meliaceae	*Xylocarpus granatum*	*2*											1	1	1	1	1	1	1	1	1	1	
Meliaceae	*Xylocarpus mekongensis*															1	1	1	1	1		1	
Myrsinaceae	*Aegiceras corniculatum*	*2*													1	1	1	1	1	1			
Myrsinaceae	*Aegiceras floridum*																	1	1				
Myrtaceae	*Osbornia octodonta*	*1*															1	1	1	1			
Palmae	*Nypa fruticans*	*1*														1	1	1	1	1	1		
Pellicieraceae	*Pelliciera rhizophorae*	*1*						1															
Plumbaginaceae	*Aegialitis annulata*	*2*																	1	1			
Plumbaginaceae	*Aegialitis rotundifolia*															1	1						
Rhizophoraceae	*Bruguiera cylindrica*	*19*													1	1	1	1	1	1			
Rhizophoraceae	*Bruguiera exaristata*																		1	1			
Rhizophoraceae	*Bruguiera gymnorrhiza*												1	1	1	1	1	1	1	1	1	1	1
Rhizophoraceae	*Bruguiera hainesii*																1		1	1			
Rhizophoraceae	*Bruguiera parviflora*														1	1	1	1	1	1	1	1	
Rhizophoraceae	*Bruguiera sexangula*														1	1	1	1	1		1		
Rhizophoraceae	*Ceriops decandra*														1	1	1	1	1	1			
Rhizophoraceae	*Ceriops tagal*												1	1	1	1	1	1	1	1	1	1	
Rhizophoraceae	*Kandelia candel*														1	1	1	1					
Rhizophoraceae	*Rhizophona xharrisonii*						1	1															
Rhizophoraceae	*Rhizophora apiculata*														1	1	1	1	1	1	1	1	
Rhizophoraceae	*Rhizophora harrisonii*		1																				
Rhizophoraceae	*Rhizophora mangle*		1		1	1	1	1	1														
Rhizophoraceae	*Rhizophora mucronata*												1	1		1	1	1	1	1	1		
Rhizophoraceae	*Rhizophora racemosa*		1			1	1	1															
Rhizophoraceae	*Rhizophora samoensis*																					1	1
Rhizophoraceae	*Rhizophora stylosa*															1	1	1	1	1	1	1	
Rhizophoraceae	*Rhizophora xlamarckii*																			1	1	1	
Rhizophoraceae	*Rhizophora xselala*																					1	
Rubiaceae	*Scyphiphora hydrophyllacea*	*1*														1	1	1	1	1			
Sonneratiaceae	*Sonneratia apetala*	*5*													1	1	1						
Sonneratiaceae	*Sonneratia caseolaris*														1	1	1	1	1	1	1		
Sonneratiaceae	*Sonneratia griffithii*															1	1						
Sonneratiaceae	*Sonneratia ovata*																1	1	1	1			
Sonneratiaceae	*Sonneratia alba*												1	1	1	1	1	1	1	1	1		
Sterculiaceae	*Heritiera fomes*	*3*														1							
Sterculiaceae	*Heritiera globosa*																	1					
Sterculiaceae	*Heritiera littoralis*												1			1	1	1	1		1	1	1
Total Families	***(15)***		**3**	**0**	**3**	**3**	**3**	**4**	**3**	**2**	**0**	**0**	**6**	**6**	**8**	**11**	**12**	**11**	**13**	**12**	**9**	**6**	**3**
Total species		*52*	**5**	**0**	**3**	**5**	**6**	**7**	**3**	**2**	**0**	**0**	**8**	**8**	**19**	**28**	**31**	**29**	**32**	**31**	**17**	**14**	**4**

Western Area
W1:15°N-15°E (W Africa)
W2:15°N-30° W(Atlantic Ocean)
W3:30°W-45°W(E. Brazil)
W4:45°W-60°W(N.E. Brasil, Gunyana)
W5:60°W-75°W (E. Carribean, N.S America)
W6:75°W- 90°W (Florida, W.Corribean, C.America, Pacific South America)
W7:90°W-105°W (Mexico)
W8:105°W-120°W (Baja California)
W9:120°W-180°E (W.Pacific)

Eastern Area
E1:15°E-30°E (African Continent)
E2:30°E-45°E (E.Africa)
E3:45°E-60E (Madagascar, Redsea)
E4:60°E-75°E (W.India)
E5:75°E-90°E(Ceylon, E.India, Andamans&Nicobars)
E6:90°E-105°E (Burma, Thailand, Cambodia, Malay Peninsula,Sumatra)
E7:105°E-120°E (S. China, Hainan, Vietnam, Borneo, Java, Lesser Sunda Is. W.Australia)
E8:120°E-135°E (Japan, Ryu-keyu Islands, Philippines, Celebes, N.Territories of Australia)
E9:135°E-150°E (Gulf of Carpentaria, N.Queensland, New Guinea, Micronesia)
E10:150°E-165°E (SE Australia, Bismarck Archipelago, Pacific Atolls)
E11:165°E-180°E (New Zealand, New Caledonia, Fiji Islands of the W.C. Pacitic)
E12:180°E-165°W (Samoa)

To avoid this confusion, mangroves should be defined by their ecology rather than by their taxonomy. Of a total of 15 families, containing 52 true mangrove species world wide (Tomlinson, 1986) only the *Pellicieraceae* and *Aviceniniaceae* are comprised exclusively of mangroves. In the popular *Rhizophoraceae,* only four genera live exclusively in mangrove ecosystems (Duke, 1981). If criteria of taxonomic exclusion is still to be considered (Tomlinson, 1986), then the intrigue on defining mangrove species will additionally remain conflicting. The issue of minor and major species should be abandoned, and a mangrove species should simply be "a tree or shrub that has adaptive salinity and flooding exclusion mechanisms and capable of thriving in intertidal zones".

2.2.2.2. Mangrove species in Africa

In Africa, there is some little variation in phytogeographical distribution of mangroves species across the continent. West Africa and Central Africa have four families with six species including: Avicenniaceae (*Avicennia germinans* – referred to as white mangroves); Combretaceae (*Laguncularia racemosa*); Rhizophoraceae (*Rhizophora harrisonii, R. mangle, R. racemosa* – usually called red mangroves); the evasive mangrove fern *Acrostichum aureum* (Pteridaceae) and the exotic palm *Nypa fruticans* origin from SE Asia. *R. racemosa* is very dominant in this region with characteristic long and straight boles in pure stands especially in tidal estuaries. While *R. harrosonii* and *R. mangle* are small trees and shrubs respectively (UNEP, 2007). In Eastern Africa including Madagascar and Red Sea nine species are represented in six families as follows: Avicenniaceae (*Avicennia marina, A. officinalis*); Combretaceae (*Lumnitzera racemosa*); Lythraceae (*Pemphis acidula*); Meliaceae (*Xylocarpus granatum, X. mekongensis*) and Rhizophoraceae (*Bruguiera gymnorrhiza*, *Ceriops tagal*, *Rhizophora mucronata*), Sonneratiaceae (*Sonneratia alba*) and Sterculiaceae (*Heritiera littoralis*) (UNEP, 2003).

2.2.2.3. Mangrove species in Cameroon

Seven true mangrove species are known to exist in Cameroon (Mbog pers com., 2006): Avicenniaceae (*Avicennia germinans*); Combretaceae (*Laguncularia racemosa, Conocarpus erectus*); Rhizophoraceae (*Rhizophora harrisonii, R. mangle, R. racemosa*) with evasive mangrove fern *Acrostichum aureum* (Pteridaceae) and the exotic palm *Nypa fruticans* origin from SE Asia. Mangrove associates include: Annonaceae (*Annona glaba*), Arecaceae (*Coco nucifera, Drepanocarpus lunatus, Elaeis guineensis, Eremospatha wenlandiana, Phoenis reclinata, Raphia palma-pinus*), Caesalpiniaceae (*Guiborutia demensei*), Euphorbiaceae (*Alchornea cordifolia*), Fabaceae (*Dalbergia ecastaphylum*, *Drepanocarpus lunatus*), Loganiaceae (*Athocleista vogeli*), Pandanaceae (*Pandanus candelabrum*), Malvaceae

(*Hibiscus tilaceus*), Poaceae (*Bambusa vulgaus*, *Paspalum vaginatum*), *Sesuvium portulacastrum*, etc. *Rhizophora racemosa* constitutes up to 90% of mangrove stands in the Douala-Edea Reserve (CWCS, 2001; Ajonina and Usongo, 2001; Ajonina and Eyabi, 2002).

2.2.2.4. Characteristics of some red and white mangrove species

The mangroves of West and Central Africa contain a large mix of stands of *Rhizophora racemosa, Rhizophora mangle* and *R. harrisonii* commonly referred to as 'red mangroves' and *Avicennia germinans* 'white mangroves'. Of the three species of *Rhizophora, R. racemosa* often attains a height of up to 60m and 2m in girth especially in tidal estuaries occupying most of the mangrove area, *R. harrisonii* and *R. mangle* are small trees and shrubs. Their leaves are brittle, of deep green colouration, grouped at the apex of banchelets. Red mangrove leaves are simple with a mean variation of 8 – 10 leaves per branchelet. The petiole is 1.5-3cm long. The flower is complete, and made up of 6-9 flowers per inflorescence. The calyx is four lobed, petals are gamopetalous and free and the bractiole is irregularly dented (Plate 6-Figure 2.2). Almost all mangrove species flower annually and abundantly. *Rhizophora* seeds are viviparous (Plate 5-Figure 2.2). These one- seeded berries germinate to a length of up to 30cm now a slender propagule while still hanging on the tree and resumes growth immediately in mud when fallen off the parent plant. Matured propagules vary from 25-50cm. At maturity, the propagules fall directly into the muddy substrate and continue growing. *Rhizophora* and other mangrove species exhibit autochory as an adaptation to their unstable substrate, and when direct implantation fails dispersal becomes hydrochorous but propagating material has limited initial ability to float (Tomlinson, 1986; McGuinnss, 1997). The propagule remains viable provided it remains in contact with the saline environment (FAO, 1994). *R mangle* and *R harrisonii* are typified by olive green fruits with a roughened surface and a hybrid of the two later species respectively (Plate 7-Figure 2.2).

The white mangrove leaves are decussately arranged, with improperly arranged terminal bud scales. The leaves have short petioles (1-3cm), with a deep basal groove. The groove bears black marginal hairs that are continuous in line across the node. The leaf is leathery with inconspicuous veins, and light to dark green in colour. The flowers are pentamerous, perfect and tetramerous to modified pentamerous usually with 5-10 decussately arranged flower pairs in dense spicate to capitate units, all aggregated into terminal axiliary paniculate assemblage on distal shoots.

Plate 1: Undisturbed stands

Plate 2: Edge effects on morphology

Plate 3: Typical mangrove aerial roots roots

Plate 4: Heavily disturbed stands

Plate 5: *Rhizophora racemosa* propagule

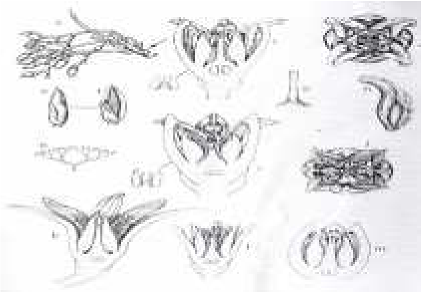


Plate 6: *Rhizophora* spp flora

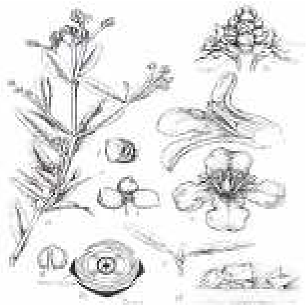


Plate 7: *Avicennia* spp shoot and flowers after Tomilison (1986)

Figure 2.2: Photoplates of bio-ecological characteristics of red and white mangrove species (Photos were taken at the Douala-Edea Reserve, Cameroon by GN Ajonina)

2.3. Regeneration of mangroves

2.3.1. Natural Regeneration

True mangrove stands are mono-specific. Regeneration, coexistence and diversity are only triggered by disturbances (Tomlinson, 1986; Aiba, 1996). Our understanding of long-term disturbances on ecosystems is still limited because of the typical time scale over which ecological processes occur, and the limited time for ecological studies (Weigand *et al*., 1998; Alvaro *et al*., 2004). Mangroves in general have a great capacity to recover from major natural disturbances (Zuleiku *et al*., 2003). Recovery will depend on: forest type, nature, persistence and recurrence of disturbance and availability of propagules (Pool *et al*., 1977; Hamilton and Snedaker, 1984; Field, 1997; Lowenfeld and Klekowski, 1992). A heavily logged mangrove forest is unlikely to regenerate to its original status (Hamilton and Snedaker, 1984; Field, 1997). Disturbances have been important in understanding the succession of mangroves in the Dry Turtugas (Doyle *et al*., 2002). Excessive interaction in the system diminishes soil stability, hardens soil, and favours washing of propagules and saplings by tides hence limiting natural regeneration (FAO, 1994; Kairo *et al*., 2001). Mangrove regeneration is conditioned by the physico-chemical and biological constituents that make up and interact with the system: salinity, geology, and stability of substrate, tidal influence, natural senescence and man operating at a local level (Hamilton and Snedaker, 1984; Tomlinson, 1986; Davidson *et al.,* 1996; Dahdouh-Guebas, 1996). Most authors have ascertained that natural regeneration in mangroves is satisfactory (Hamilton and Snedaker, 1984; Dahdouh-Guebas, 1996; Focho *et al*., 2001; F.A.O, 2002; Kairo *et al*., 2001). But their subsequent growth and development is limited (Field, 1997; Focho, *et al.* 2001). Regeneration and recruitment in mangroves is controlled by gaps in the canopy generated by natural or anthropogenic disturbances (Clarke and Kerrigan, 2000; Zuleiku *et al*., 2003; Clarke, 2004). The chances for successful natural regeneration within mangrove ecosystems usually decrease as the canopy gap size increases (Hamilton and Snedaker, 1984). The *Acrosticum* spp has been reported to limit up to 60% regeneration of *R mangle*, either competing for nutrients and/or acting as a barrier to the free landing of propagules (Hamilton & Snedaker, 1984). Crab predation limit up to 25% of the regeneration of *R mangle* in the Meda Creeks in Kenya (Dahdouh-Guebas, 1996). Crab damage of seedlings has been attributed to lack of normal food supply as a result of human intervention in the ecosystem. Natural regeneration after intensive exploitation is poor and the chances of a floating propagule coming to undisturbed rest, in a minimum time to secure root anchorage in a substrate before the expiration of its vigour is rather remote. However, the existence of submerged slash may facilitate propagule implantation (Hamilton and Snedaker, 1984). Invasion by other tree species like *Bruguiera pavittora, Hibiscus tiliaceus* is a major factor limiting the regeneration of more economic genera like *Rhizophora*.

2.3.2 Artificial Regeneration

According to Hamilton and Snedaker (1984) the search of planting materials for reforestation is a confession of nature's failure to regenerate the area free of charge. Natural regeneration is always sufficient provided the area is not over exploited. A number of mangrove genera (*Avicennia, Rhizophora, Sonneratia)* have a limited ability to spread vegetatively, but this is of no significance. No mangrove species can spread vegetatively by root suckers. No form of agamospermy has been reported for mangroves although the *Nypa* palm, *Acrosticum* spp can spread by rhizome or recumbent stems. *Rhizophora* and other genera do not coppice because they lose the ability to produce reserve meristems at a very early stage.

The initial planting materials were propagules or seedlings collected from the natural forest floor. However, with changing management approaches and concern for mangroves, sources of planting materials have increased to include; wildings, seeds and propagules and nursery seedlings. All of these material of variable ages, obtainable from the natural forest has been very successful in regeneration projects. This technique is interesting because it reduces competition (Hamilton and Snedaker, 1984, Choubhury, 2002). Attempts have been made in nursing mangrove seedlings with variable results. *R mangle* seedlings have been grown in pots and transplanted with survival rates of up to 80%. Despite these advances, acquiring planting material remains difficult and nursery information on different species is scarce. Calderon and Echeverri (1997) have experimented and proposed an air layering technique as an effective means of producing *R mangle* clones for regeneration purposes but this is very expensive. Storage of propagules in polythene bags for up to three days, painting the propagule yellow, or placing them within bamboo fences limits crab predation (FAO, 1994; Streever, 1997).

2.3.3. Growth and Yield of Mangrove Stands

Information on the growth and yield of mangrove stands is scarce (Dahdouh-Guebas-1996; Ajonina and Usongo, 2001; Din and Ngollo, 2003). However, according to Olsen *et al.* (1997), and Clarke (2004) canopy gaps offer better growth conditions for mangroves. Tomlinson (1986) reported that shaded mangrove seedlings remain suppressed with little or no branching, with short internodes. Growth and recruitment of *Rhizophora spp* in green houses is higher than *in situ* (Doyle, 2003). Working in the Meda Creeks in Kenya Kairo *et al*. (2002) observed mangrove stocking rates of 1585 stems ha^{-1} while Ajonina and Usongo

(2001) observed stocking rates of 1,247.5 stems ha^{-1} $42.36m^2$ ha^{-1} basal area and 558.20 m^3 of standing volume ha^{-1} in the Douala-Edea Reserve. Variation in the growth characteristics of trees occurs between ecosystems, habitats and even within species (Akinsanmi, 1976). Variation in growth is due to differences in local responses like sunlight, wind direction, nutrient availability and perturbation (Doyle, 2002). Input nutrients from interacting fauna (e.g.birds) may enhance photosynthesis, water use efficiency and hence growth (Doyle, 2002). Phosphorus (P) and Nitrogen (N) are limiting factors to the growth of *Rhizophora spp*, with N limiting at the seaward margin while P is limiting in the higher inter-tidal zones. With *Kandelia candel* whose N and P uptake is conditioned by saline levels, high N content at low salinities promotes growth and CO_2 assimilation and vice versa (Yuan-Hsun and Shuh-Chun, 2001; Ellison, 2000). Associated fauna can affect individual plant growth rate, population dynamics, community structure and patterns of primary production (Ellison, 1996; Kairo *et al*., 2002; Doyle, 2002). The association of root fouling sponges with the roots of mangrove trees facultatively improve nutrient uptake. In the Suberbans, human intervention in the waterways has drastically reduced mangrove stands yield to $1.12m^3$/ha/yr as a result of increase salinity and increase siltation (Siddiqi, 1997; Ellison.1998). Variation in climatic conditions has led to the identification of growth rings in *R mucronata (*Verheyden *et al*., 2004).

2.4. Mangrove Fauna

Although mangroves may be generally poor in plant species, they contain a very wide spectrum of fauna species (Kjerfe *et al.*, 1997) from insects, crabs, molloscs, amphibians, reptiles, to large mammal species including monkeys. Mangroves serve as a breeding site to marine organisms, water birds and migratory birds (Hong, 1998). According to Tomlinson (1986) there is very little precise information about plant animal interactions in mangroves, apart from pollinators and crabs that destroy seedlings. This limited interaction may be due to the almost exclusive dispersal of fruits and seeds by water. Mosquitoes and midges that abound in this ecosystem make it offensive and almost inhabitable. However, it has been reported that increase in faunal interactions within the system can increase nutrient content, increase productivity, favour pollination, limit seedling recruitment and contribute to the maintenance and establishment of mangrove species zonation patterns (Doyle, 2002). Numerous water birds species abound in the adjacent rivers of the Douala-Edea Reserve; where more than 60 species have been identified (CWCS, 2001). Apart from attempted avifauna surveys in this area, the observed abundance of mosquitoes, information on Itchyo-fauna, insects and macro fauna is very limited in the mangroves of this reserve.

2.5. Importance of Mangroves

The biological, ecological, environmental and socioeconomic uses and importance of mangrove forests have equally been widely documented.

2.5.1. Economic Importance

The economic potentials of mangroves stem from three main sources: forest products, marine products and tourism (Hamilton and Snedaker, 1984). Mangroves host natural resources including timber for construction, fuel wood for cooking, fishing gear, non-timber forest products like tannins, thatching materials for roofing and raw materials for indigenous medicine. As a forest ecosystem, it provides edible products like honey, wax, game, fish, fruits and drinks. Hong (1998) has also reported the use of certain mangrove species as fertilizer in farms and the practice of agriculture inside mangrove areas. However, considering soil pH, salinity levels, mangrove soil is marginal for agriculture (Tomlinson, 1986). This is due to acid sulphate conditions caused by the oxidation of the typical hydrogen sulphide thriving in anaerobic conditions under disturbance to toxic sulphuric acid.

2.5.2. Biological Importance

As breeding sites and/or nursery grounds for fish, 60% of all fish caught in the Gulf of Guinea and Angola breed in the mangrove belts of the Niger Delta (WRM, 2001). Eighty percent (80%) of all marine species, commercial or recreational in Florida, USA, are dependent on mangroves (Hamilton and Snedaker, 1984). In Western Australia, 67% of all commercial sea products are collected in mangrove zones (Hong, 1998). Mangroves serve as feeding ground for both marine and terrestrial organisms, nursery supporting marine fisheries, nesting and resting ground for migratory birds. It is a natural spawning ground for fish and crustaceans, especially for shrimp and prawns.

2.5.3. Ecological Importance

Mangroves stabilise the coastline by preventing erosion, preventing siltation of the coral reefs by trapping sediments, building up land through accumulation of silt and detritus from decomposing leaves, preserving the purity of coastal water, absorbing pollutants, as a wind break to coastal habitations, improvement of local climate and as fodder for animals

2.5.4. Social and cultural Importance

In the Solomon Island and elsewhere, they are considered as sacred sites for the disposal of the death (Vannucci, 1997). Tourists for leisure activities extensively visit mangrove areas worldwide. Apart from the above-mentioned benefits and/or services of mangroves, its true value is only often realised when negative consequences related to mangrove destruction become evident in a short time frame.

2.6. Threats to Mangroves

2.6.1. Natural threats

Natural threats stem from physiological influence of adult mangrove vegetation on young juvenile individuals (on which little has been studied), propagule predation, tree mortality caused by erosion, hyper- salinity, sand intrusion, hurricanes and cyclones and frost damage (Davidson *et al.*, 1996; Doyle, 2002; Zuleiku *et al*., 2003) including the recent tsunamis disaster in SE Asia sweeping thousands of hectares of mangroves destroying lives and properties. Another natural threat to the mangrove ecosystem is the proliferation of invasive species especially Nypa palm (*Nypa fructicans*) in West Africa especially in the Gulf of Guinea. This exotic palm has origin from SE Asia where it was introduced first in Nigeria in 1906 to control erosion but later spread displacing valuable indigenous mangrove species (UNEP, 2007).

2.6.2. Anthropogenic threats

Anthropogenic interference in mangrove areas has caused substantial changes in both physiognomy and species composition within this ecosystem (Dahdouh-Guebas, 2001; Zuleiku *et al*., 2003). Globally, this ecosystem is subjected to increasing anthropogenic stress and to a lesser extent natural stress (Hamilton and Snedaker, 1984). Current threats to this ecosystem stems from the difficulty in placing a monetary value in all mangrove components, lack of ecological knowledge and holistic approach amongst those performing the evaluation and the focus on short term returns rather than long-term ecological returns from the system (Babier *et al*., 1999; WRM, 2001). Mangrove depletion as a result of man may lead to climatic changes. Predicted sea rise as a result of global warming is expected to affect mangroves and cause them to occupy new localities because they cannot tolerate prolong inundation by fresh water or salt water (Kjerfve and Macintosh, 1997; Gopinath and Gabriel, 1997; Dahdouh-Guebas, 2001). Major factors that seriously jeopardise the existence of mangroves worldwide include: human habitation and population expansion; higher short term benefits; lack of appropriate government attention and environmental awareness and education on mangroves, inefficient restoration techniques; pollution from crude oil, sewage and other effluents; timber and fuel wood extraction**.**

2.6.2.1. Human habitation and population expansion

The peculiar location of mangroves has resulted in a highly specialised flora and fauna (James, 2002). People are attracted into coastal areas to exploit marine, petroleum and mangrove resources. This influx has increased pressure on coastal resources, and resulted in deterioration and depletion of mangroves. In Indonesia, 75% of all major cities are located in coastal areas. In Fiji, 80% of all mangrove land has been reclaimed for development purposes. All of these activities act like a gateway for other destructive activities like solid and liquid waste disposal, crudeoil and other hazardous chemicals. In 1978, population increase had decreased the Singapore mangroves area from 73 km^2 to 18km^2 over a 150 year period. About 1,000 ha of mangrove land have been lost to housing and factory purposes (Hamilton and Snedaker, 1984). In Cameroon, more than 30% of the population lives in the coastal zone with major cities like Limbe, Tiko, Douala, Manoka, Kribi and Campo. In the Douala-Edea Reserve, 22 villages with a population size of 5104 inhabitants live and depend on mangrove areas and resources (CWCS, 2001). Mangrove area conversion as a result of human habitation and population expansion has not yet been evaluated in Cameroon. But over the last fifty years, over 33% of the Cameroon mangroves have been lost.

2.6.2.2. Higher short term benefits

The major threat to mangroves in the world has been the Southeast Asia and South America conversion of mangrove land for aquaculture (WRM, 2001). Conversion of mangrove land for fish and prawns production succeeded in fetching higher monetary gains over a short period and led to the conversion of mangroves to fish ponds, salt beds and rice fields (Akoeginou *et al.*, 1997; Choudhury, 2002). This conversion has been facilitated by multinationals like the World Bank, and Asian Development Bank, which have sponsored this activity to the tune of 82 million dollars between 1997-2000 in Latin America (Rodriguez, 2001). The poor management planning of these ponds (Stevenson and Burbridge, 1997) always result in their abandonment in the short run, forming waste piles and polluting stores to surrounding areas and a potential danger to coastal aquifers and agricultural land. They result in decreased plankton levels with a corresponding increase in *Oscillatoria spp*, algae with poisonous residue, which is a source of fowl smell (Hong, 1998; WRM, 2001). Diseases like *Monodon Baculovirus*, *Yellow head baculovirus* and the white spot diseases of prawns have been observed in many abandoned ponds in the Philippines (Stevenson and Burbridge, 1997; Seanger *et al*., 1997). Ponds and salt bed creation within mangroves have been reported in Africa (Akoegninou *et al*., 1997; Akpagana, 1997; Rasolofoharinoro *et al*., 1997; WRM, 2004). No such activity has been reported in Cameroon. Conversion of mangrove land for subsistence agriculture has been observed in the south west of Cameroon (Tiko-Moliwe Mabeta creeks) (Focho *et al*., 2001). Large-scale conversion by the Cameroon Development Cooperation has been observed in the Modeka creeks of the same region.

2.6.2.3. Lack of government attention and public awareness on mangroves

Mangrove management options are often money oriented, consisting in simple conversion and hence transformation of the ecosystem (Choubhury, 2002; WRM, 2001). Most mangrove areas are given little or no managerial attention at all by governments. For example, in the 18th century, the Sunderbans in Bangladesh was twice its present size. Most of it was lost for agricultural purposes (Chowbury and Ahmed, 1994). Lack of government concern and effective management policies have resulted in the loss of 50% of mangrove areas worldwide over the last decades (Rodriguez, 2001). In the Philippines for instance, and most other countries, policy prohibits the cutting of mangroves, however, this is just “paper pack” because cutting and conversion of the ecosystem still continues (Olsen *et al.*, 1997; Saenger *et al.*; 1997, Kairo *et al*., 2002). Most countries are still experimenting over effective mangrove management designs (Choubhury, 2002). In Africa most mangrove stands especially in Nigeria, Benin, Togo, and Congo Democratic are engulfed within terrestrial forest management (Akpagana, 1997; Akoeginou, 1997; Ajao and Dore 1997; Kipalu and Lukamba, pers-com, 2004) rather than giving it a special attention. In Cameroon, the 1994 forestry law gives no attention to mangroves while the 1995 National Forestry Action Program document just states the mangrove surface area and extent and gives an action plan for it. Also local people do not know and understand the virtues of mangrove ecosystems. Mangroves in Cameroon, like the communal forest suffers the fate of open access i.e. each user exploits the forest to the fullest under no control, and nobody accepting responsibility for the depletion. This coupled with the non-custodianship and migratory habit of those mostly exploiting the resource (Nigerians, Beninois and Ghanaians) result to resource depletion. This inevitably leads to the “Tragedy of the commons” a situation favoured by the lack of institutional organisation by the government. A similar situation reigns in most African countries.

2.6.2.4. Inefficient restoration techniques

Most countries are still getting to understand the complexity of mangrove ecosystems. Most often, local NGOs initiate reforestation programs without prior knowledge of the forces that extinguished nature's efforts in such areas (Hamilton and Snedaker, 1984; Lewis, 2005). Most mangrove seeds and/or propagules are short lived. Agamospermy is insignificant and knowledge on nursery development is scanty (Tomlinson, 1986; Calderon and Echverri, 1997). Most species do not coppice making regeneration from stumps impossible.

2.6.2.5 Pollution from crude oil, sewage and other effluents

The oil industry is a very important factor of mangrove destruction worldwide. It has destroyed mangrove ecosystems and displaced local communities in Nigeria (WRM, 1999). From 1970 to 1982, one thousand five hundred and eighty one oil spills occurred in the Niger delta spilling up to 2 million barrels of oil (Saenger *et al.*, 1997). Spilled oil, industrial and domestic sewage has been reported to kill sea birds and other animals in Vietnam (Hong *et al*. 1998). According to Lamperelli *et al*. (1997) oil spills can be very dangerous on mangrove dynamics, having acute, chronic and immediate effects with a resident time of up to ten years. Extensive use of nutritive additives in fishponds and use of herbicides is deleterious. Application of herbicides by the US army during the Vietnam War depleted 104123 ha of mangroves and may have resulted in the extinction of some fauna and flora species in the area (Hong, 2001). In Cameroon, potentials for mangrove pollution in Mudeka along the Tiko Douala road from the Cameroon Development Corporation (CDC) effluents are high. According to Chuyong *et al*. (2000) petroleum exploration in the Douala-Edea Reserve seriously threatens the mangrove biodiversity in the area. Industrial effluents from Douala seriously threaten the biodiversity of the Rio-del-Rey mangroves in Cameroon.

2.6.2.6. Timber and Fuel wood extraction

About 30% of the earth's surface is covered by forest (World bank, 1994) with about 140 million people directly dependent on it for their livelihood worldwide, depleting it at a rate of 1% per annum in search of food, fuel wood and jobs (World Bank, 1994). As forests disappear, women and children work harder to gather fuel wood, flooding is perpetuated, soil erosion, loss of genetic material, habitat destruction and change of climate. Wood is extensively harvested from mangrove stands for construction, pulpwood, charcoal and fuel wood for energy generation (Choubhury, 2002; Choudhury *et al*., 1994; Ajonina and Usongo, 2001). In East Africa, extensive areas of mangrove forest have been indiscriminately felled and extensive mangrove stand exploitation has resulted in ecological disaster with clear-cut areas in Gazi bay and Ngomeni (Kenya) and in Tanzania (Kairo *et al*., 2002). Cutting of mangrove wood for charcoal, fuel wood and construction is probably the second and most pervasive intrusion on the mangrove resource (Olsen *et al*., 1997). In Cameroon current mangrove cutting rates in the DEWR is unsustainable and is depleting the resource (Ajonina and Usongo, 2001). Fuel wood particularly for energy generation is of particular interest to developing countries where it is used for cooking, fish smoking, dehydration of salt beds, etc (Phillips, 1994; Ajonina and Usongo, 2001). The importance of mangroves as an adequate source of fuel wood is recognised particularly the *Rhizophora* (Duke, 1981; Focho, 1996;

Focho *et al*., 2001) however its recognised virtues have been classified only by few. In Bangladesh Siddiqi (1997) says *Cynometra ramiflora* is high quality fuel wood. In Cameroon, *Rhizophora racemosa* is first class fuel wood (Focho, 1996; Focho *et al.*, 2001). Suitability of wood as fuel wood is a function of dimension, absence of thorns, and ease of splitting, calorific value availability and cost (Babajide, 1984; Phillips, 1994). Mangrove wood extraction for heating of salt beds, charcoal and fish smoking formation have been reported in Benin, Togo, Congo Democratic, Philippines, Bangladesh, Thailand, Cameroon (Focho, 1996; Akpagana, 1997; Akoeginou *et al*., 1997; Ajonina and Usongo, 2001; Focho *et al*., 2001; Kipalu and Lukamba, pers-com, 2004). In the DEWR, the fish smokers depend almost entirely on mangroves for fuel wood.

2.7. Sustainable Management of Mangrove Ecosystems

Given the importance and current level of threats on the mangrove ecosystems and to meet increasing human needs for mangrove services and products very much limited by the fragile nature of the mangrove ecosystem and limited opportunities for regeneration, there is a dire demand worldwide to carry out sustainable utilization of this important but fragile ecosystem in a way that meets the needs for its present and future demands for its products and services. Efforts have been made in mangrove countries in this regard through enacting specific mangrove policies, creating mangrove protected areas, putting in place mangrove site management plans, undertaking restoration schemes, adopting efficient use of fuel wood involving the local communities and the use of models to regulate harvests.

2.7.1. Mangrove policies

Because of the economic values and the ecological functions of wetlands, a lot of concern has been directed towards the sustainability of wetlands including mangroves in order that communities can continue to benefit from their services and functions. The Ramsar Convention on Wetlands is the most important international regulatory instrument, being the first global, inter-governmental treaty that specifically deals with the wetland ecosystems including mangroves and provides the framework for cooperation in the conservation, sustainable management and wise-use of wetlands (Frazier, 1996).

Many countries are yet to have specific mangrove management policies. They tend to be locked up in general environmental, coastal area management, wetland and forest policies and legislations without any specific directions on mangroves. In Africa, institutional coordination for the implementation of mangrove conservation programmes are weak resulting in conflicts in cross-cutting issues as mangrove conservation where several ministries may be involved.

Most of these policies emphasize the need for the participation of local communities in the management of the natural resources of which they are custodians. Even such policies exist the level of implementation in the field leaves much to be desired as there is acute paucity of scientific information on the mangrove ecosystem for any meaningful and effective operationalisation of concepts on ground. This is particularly true for Africa where in addition to the paucity of scientific information, policy, legal and institutional frameworks are weak. Even such information is largely available through modern technological frameworks as the internet, we still lack the required communication skill and capacity to adequately access and use it.

2.7.2. Gazettement of mangrove protected areas

There are 685 protected mangrove forest protected areas in 73 countries and territories (Spalding 1997). However, creation of reserves is no guarantee for protection if a management plan and suitable control mechanism put in place to monitor the use of resources. This is lacking in Africa to very limited number of mangrove protected areas. There is the evolving concept of Marine Protected Areas (Anon, 2003) where mangrove areas form an integral component and are managed in perpetuity with local communities to conserve fisheries nursery areas and increase fisheries stock. Though the concept is still new, the proposed Douala-Edea National Park in Cameroon is expected to include this component.

2.7.3. Mangrove site management plans

In a bid to achieve sustainable utilisation of mangrove forests, few countries have put in place management plans with well defined cutting or rotation cycle based on sustained yield concept.

Among these few mangrove forests are Malaysia, Thailand, Philippines and Pakistan where mangroves are managed mainly for wood products (poles, pulp, logs, and chips, charcoal and fuel-wood). Malaysia has one of the best managed mangrove stands world wide, with a rotation cycle of 40 years for concessions, relics of seven seed trees/ha sometimes supplemented by artificial planting. In Thailand, the rotation period is 30 years and minimum cutting diameter at breast height (d.bh) of 10 cm, leaving 190-250 seed trees /ha. The largest single chunk of productive forest (mangrove) worldwide is found here. In the Philippines, the major activity is tapping and extraction of *Nypa* palm juice with an annual production of up to 18000 litres/ha. Indonesia with 4.25 million ha of mangroves, has the largest mangrove area in the world. Here mangrove concessions have been leased out to concessionaires, on grounds that they reforest after felling. In Pakistan, levels have been set at a maximum of $14m^3$/ha extraction/year for any form of mangrove exploitation (Hamilton and Snedaker, 1984).

Combining afforestation to the concept of sustainable management has gained grounds within mangrove ecosystems (Choudhury, 1996).

In Africa, Tanzania appears to be the only country with a well defined mangrove management plan. The plan divides its 115 475 ha mangroves covering its 800km coastline into 10 blocks with each divided into four zones: total protection forest; production forests, ecologically stable areas with sufficient regeneration potential to permit controlled harvesting on a sustained basis by cutting poles and fuel wood every 10 years; recovery and rehabilitation forests, degraded areas closed from cutting for periods varying lengths to allow regenerate unaided from 3-25years; and development zones for controlled development of aqua cultural ponds and other human activities (MTNR,1991). The major problems associated with such plans especially in Africa is the lack of operational mechanisms for monitoring management implementation and complete local participation in all the phases of elaboration to the implementation of the management plan.

2.7.4. Restoration and rehabilitation of mangrove ecosystems

The terms "restoration" and "rehabilitation" are often used interchangeably in conservation literature. Dent (1986), Sincrope (1990), Barret (1993), Peck *et al.* (1994), Thompson and Luthin (2004) consider ecological restoration as the intentional alteration of a site to establish the approximate biological, geological and physical conditions that existed in the pre-disturbance indigenous ecosystem or habitat. Generally, restoration projects attempt the re-establishment of all the pre-disturbance characteristics of a site, including plant and animal species and a variety of community attributes such as structure, function, and habitat values. Restoration embraces a much broader activities including conservation, rehabilitation, reestablishment, enhancement, and the maintenance of functioning of wetland ecosystem.

Mangrove restoration is an excellent initiative to reinstate degraded areas (Streever, 1997) Successful restoration requires thoughtful investigation of the cause of degradation, including effective nutrient level studies, the elimination of stress factors and the identification of sources of planting materials (Hamilton and Snedaker, 1984; Field, 1997; Lewis, 2005). Tidal and wave energy as well as biotic factors affecting seeds and /or propagules, spacing and thinning of mangroves (FAO, 1994) weed eradication and community participation in the process need to be assessed (FAO, 1994; Choudhury, 2002). Mangrove planting site cannot be created, but only precede clear-cut or degraded areas. Information on degraded mangrove sites is lacking (Field, 1997).

The first restoration projects in Africa probably took place after the First World War in Kenya (1914-1918) (Kairo *et al*., 2001). Mangrove plantations are easy to establish, as no special site preparation is required (FAO, 1994), and failure of multiple attempts worldwide has been due to lack of feasibility studies prior to project initiation (Hamilton and Snedaker, 1984). Mangrove plantations have been very instrumental as a tool in the conservation of this ecosystem. Some 1957 km^2 of plantation mainly in Bangladesh, Philippines, Vietnam, Pakistan, Cuba (Spalding, 1997; Olsen *et al*., 1997) and other countries around the world have successfully been established.

2.7.5. Fuel wood use efficiency

Fishing and fish smoking is a major activity along the Gulf of Guinea. The main forms of preservation being, open drying, dry salting, salting, icing, refrigeration and smoking (Nyagambi, 1988; Labarriere *et al*., 1988; Eyabi, 1996). The most important method of fish preservation is fish smoking. This reduces post harvest losses, complementing the time lapse from the point of catch to the fishing port, coupled with the absence of access roads to fishing villages (Oladosu *et al*. 1996; Akande *et al*., 1996; Abalagba *et al*., 1996). The ever-increasing fuel wood demand for fish smoking has resulted in observed mangrove forest degradation (Ajonina and Usongo, 2001, Ajonina *et al*., 2005). Open cooking systems have poor fuel wood efficiency and are sources of disease and suffering particularly for women and children. Some 400-700 million women and children in developing countries breathe harmful fumes because of open cooking systems from wood/charcoal (World Bank, 1994). Exposures to high levels of pollution from such sources have been estimated to be responsible for infections of the respiratory system with diseases like bronchitis, tuberculosis, still births, etc, one of the major causes of morbidity and mortality in the world (Smith *et al*., 2000). Meeting up with energy requirements for fish smoking, improving working conditions of fish smokers and conservation of forest has been a major concern for many workers along the Gulf of Guinea (Zinsou, 1986; Akoeginou, 1997; Zannou *et al.,* 1988; Stroud, 1998; Ikeme, 1988; Motta, 1988; Ajonina and Eyabi, 2002). Many workers have carried out comparative studies of traditional smoke houses with improved smoke houses and demonstrated the relative efficiencies of improved smoke houses over the traditional ones (Zinsou, 1986; Zannou *et al*., 1998; Stroud, 1998; Labazziere *et al*., 1988). While in other countries improvement on fishing kilns is on kiln form, size and manipulation procedures in order to reduce smoking time and improve turn over rates, in Cameroon, improvements in some areas of the Douala-Edea under the auspices of CWCS project is mainly focused on closing the base of the open smoking plate from the locally called “Banda” to concentrate heat energy to more than 45% (Feka, 2005).

2.7.6. Community involvement in mangrove management

In all the above initiatives, there is the evolving concept of collaborative management of natural resources (FAO, 1999) in which the local communities are supposed to play a greater role in all the phases of the project as they are custodians of these resources. This is especially true for the general maintenance of ecological stability in areas outside protected forests. Still a new concept, the operational mechanisms and frameworks for the implementation of the concept are still lacking. However there is growing hope that this approach is more sustainable.

2.7.7. Use of models

Models have been widely used to enhance management of forest ecosystems. Though definitions of models vary from author to author, they can be described as simplified representations of the real world situations. They are useful for the purpose of thinking, forecasting and making decisions (Buongiorno and Gilles, 1987). According to Muetzelfeldt and Sinclair (1993), they also function in describing a system (descriptive models), generating management recommendations (prescriptive models), and predicting system behaviour and the consequences of management actions (predictive models).

Model development and application has witnessed a steady evolutionary trend in ecology and forestry especially in the area of forest growth and yield studies. This trend is obvious from graphical illustrations used to describe stand parameters such as top height, basal area, mean diameter, and volume; to mathematical descriptions of growth processes including matrix models in population dynamics and the use in recent years of regression analysis, multivariate analysis and other statistical tools accelerated by the advent of computers. This has considerably increased the level of sophistication in modeling enabling the manipulation and use of large number of variables (Okojie, 1981a; Adegbehin, 1985; Jeffers, 1990). Some of the modelling approaches will be briefly reviewed.

2.7.7.1. General and historical overview

The greater part of the empirical information available on forests and forests resources, about a century ago, were obtained by mere visual assessment. In the early 20s and 30s, systematic forestry data were summarised in form of graphs and tables and then used for predicting future trends of development in some forests stand (Paille and Smith, 1970).

The introduction of regression analysis in 1930 led to rapid developments in the field of growth and yield modelling. The scope of modelling in forestry was further broadened with the introduction of fast electronic computers enabling the use of complex mathematical equations which accommodate a large number of variables (Omiyale, 1989; Jeffers, 1990).

Accumulation of information on tree and stand growth was followed by the creation of simulation and growth models. These models were aimed at simulating the long term effect of management options, cultural treatments and yield predictions. A number of simulating models were devised to analyse forest sampling (Grevatt and Wardle, 1967), harvest and designs of logging equipment (Newham, 1968), pest and fire control (Watt, 1963), forest fuels and complete management of small forest properties for timber production (Bare, 1970; Pelz, 1977).

Apart from simulation modelling, other modelling approaches often adopted to measure the response of tree and stands to various treatment include:

(i) volume/yield table method and development of allometry biomass equations;
(ii) differential/difference equation method;
(iii) statistical distribution models and ;
(iv) Matrix models (Okojie, 1981a; Adegbehin, 1985; Osho, 1988).

A brief review of the various modelling approaches in forestry will be carried out. The section ends with current techniques used in modelling the dynamics of uneven-aged forest stands.

2.7.7.2. Volume/Yield Table Approach and development of allometric biomass equations

a) Volume/Yield Table Approach

Foresters in the 18th and 19th centuries assembled their data in the form of tables which were based on graphically produced relationship between the crop characteristics (Omiyale and Joyce, 1982). Two types were prominent: Volume and yield tables.

A volume table according to Hush *et al.* (2003) is a tabular presentation of the volume of a tree of some specified dimensions. Depending on the number of independent variables and area covered, volume table could be divided into three types: local volume tables (only Dbh), standard volume table (Dbh, Merchantable or total height) and form class volume tables (Dbh, merchantable or total height and some measure of form included).

The introduction of regression analysis and advent of computers have made possible the establishment of various objective relationship (Volume equations) between tree volume and other measured parameters such as height, tree diameter at breast height (Dbh) or basal area (BA) from which such tables can be constructed. Multiple regression procedures (usually stepwise) is often used to select the best combination of independent variables from a series of equations which may take the following forms:

(i) Simple linear regression model

$V = b_0 + b_1D^2$ ....(2-1)

$V = b_0 + b_1D^2H$ ....(2-2)

(ii) Multiple linear regression model

$V = b_0 + b_1D^2{}_+b_2H$ ....(2-3)

$V = b_0 + b_1D^2{}_+b_2D^2H$ ....(2-4)

$V = b_0 + b_1D^2H_+b_2H$ ....(2-5)

(iii) Quadratic model

$V = b_0 + b_1D_+b_2D^2$ ....(2-6)

(iv) Logarithmic transformed model

$LogV = b_0 + b_1\ logD$ ....(2-7)

$logV = b_0 + b_1logD + b_2logH$ ....(2-8)

(v) Weighted (by D^2 and D^2H) model

$V/D^2 = b_0 + b_1\ 1/D^2 + b_2H$ ....(2-9)

$V/D^2\ H = b_0 + b_1\ 1/D^2\ H + b_2\ 1/H$ ....(2-10)

Where in all cases,

V = volume (in cubic metres)

D = diameter at breast height (in metres)

H = tree height (in metres)

b_0, b_1 and b_2 are regression constants and coefficients respectively.

The best equations are often selected based on high coefficient of determination, R^2; low residual standard deviation, SD; significant F-ratio; and low Furnival index (Furnival, 1961), FI.

Where $FI = \text{antilog}\ [(\sum logY)/n]*RMSE$.

Abayomi (1983) found weighted (by D^2) model appropriate for volume table construction for *Nauclea diderrichii* in Omo Forest Reserve in Nigeria while logarithmic transformed model was suitable as stand volume tables for *Gmelina arborea* plantations in Omo and Awi Forest Reserves in Nigeria (Okojie, 1980). Elsewhere Volume tables have been constructed for different species (Salih *et al.*, 1989; Pohjonen, 1991; Latif *et al.*, 1995).

One major limitation of volume equation is that there are site specific with non universal application.

Yield tables on the other hand, (also similar to volume table in construction) are tabular presentations of volume of wood per unit area of land and other characteristics of even-aged stands by age classes, site classes, species, and stand density. Yield tables for even-aged stands are of several types depending on the independent variables used (Husch *et al.*, 2003):

(i) normal yield table which uses only two independent variables usually stand age and site index with the variable, stand density held constant by selecting sample plots of same density and site judged to be fully stocked;

(ii) empirical yield table, uses sample plots of average density than full stocking;

(iii) variable density yield tables which provide yield for various levels of stocking or densities for each age and site combinations. For unevenaged stands, yields to a rotation age are replaced by periodic yields over some specified time intervals.

According to Peng (2000), most yield table methodologies were first developed in Europe in the 1920s and later in North America in 1950s. Attention also has been drawn to the limited usefullness of yield tables in comparing silvi-cultural alternatives since the methodologies were only intended to describe undisturbed development of natural stands (Osho, 1988).

b) Development of allometric biomass equations

There is an increasing need in recent times to improve the accuracy of total biomass quantities for several reasons (Brown, 1997; Husch *et al.*, 2003 citing others):

- Multiple uses of forests. Forests have traditionally been used for many products, including timber, fuel, and fodder. Determining the biomass of forests is a useful way of providing estimates of the quantity of these components. Assessing the total aboveground biomass of forests, defined as biomass density when expressed as dry weight per unit area, is a useful way of quantifying the amount of resource available for all traditional uses. It either gives the quantity of total biomass directly or the quantity by each component (e.g., leaves, branches, and bole) because their biomass tends to vary systematically with the total biomass.
- Assessment of changes in structural and functional attributes of forests. The quantity of biomass in a forest is a result of the difference between production through photosynthesis and consumption by respiration and harvest processes. Thus it is a useful measure for assessing changes in forest structure. Changes in forest biomass density are brought about by natural succession; human activities such as silviculture, harvesting, and degradation;

and natural impacts by wildfire and climate change. Biomass density is also a useful variable for comparing structural and functional attributes of forest ecosystems across a wide range of environmental conditions.

- Relevance to climate change and other global change issues. Biomass of forests is also very relevant for issues related to global change. For example, the role of tropical forests in global biogeochemical cycles, especially the carbon cycle and its relation to the greenhouse effect, has heightened interest in estimating the biomass density of tropical forests. The biomass of forests provides estimates of the carbon pools in forest vegetation because about 50% of it is carbon. Consequently, biomass represents the potential amount of carbon that can be added to the atmosphere as carbon dioxide when the forest is cleared and/or burned. Attempts to estimate the biomass density of tropical forests have been made by the scientific community for use in models that assess the contribution of tropical deforestation and biomass burning to the increase in atmospheric carbon dioxide and other trace gases. Biomass density estimates also provide the means for calculating the amount of carbon dioxide that can be removed from the atmosphere by re-growing forests or by plantations because they establish the rates of biomass production and the upper bounds for carbon sequestering. This issue is receiving more attention of late as countries look to forests as a means of mitigating greenhouse gas emissions, particularly carbon dioxide, a major greenhouse gas and the one fixed during photosynthesis. Practices such as sustainable forest management, slowing deforestation, and low-impact-logging decrease emissions or conserve carbon dioxide. Other practices such as plantation establishment or other tree planting programs on previously non-forested land sequester carbon dioxide.
- For studying other global geochemical cycles. Furthermore, biomass density estimates of forests are extremely relevant for studying other global biogeochemical cycles, such as nitrogen, because the amount of other nutrient elements in forests is also related to the quantity of biomass present.

i) Methods of estimating biomass of forests

Over the years, forest ecologists have developed various methods for estimating the biomass of forests. Komiyama *et al.* (2008) classified these methods into three main types: the harvest method, the mean-tree method, and the allometric method. These methods have their merits and demerits. The harvest method appears to be difficult in mature forest where total weight of an individual tree often reaches several tons. Moreover, it is not reproducible because all trees must be destructively harvested. The mean tree method is utilised only in forests with a homogenous tree size distribution, such as even-aged stands including plantations. The allometric method estimates the whole or partial weight of a tree from measurable tree dimensions including trunk diameter and height, using allometric equations. Allometry makes use of the fact that there is proportionality between the relative growths of two different parts of the plant. Therefore for example, the tree trunk is highly correlated with trunk weight. A regression equation can be derived for predicting tree weight from a range of tree sizes (diameter) very easy to measure to estimate the very difficult to measure parameter tree biomass. This is a non destructive method and is thus useful for estimating temporal changes in forest biomass by means of subsequent measurements. However, the site- and species-specific dependencies of allometric equations pose a problem to researchers because tree weight measurement especially in mangrove forests is labour intensive. Based on studies of forest biomass using the allometric method and other characters, Kira and Shidei (1967) summarised the so-called "summation method" for estimating the net primary production (NPP) of forests. In this method, the rates of growth increment, death and consumption by herbivores are summed to obtain the NPP. The gross primary production (GPP) of forests can then be calculated by adding the rate of metabolic respiration to NPP.

ii. Estimating biomass from existing forest inventory data

The most economic approach for estimating above-ground forest biomass is to use data from forest inventories. Brown (1997) noted that the use of forest inventory data overcomes many of the problems present in ecological studies especially sample size and coverage limitations. Data from forest inventories are generally more abundant and are collected from large sample areas (sub-national to national level) using a planned sampling method designed to represent the population of interest. However, inventories are not without their problems:

- Inventories tend to be conducted in forests that are viewed as having commercial value, i.e., closed forests, with little regard to the open, drier forests or woodlands upon which so many people depend for non-industrial timber.
- The minimum diameter of trees included in inventories is often greater than 10 cm and sometimes as large as 50 cm; this excludes smaller trees which can account for a large proportion of the biomass.
- The maximum diameter class in stand tables largely lumps the very large trees in a single class. The actual diameter distribution of these large trees significantly affects aboveground biomass density.
- Frequently, only commercial tree species are included in the inventory volume.
- The definition of inventoried volume is not always consistent.

Despite the above problems, many inventories are very useful for estimating biomass density of forests. To use inventory volume data to estimate above-ground biomass density (defined as above ground biomass in trees per unit area) it is necessary to take into consideration a reduction factor for rot and an expansion factor, biomass expansion factor (BEF) to account for the additional components of trees, such as branches, twigs, bark, stumps, foliage and seedlings and saplings (Husch *et al.*, 2003). Brown (1997) also demonstrated how the volume expansion factors (VEF) for integration into the biomass density estimation can be derived to unify inventory volumes taking at different diameter limits to a base diameter limit of 10cm.

iii. Progress of studies on mangrove allometry

Komiyama *et al.* (2008) noted that allometric equations for mangroves have been developed for several decades to estimate biomass and subsequent growth. Most studies have used allometric equations for single-stemmed trees (e.g. Smith and Whelan, 2006), but mangrove also have multi-stemmed tree forms as often seen in *Rhizophor*a and *Avicennia*. Clough *et al.* (1997) showed that the allometric relationships can be used for trunks in a multi-stemmed tree while Ross *et al.* (2001) developed them for dwart mangrove trees. On an extensive review, Saenger (2002) cited 43 allometric equations on above-ground biomass and found that species –specific trait of allometry is significantly different among mangrove tree species. However, as Komiyama *et al.* (2008) pointed out, the question of whether the allometry of a particular mangrove species is site specific remains contentious. Clough *et al.* (1997) found different relationships in different sites, although Ong *et al.* (2004) reported similar equations applied to two different sites for *Rhizophora apiculata*. This issue is important for practical uses of allometric equations. If the equations are segregated by species and site, then different equations have to be determined for each site. On both species- and site- specific issues of allometry, Chave *et al.* (2005) and Komiyama *et al.* (2005) proposed the use of common allometric equation for mangroves. Komiyam *et al.* (2005) proposed common allometric equations based on pipe model (Shinozaki *et al*., 1964) and the static model of plant form (Oohata and Shinozaki, 1979). These models predict that the partial weight of the trunk at a certain height physically sustains the weight of the upper tree body, regardless of tree species and locality. By using the two theories, Komiyama *et al.* (2005) derived equations with trunk diameter and woody density as parameters and found good fits with 104 sample trees comprising 10 mangrove species from Thailand and Indonesia. The common equation of Chave *et al.* (2005) was established based on statistical analysis but never-the-less consisted of same two parameters used by Komiyama *et al.* (2005). Komiyama *et al.* (2008) further compared the common equations they developed with many other site specific equations developed across several sites in America, Australia and SE Asia and found them to estimate the above –ground weight within 10% relative error compared to the use of site-specific equations. Komiyama *et al.* (2008) then concluded that, this would imply that the allometric relationship of mangrove species does not differ greatly among sites for the same species, suggesting that woody density may be an important determinant. Thus, the allometric equation of mangrove species is considered to be highly species-specific but less site-specific. For total understanding of forest biomass, the allometric equations for root weight are essential. Unfortunately as Komiyam *et al.* (2008) further noted, only a few equations are available because complete extraction of roots from mangrove soils is a difficult and tedious process. Nevertheless, they also included root biomass from a few equations in their generic biomass equations though further studies on the allometric relationship of mangrove roots are still needed due to paucity of study cases as well as the difference in root extraction methods.

2.7.7.3. Differential / Difference Equation (Dynamic) Model Approach

In this approach, a system of equations is used to express the levels of state variables in terms of rate of change controlled by decision functions. The level equations represent accumulations within the system such as weight and numbers of organisms and the rate equations govern the change of levels with time. The decision functions represent the policies or rules explicitly or implicitly assumed to control the operation of the system (Jeffers, 1990).
In forestry, differential equations have been used to describe growth behaviour of forest stands since early 1950s. Using this approach, growth is used to describe the size attained by

the examined element (e.g. diameter increment of tree) within a defined period of time. The increment which refers to the increase in size of the element within a specified time interval can be represented in differential equation form with subsequent solution to obtain yield equation. That is a yield model can readily be obtained from a growth model (Clutter, 1963) by summation of the predicted growth through the appropriate growth periods or more precisely, when the algebric form of the yield model can be derived by mathematical integration of the growth model.

Generally the following best known deterministic growth models have been identified (Osho, 1988; Zeide, 1990):

(i) Von Bertalanffy's growth model

$dy\ (t) / dt = nY^{m} - KY$ ....(2-11)

where n and k are constant of proportionality with the value of m restricted to 2/3:

$dY\ (t) / dt = nY^{2/3} - KY$ ....(2-12)

$\Rightarrow Y\ (t) = A[1 - Be^{-kt}]^{\frac{1}{1-\frac{2}{3}}}$ ....(2-13)

(ii) Monomolecular function (Mitscherlich model)

$dY\ (t) / dt = k(A-Y)$ ....(2-14)

$\Rightarrow Y\ (t) = A(1 - Be^{-kt})$ ....(2-15)

(iii) Logistic growth function (Verhust-Pearl Model)

$dY\ (t) / dt = \frac{KY(A-Y)}{A}$ ....(2-16)

$\Rightarrow Y\ (t) = \frac{A}{(1 + Be^{-kt})}$ ....(2-17)

(iv) Gompertz function

$dY\ (t) / dt = KY\log\ (A/Y)$ ....(2-18)

$\Rightarrow Y(t) = Ae^{-Be^{-kt}}$ ....(2-19)

Where in all cases

Y(t) = size of dependable variable (e.g. diameter, basal area, tree or stand volume) evaluated at time t.

A = maximum possible value of Y(t)

B = initial value of Y(t)

K = rate constant which defines the spread of the curve along the time axis.

The structure of the growth equations reflects the process of growth, which includes a number of opposing components. The basic components are intrinsic tendency towards unlimited increase (biotic potential) and its opposing environmental resistance. The expansion tendency prevails in the beginning of a tree’s life, while growth decline becomes prominent towards the end. Zeide (1990) further observed that the common feature of all growth equations is that they contain two basic terms or groups of terms which express opposing components. Usually the positive components are connected by substraction or division. The differences in structure of the equations result from the differences in forms, predictions and combinations of terms, as well as in the number of opposing components.

The Von Bertalanffy’s model was developed based on the hypothesis that the rate of growth of an organism represents the difference between the anabolic rate (constructive metabolism) and catabolic rate (distributive metabolism). Richard (1959) and Chapman (1961) have adapted Von Bertalanffy’s model for plant growth and fish growth studies respectively. The generalised growth function termed Chapman – Richard growth model is similar to the original model except that the value of the allometric constant (2/3) found to be too restrictive, was subjected to an undefined m-value.

Many workers have used this generalised form of Chapman-Richard equation is varying degrees in growth studies of forest stands. For instance, Moser and Hall (1969) for uneven-aged stands in parts of Wisconsin (USA); Piennar and Turnbull (1973) to model basal area growth and yield in even-aged pure stands of spruce (*Picea abies*) and slash pine (*Pinus elliottii*) ; Bada (1984) used the modified version to study the growth patterns of an untreated natural forest in Usonigbe is South-Western Nigeria.

Nokoe (1974) has observed that the modified Gompertz growth function was one of the best non-linear growth models for Volume-age description in selected coniferous stands. Nokoe (1978) also demonstrated the flexibility of the Gompertz growth function as a yield model using data on Western cedar (*Thuja plicata*) lodge pole pine (*Pinus contorta*) and Douglas fur (*Pseudotsuga menziesii*) for parts of British Columbia (Canada). Volume production by the three species was compared using the modified Gompertz function expressed as:

$V = ae^{-e^{-c(X-g)}}$ ....(2-20)

Where

V = stand volume per unit area (dependent variable)

X = average stand age (independent variable)

a, c, g, are coefficients to be determined and e, the exponential constant (2.71828). He established that the ultimate maximum yield corresponds with the point at which the first derivative V'(X) of the model with respect to age is zero. This expression was used to derive the cumulative annual increment (CAI) using the equation:

V' (X) = $ace^{-\left[e^{-c(X-g)}\right]} + c(X-g)$ ....(2-21)

Furthermore, the modified model was used to determine the age of maximum CAI as well as the corresponding yield. Also the MAI was obtained through the point of tangency of the yield curve with the straight line from the origin.

Osho (1988) has drawn attention to the major drawbacks of differential equation system approach which include:

(i) Non linear differential equations were often very difficult to solve hence the models are not very easy to apply although the advent of computers have greatly enhanced the applicability of these models.

(ii) Deterministic functions in which an effect or response was assumed to be absolutely determined by the formulated cause might not be biologically feasible, reasonable and meaningful. A more realistic approach incorporating stochastic or probabilistic occurrence of events should be included in the formulation of the structure of such functions.

Zeide (1990) has also noted that the existence of many growth equations describing the same phenomenon of growth draws attention to the fact that either there are distinct patterns of growth or that the pattern of all types of growth is the same but not known equation matches it which deserves further research attention.

2.7.7.4 Statistical Distribution Models Approach

Forest management systems are becoming increasingly intensive and many decisions are dependent on knowledge of forest stand dynamics. Several studies have been carried out to describe the distribution patterns of forest data, particularly tree diameters, basal areas, and volumes. Most of these studies appear to concentrate more on diameter distribution pattern which characterises the structure of a stand, and is one of the growth parameters that is most accurately measured and can also be used to predict basal area or volume.

Diameter distribution represents the number of trees in specific size classes. The observed diameter distribution results from the natural development of the trees in relation to age, site index and total number of stems per hectare. Diameter distribution models help to provide answers to such questions as when, how and where to cut timber. They are therefore very important in forest management.

According to Okojie (1981b) citing other authors, efforts to describe stem diameter distribution from empirical data date back many years. He added that in 1899 De Liocourt constructed a model using geometric progression for diameter distribution in uneven-aged forests which was also found satisfactory in describing diameter distribution in old growth forests in Indiana by Schmelz and Lindsey (1965). Several distribution models have now been in use although only some of these are flexible enough to describe the growth curves. These models include: normal, lognormal, beta, gamma, negative/double exponential and Weibull probability distribution functions (see Figure 2.3).

(i) Normal distribution

A random variable X, assuming all real values from $-\infty < X < \infty$ has a normal distribution if its probability density function is of the form:

$$f(X) = \frac{1}{\sigma\sqrt{2\pi}} \quad \exp - \left[\frac{1}{2}(X-\mu)^2 / \sigma^2 \right] \qquad \text{..................(2-22)}$$

where

μ = mean = Expected value of X

$-\infty < \mu < +\infty$ and σ^2 = variance.

For a normally distributed population, it is expected that 68.27% of the cases will fall between $\mu-\sigma$ and $\mu+\sigma$ and 95.45% between $\mu-2\sigma$ and $\mu+2\sigma$ while 99.73% of the cases are found between $\mu-3\sigma$ and $\mu+3\sigma$.

The standardised normal distribution in most cases does not meet the flexibility desired in growth studies. However, its importance is due to the fact that it is tabulated hence facilitating practical tests of a data set for normality. A standardised form is obtained by transformation of original X values with unit standard deviation and zero mean.

Among the few others who obtained some promising results in application of normal distribution to growth studies is Gringrich (1967); he used the distribution to describe species composition and diameter data in upland hardwood forests.

(ii) Lognormal distribution

A lognormal distribution occurs in practice whenever a random variable X has its logarithm showing a normal distribution. Its probability density function is expressed as:

$$\text{f (X)} = \frac{1}{\sigma\sqrt{2\pi}} \text{X}^{-1} \text{ Exp - } \left[\frac{1}{2} (\ln X - \mu)^2 / \sigma^2 \right] \qquad \text{............(2-23)}$$

where $X, \sigma > 0$ lnX = natural logarithm of X.

This distribution is positively skewed with

mean = Exp ($\mu + \sigma^2 / 2$) and variance = Exp ($2\mu - \sigma^2$) (Exp $\sigma^2 - 1$).

Bliss and Reinker (1964) found this suitable in describing diameter distribution in some even-aged stands. However, the lognormal distributions are of limited use in growth studies as they generate only positively skewed curves (see Figure 2.3).

(iii) Gamma distribution

A continuous random variable X has a gamma distribution if its probability density function is given by:

$$\text{f (X)} = \frac{\lambda^n}{\Gamma(n)} X^{n-1} e^{-\lambda X} \qquad \left| \begin{array}{l} X > 0 \\ n \geq 1 \\ \lambda > 0 \end{array} \right. \qquad \text{................(2-24)}$$

otherwise

mean, $\overline{X} = \frac{n}{\lambda}$

Variance, $\sigma^2 = \frac{n}{\lambda^2}$

Gamma distribution is generally noted for generating positively skewed curves. Nelson (1964) found this appropriate for describing diameter distribution in a loblolly pine stand.

(iv) Beta distribution

If a random variable X has a probability density function

$$\text{f (X)} = \frac{\Gamma(\alpha + \beta)}{\Gamma(\alpha)\Gamma(\beta)} X^{\alpha - 1} (1 - X)^{\beta - 1} \qquad \text{.................(2-25)}$$

where $0 < X < 1$, $\alpha > 0$, $\beta > 0$, then X is said to have a beta distribution. The mean of the distribution is given by

$$\overline{X} = \frac{\alpha}{(\alpha + \beta)} \qquad \text{................(2-26)}$$

and its variance, $\sigma^2 = \frac{\alpha\beta}{(\alpha + \beta)^2} (\alpha + \beta + 1)$ ....(2-27)

Because of its ability to assume a wide variety of shapes, beta distribution has been used in describing diameter distribution in stands of different species. Among those who have come out with such studies are: McGree and Della-Bianca (1967), Lenhart and Clutter (1971), Burkhart and Strut (1974), Jayaraman and Rugruini (1988).

At interval (0,1) if $\alpha = \beta$, Beta distribution reduces to uniform (rectangular) distribution so called because its density is uniform or constant over a certain interval say (a,b). Its probability density function is given by:

$$f(X) = \frac{1}{(b-a)} \qquad \text{..................(2-28)}$$

where the parameters a and b satisfy

$-\infty < a < b < \infty$

$$\text{Mean, } \overline{X} = \frac{1}{2}(a+b) \qquad \text{..................(2-29)}$$

$$\text{and variance, } \sigma^2 = \frac{1}{2}(b-a) \qquad \text{..................(2-30)}$$

The gamma and beta functions have their density functions highly flexible in shape and are therefore more promising for adaptation in growth studies.

(v) The Weibull distribution

The Weibull function equally flexible in terms of the ability to assume various shapes (both positive and negative skweness) have become increasingly popular for characterising stand diameter distributions. Weibull distribution was developed in an entirely different context from its application in forestry. Weibull was a Swedish physicist who derived and used the functions in his experiments. It has since been recognised as a useful and most appropriate model in reliability studies and life lasting experiments (Osho, 1988).

A random variable is said to have a two parameter Weibull density function of

$$f(Y) = (\alpha / b)(Y / b)^{\alpha-1} \exp\left[-(Y / b)^{\alpha}\right] \qquad \text{.................(2-31)}$$

where

α = shape, b= scale parameters.

The cumulative distribution function of the two parameter Weibull function is given by:

$$f(Y) = 1 - \exp\left[-(Y / b)^{\alpha}\right] \qquad \text{..................(2-32)}$$

when the location parameter C is included, we have a 3 parameter density function given by

$$f(Y) = \left[Y / b\right]\left[(Y-C) / b\right]^{\alpha-1} \exp\left[-(Y-C) / b)^{\alpha}\right] \qquad \text{................(2-33)}$$

$Y > C$, $b \geq 0$ $\alpha \geq 0$

The corresponding cumulative function is given by

$$f(Y) = 1 - \exp\left[-(Y-C) / b)^{\alpha}\right] \qquad \text{..................(2-34)}$$

A number of workers have used Weibull distributions to characterise stem diameter distributions including Bailey and Dell (1973), who used it to predict development of *Pinus radiata* in New Zealand. Rustagi (1978) has used the 3 parameter function for quantifying diameter distributions in both even-aged and uneven-aged stands.

Others include Yang *et al.* (1978), Hyink *et al.*, (1983) and others.

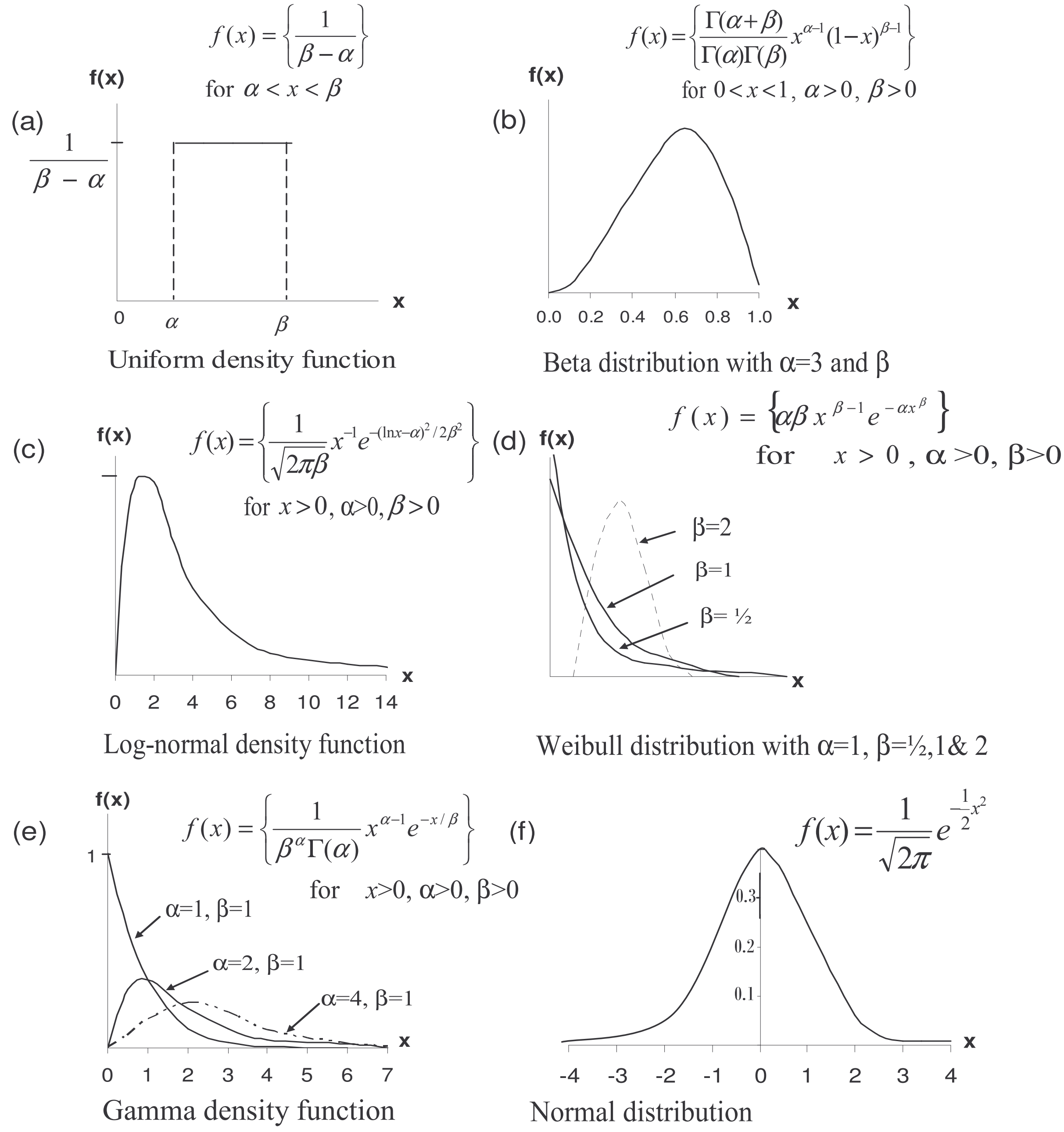


Figure 2.3: Some distribution functions. Adapted from Okojie (1981b).

In Nigeria, Okojie (1981a) and Adegbehin (1985) have used Weibull functions to characterise the stem diameter distributions for plantations of indegenous meliaceae and exotic tree species respectively.

The negative exponential commonly called J-shaped distribution have been described by Leak (1964). This is a special case of a two parameter Weibull model.

Osho (1988), Murray and Von Gadow (1991) have drawn attention to some shortcomings of the distribution modelling approach which include: Inability to permit any silvicultural alternatives since only the undisturbed development of stands were described; irregular size class distributions, resulting from management or other disturbances do not lend themselves to characterisation; moreover, variation exhibited between and within species in the same and different size-class diameters severely limit the predictive capabilities of the distributional models. Also often the type of distributional models suitable for describing different structures in forest stands are unknown.

Osho (1990) has attempted to compare the relative effectiveness of Weibull distribution and matrix model (to be reviewed) in characterising diameter distribution in an uneven-aged forest stand of Idanre-forest Reserve in Nigeria. Predictions of diameter distributions had varied degrees of accuracy. The matrix model produced better fit for the larger diameter classes. The bias in the predicted values lied mostly at both ends of the diameter classes. Significant movements were observed between Weibull parameters and stand factors like stem density and mean diameters.

2.7.7.5. Development and Application of Matrix Models in Plant Demography

Matrix algebra has received considerable application in population dynamics. It has been used to examine population trends especially in animals. Animals probably enjoyed such studies over their plant counter parts because of the ease of identification and isolation of individuals (Harper, 1977; Pielou, 1977). Besides matrix algebra form the vehicle by which multivariate data (principal component analysis, factor analysis, etc.) are analysed. Further treatments of matrices are given by Searle (1966), Davies (1971) and Stephenson (1993).

The Markov process (on which the matrix models are based) is the approach used most frequently in stochastically based descriptions of stand development. The growth models developed under this system have their roots in Leslie’s and Lewis’ growth models. Lewis (1942) and Leslie (1945) working independently have pioneered the application of transition matrix models in predicting changes in animal populations over a given space of time.

According to Sarukhan and Gadgil (1974) also citing other authors, these models probably stemmed from the calculus model in demographic analysis where the primary aim is to understand the way in which the size of a population changes with time that is, to estimate

$\frac{dN}{dt}$ where N = the number of individuals in the population and t = time. The simplest formulation of population dynamics is:

$$\frac{dN}{dt} = f(n) \qquad ....(2\text{-}35)$$

whose elaborations lead to the development of the exponential or logistic models. Further formulation structures the population into age such that

$$\frac{dN_i}{dt} = f(N_o, \ldots, N_i, \ldots, N_m) \qquad ....(2\text{-}36)$$

For a discrete time model:

$$N_i(t+1) = f[N_o(t) \ldots N_i(t) \ldots N_m(t)] \qquad ....(2\text{-}37)$$

whose functional dependence is specified by age specific fertility and mortality rates. The discrete time model then developed by Leslie (1945) resulted into a set of m+1 linear algebraic equations:

$$\begin{array}{l}
N_o(t+1) = a_{oo}N_o(t) + \ldots + a_{oi}N_i(t) + \ldots + a_{om}N_m(t) \\
\quad\vdots \qquad\qquad \vdots \qquad\qquad \vdots \qquad\qquad \vdots \\
N_i(t+1) = a_{io}N_o(t) + \ldots + a_{ii}N_i(t) + \ldots + a_{im}N_m(t) \qquad ....(2\text{-}38) \\
\quad\vdots \qquad\qquad \vdots \qquad\qquad \vdots \qquad\qquad \vdots \\
N_m(t+1) = a_{mo}N_o(t) + \ldots + a_{mi}N_i(t) + \ldots + a_{mm}N_m(t)
\end{array}$$

where in general, the coefficient a_{ij} specifies the contribution by the jth category individuals living at time t to the ith category individuals that come into existence at time t+1. Casting these equations into a matrix form produces:

$$N(t) = \begin{bmatrix} N_o(t) \\ \cdot \\ \cdot \\ \cdot \\ N_i(t) \\ \cdot \\ \cdot \\ \cdot \\ N_m(t) \end{bmatrix} \text{ and } M = \begin{bmatrix} a_{oo} & \cdot & \cdot & \cdot & \cdot & \cdot & a_{om} \\ & & & & & & \\ & & & & & & \\ a_{io} & \cdot & \cdot & \cdot & \cdot & \cdot & a_{im} \\ \cdot & & & & & & \cdot \\ \cdot & & & & & & \cdot \\ \cdot & & & & & & \cdot \\ a_{mo} & \cdot & \cdot & \cdot & \cdot & \cdot & a_{mm} \end{bmatrix}$$

The square Leslie's matrix L, was eventually developed from M when all the elements of M are zero except the sub-diagonal and the first row. This is biologically meaningful since contribution to the first stage by other stages (a_{oj}) can only be through reproduction and to other stages ($a_{i+1,j}$) by individuals that survive till that stage at the time period over which the matrix operates (time interval is assumed be the same as the age interval). The Leslie's matrix L is usually represented by:

$$L = \begin{bmatrix} b_0 & b_1 & b_2 & . & . & . & b_{n-1} & b_n \\ p_0 & 0 & 0 & . & . & . & 0 & 0 \\ 0 & p_1 & 0 & . & . & . & 0 & 0 \\ . & . & . & . & . & . & . & . \\ . & . & . & . & . & . & . & . \\ . & . & . & . & . & . & . & . \\ 0 & 0 & 0 & . & . & . & p_{n-1} & 0 \end{bmatrix}$$

where the elements in the top row b_{ij} ($b \geq 0$) define the specific fecundity while P_{ij} ($0 \leq P \leq 1$) represents the probability that an individual aged j will survive to age i = j+1. b_{ij} is the number of off springs produced per animal by a surviving individual in the ith age during the interval (i,j). The matrix L describes the transition probabilities from one time to another. The state of the population at time t+1 being dependent only upon the state at time t (Usher, 1975; Caswell, 1989) but not upon how the population achieved that current state, t. This situation is reminiscent of the Markov processes of probability theory but the matrix L, itself is not of the Markov type which demands that all its columns sum up to unity.

In the application of Leslie matrix to model population changes, the following procedures were often adopted. The population would be assumed to be divided into k+1 equal groups corresponding to the transition probabilities in the Leslie Matrix. The number of individuals in each age group could be written in a form of a column vector, $N_{t,I} = [N_{t,o} \ldots N_{t,k}]$ where $N_{t,I}$ represents the number of individuals in age class i at time t. The vector summarises the age structure or distribution of the population after one time interval. The sum total of the individuals within each age category gives the total population size. The state of the population after on time interval can be determined by premultiplying the column vector $N_{t,i}$ with the matrix L. Thus we have:

$$N_{t+1} = LN_t \text{ or } \begin{bmatrix} N_{t+1},0 \\ . \\ . \\ . \\ . \\ . \\ . \\ . \\ . \\ N_{t+1},k \end{bmatrix} = \begin{bmatrix} b_0 & b_1 & b_2 & . & . & . & b_{k-1} & b_k \\ p_0 & 0 & 0 & & & & 0 & 0 \\ 0 & p_1 & 0 & & & & 0 & 0 \\ . & . & . & & & & . & . \\ . & . & . & & & & . & . \\ . & . & . & & & & . & . \\ 0 & 0 & 0 & & & & p_{k-1} & 0 \end{bmatrix} \begin{bmatrix} N_t,o \\ . \\ . \\ . \\ . \\ . \\ N_t,k \end{bmatrix} \quad \text{..................(2-39)}$$

Similarly the change over two time periods is given by

$$N_{t+2} = LN_{t+1} = L\,(LN_t) = L^2N_t \quad \text{.........................(2-40)}$$

Generally, when a change over long time periods say k is considered where k is any positive integer, we have:

$N_{t+k} = LN_{t+k-1} = L^2N_{t+k-2} = \ldots = A^kN_t$ ....(2-41)

The steady state or stable age (equilibrium) is obtained by finding the value of λ, such that

$LN = \lambda N$ ....(2-42)

Where λ is an eigenvalue and N is the associated eigenvector. The mathematical properties of this matrix has been investigated by Leslie (1945, 1948), Sykes (1969) and Searle (1966). According to Egunjobi (1979), some of the biologically important properties include: one of the latent roots of the matrix is dorminant; corresponding to this dorminant latent root is the associated vector which has all its elements non-negative, thereby giving a biologically meaningful population structure; and the natural logarithm of the dorminant latent root gives the intrinsic rate of natural increase. Depending on the magnitude of the eigenvalue, the population is judged to be declining ($\lambda < 1$), stable ($\lambda = 1$) or increasing ($\lambda > 1$).

The Leslie model has since been modified by different authors for various applications. For example, because it is often difficult to make accurate estimates of ages of organisms, Lefkovitch (1965) has extended the Leslie matrix model to study the growth in animals (insects). He divided his insect population into unequal stage groups (e.g. egg, larva, pupa) rather than the conventional equal age groups without making assumptions about the variation of the duration (time) of the stage that different individuals may show. According to him, at a given time t, for a given species, there would exist distinct stages and $N_{t,i}$ individuals in stages i (i = 1,2,…,s). The total population size at time t would be equal to N_T where

$N_T = \sum N_{it}$ ....(2-43)

The number of individuals in each stage at time t+1 would necessarily be functions of the number at time t, the mortality, growth, fecundity ,immigration and emigration of each stage during the time interval [t, t+1]. The numbers in stage say i at the time t+1 to those in all other stages at time t would be described deterministically by the linear equation:

$N_{i,\,t+1} = n_{lt}\, m_{i,\,l,\,t} + n_{2,\,t} + \ldots + n_{s,\,t}\, m_{i,\,s,\,t}$

$= \sum_{j=1}^{S} n_{j,t} m_{ij}$ ....(2-44) where the constant $m_{ij} \geq 0$ (j = 1,…s) represent the biological dependence of the i^{th} stage at time t+1 on the jth stage at time t. The series of simultaneous equations for all the s stages at times t and t+1, obtained this way can be expressed in matrix notation as:

$$\begin{bmatrix} m_{1,1} & m_{1,2} & . & . & . & m_{1,s} \\ m_{2,1} & m_{2,2} & . & . & . & m_{2,s} \\ . & . & . & . & . & . \\ . & . & . & . & . & . \\ . & . & . & . & . & . \\ m_{s,1} & m_{s,2} & . & . & . & m_{s,s} \end{bmatrix} \begin{bmatrix} n_1 \\ n_2 \\ . \\ . \\ . \\ n_s \end{bmatrix}_t = \begin{bmatrix} n_1 \\ n_2 \\ . \\ . \\ . \\ n_s \end{bmatrix}_{t+1} \qquad \text{..................(2-45)}$$

$$\text{or } m_t n_t = n_{t+1} \qquad \text{..................(2-46)}$$

where n_t and n_{t+1} are vectors representing the stage composition of the population N_t and N_{t+1}, and M_t is a matrix of the coefficients $m_{ij,t}$. M_t is a square matrix of order s.

Leslie and Lefkovitch matrices have since been used with varying modifications in the study of plant population: herbs classified according to age (Leverich and Levin, 1979; Kalisz and McPeek, 1992), size or stages (Sarukhan *et al.*, 1974; Aberg, 1992; Harvitz and Schemske, 1995); or combination of age and size (Law, 1983; Law and Edley 1990); size structured shrub populations (Huenneke and Marks, 1987) ; and trees (Usher, 1966, 1969, 1972; Bosch, 1971; Hartshorn 1975; Enright and Ogden, 1979; Bada *et al.*, 1989; Osho, 1991) usually according to size. Age classification for trees is usually not feasible because of the difficulty in accurate tree age determination. The annual ring count method of the age determination appears unreliable in the tropical and subtropical areas due to continuous growth. Moreover several growth periods lead to more than one annual ring per year (false rings).

Usher (1966) was the first to apply matrix approach to study tree populations and forest management, he developed the Leslie type model to study growth and harvest of a selection forest based on the sustained yield concept. He described the changes in the tree population by a stochastic square matrix P.

Where P was defined thus:

$$P = \begin{bmatrix} a_o & 0 & 0 & 0 & 0 & 0 & . & . & . & . & 0 \\ b_o & a_1 & 0 & 0 & 0 & 0 & . & . & . & . & 0 \\ 0 & b_1 & a_2 & 0 & 0 & 0 & . & . & . & . & 0 \\ 0 & 0 & b_2 & a_3 & 0 & 0 & . & . & . & . & 0 \\ . & . & . & & & & & & & & \\ . & . & . & & & & & & & & \\ . & . & . & & & & & & & a_{n-1} & 0 \\ 0 & 0 & 0 & & & & & & & b_{n-1} & a_n \end{bmatrix}$$

where a_i ($i = 0, 1, 2, \ldots, n$) is the probability that a tree in the ith diameter class would remain in class i during the growth period and b_i ($i = 0, 1, 2, \ldots, n-1$) is the probability that a tree in the ith class would move to a higher class i.e. $(i+1)^{th}$ class during the growth period. Also $a_i + b_i = 1$ ($i= 0, 1, 2, \ldots, n-1$) and $0 \leq a_i < 1$ and $a \leq b < 1$.

The matrix P only accounted for the growing stock of the forest stand. But under normal conditions, other processes like ingrowth (regeneration) and mortality contributed to the growth or decline of the total population. The regeneration process was accounted for by the development of another matrix R called the regeneration matrix, R such that

$$R = \begin{bmatrix} r_1 & r_2 & r_3 & . & . & . & r_n \\ 0 & 0 & 0 & . & . & . & 0 \\ 0 & 0 & 0 & . & . & . & 0 \\ . & . & . & . & . & . & . \\ . & . & . & . & . & . & . \\ . & . & . & . & . & . & . \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

The matrix R contained zero elements except for some positive elements r_1 ($i = 0, \ldots, r_1$) in the first row. The positive elements r_i represented the functions of the regeneration in the ith diameter class. The two matrices (P and R) were then combined to a single matrix Q such that

$$Q = P+R \qquad \text{..................(2-47)}$$

$$\text{i.e. } Q = \begin{bmatrix} a_o + r_1 & r_2 & r_3 & r_4 & . & . & . & r_n \\ b_o & a_1 & 0 & 0 & . & . & . & 0 \\ 0 & b_1 & a_2 & 0 & . & . & . & 0 \\ . & . & . & . & & & & \\ . & . & . & . & & & & \\ . & . & . & . & & & & \\ . & . & . & . & & & a_{n-1} & 0 \\ 0 & 0 & 0 & 0 & & & b_{n-1} & a_n \end{bmatrix}$$

and $N_t = [N_{t_1} N_{t_2}, \ldots, N_{t_n}]$,

$N(t) = [N_1(t), N_2(t), \ldots, N_n(t)]$

where the column vector N_{t_i} represents the structure of the tree population at time t and i represents the diameter class (or age class). Similarly, $N_{t+1,\, i}$ represented the structure of the population at the time t+1. The matrix Q was then used to project the population changes between time t and t+1 that is

$$N(t+1) = QN(t) \qquad \text{..................(2-48)}$$

With this equation, the evolution of the forest stand could be projected over several decades. The stability or otherwise of the forest could be investigated by comparing the structures at various times t, $t = 0, 1, \ldots, n$.

$N_1 = QN_0, N_2 = QN_1 = Q(QN_0) = Q^2N_0 \ldots N_{k_i} = Q^k N_{0_i}$ ....(2-49)

where N_{0_i} represented the initial population structure. Given the initial condition of forest stand as described by N_{oi}, equation (2-49) could be used to compute the stand situation after K growth periods. Also the dynamic evolution during the immediate years could be similarly obtained if required.

In other applications to forest stands, Hartshorn (1972) developed a matrix model to describe the population dynamics of two tropical tree species – *Pentaclethra macroloba* and *Stryphnodendron excelsum*. The coefficient of Lefkovitch projection matrix were calculated through life table analysis. The life cycle was split into 15 unequal stages from seeds to trees of diameter less than or equal to 100cm, with arbitrarily chosen class limits to take advantage of large amount of data on the seedling and sapling stages. The total number of trees at the beginning of the cycle, the number of life trees at second assessment and mortality rates were all based on a study of marked trees in 4-ha plot of mature natural and undisturbed tropical forest.

Using the model, Hartshorn assumed that the population of individuals moving to the next class were those individual trees that were promoted when the average annual growth increment for their size class was added to their present diameter. Individual trees not promoted were assumed to remain in their present size-class. There was no room for the decline in diameter of any tree. Except for the diagonal and sub-diagonal, all coefficients of the matrix he developed were zero. Thus the species did not regress a stage nor pass trough two stages in the one year growth period of the study.

Burner and Moser (1973) also employed the Markov chains procedure to describe natural transition of stems through diameter classes over discrete time for uneven-aged stands. A simple stochastic matrix model was used to predict future diameter distribution, number of survivor trees, number of mortality plus number of harvested trees from the continuous inventory data. Twenty-five states for mortality and harvest were used. A usual formulation in the tree developmental processes was adopted. A tree in any class was supposed to move to a higher diameter class, remain in that class or become dead or harvested. The two states of mortality and harvest were treated as absorbing states since once a tree has entered one of these states, it cannot leave it. The information to determine the probabilities for transition between states, the verification of predictive ability of the model were obtained by summarising the progression of the initial tree in each diameter class over the 19 year period of growth measurements.

$T^o = (T_1^{(o)}\ T_2^{(o)}\ \ldots\ T_n^{(o)})$ represented a vector whose elements corresponded to initial number of trees in each state. The matrix for the transition probabilities was then used to predict the deposition of the initial tree population after 18-year growth period.

Other studies include Enright and Ogben (1979), Buongiorno and Michie (1980), Bada *et al.* (1989), and Osho (1991). Michie and Buongiorno (1984) has observed that in most of these studies, the difficulty is regeneration, i.e. the estimation of the elements of the first row of the transition matrix as most authors assumed a constancy and equality of contribution by higher diameter classes. They suggested an ingrowth function (I_t) of the form:

$$I_t = B_0 + B_1 \sum_{i=1}^{n} B_i \left(Y_{it} - h_{it}\right) + B_2 \sum_{i=1}^{n} \left(Y_{it} - h_{it}\right) \qquad \text{..................(2-50)}$$

Y_{it} = live number of trees in diameter class i

h_{it} = number of dead trees in diameter class i (i = 1,2, …n).

B_i = the basal area of the tree of average diameter in size class i

B_o, B_1 an B_2 are multiple regression coefficients. This was tried by Osho (1991) in the study of tree population dynamics which resulted in a poor fit ($R^2 = 0.17$). He therefore reverted to the assumption of modelling ingrowth as being a uniform contribution by the mature trees in the higher diameter classes but weighted proportionality to the number of trees present in each diameter class.

Stationary Markov chain principle has also been used to model and predict successional changes in forest stands. Stephen and Waggoner (1970) have used it to describe 40-year changes in species composition of mixed hardwood stands in Connecticut USA. They represented an orderly way of comparing forest changes during periods of different lengths and extrapolating into the future.

Foster (1981) has assessed the vegetation of the Nanth Porth Nature Reserve in North Wales. He estimated the replacement probabilities of one canopy species being replaced by its kind or by another species using the Markov model. He built a matrix of replacement probabilities of each species in the canopy. By multiplying the matrix by a vector representing the current canopy composition, he was able to obtain the species compositions of the next generation. An intrinsic property of this type of mathematical process is that either a stationary age composition (stable structure) is reached after some generations, or a regular cyclic change in canopy composition emerges. Osho (1988) has also developed a matrix of replacement probabilities to predict successional changes in Idanre forest Reserve, in South-Western Nigeria. Linear programming approach based on Leslie matrix has been used to determine optimal sustainable harvesting of a forest by Rorres (1976, 1978), Osho (1988).

The major attractiveness of matrix models is that they are simple; entries are easily computable from successional or continuous inventory data; parsimonious summaries of essential parameters of dynamic changes in the system in a way few other families achieve including readily adaptable results to cartographic representation which is readily understood by forest resource managers.

However, apart from the requirement of substantial data base to develop meaningful transition probabilities, the major defect of the matrix approach is the assumption that the Markov process remains stationary that is constancy of the transition (or replacement) probabilities through out the growth period. In reality the tree population in future would likely relate not only to present size but also to the sizes during previous years. Other population regulating mechanisms like competition, the effects of environment and stocking densities were not covered. According to Osho (1988) the proposed restrictions on Markov chains under stationary conditions have been reduced by the development of time dependent transition probabilities. Also sensitivity analysis of matrix elements offer some ameliorating measures as to the effect of perturbation on population changes. However, the stationary Markov chain does offer us the first approximation to a stochastic picture of reality.

On their own part Haight and Getz (1990) have developed density dependent matrix models using growth equations from the California conifer timber output simulator. They found no significant difference in the matrix model projection of total volume and yield by produce class in the hypothetical stands.

2.7.7.6. Modelling dynamics of uneven-aged forest stands

Forests are long-lived dynamic biological systems that are continuously changing. It is often necessary to project these changes in order to obtain relevant information for sound decision making. Forest management decisions are made based on information about both current and future resource conditions. Inventories taken at one instant in time provide information on current wood volumes and related statistics. Growth and yield models describe forest dynamics (i.e., the growth, mortality, reproduction, and associated changes in the stand) over time and hence have been widely used in forest management because of their ability to update inventories, predict future yield, and to explore management alternatives and silvicultural options, thus providing information for decision-making (Vanclay, 1994; Peng, 2000), consequently predicting future forest growth and yield under different management scenarios is a key element of sustainable forest management (Peng, 2000 citing others). Vanclay (1994) refered to growth as the increase in dimensions of one or more individuals in a forest stand over a given period of time (e.g. volume growth in m^3/ha/yr). Yield refers to their final dimensions at the end of a certain period (e.g. volume in m^3/ha). In even-aged stands (stands of single age), a growth equation might predict the growth of diameter, basal area or volume in units per annum as a function of age and other stand characteristics, whereas a yield equation would predict the diameter, stand basal area or total volume production attained at a specified age. In an uneven-aged stand, yield is the total production over a given time period, while growth is the rate of production. Growth and yield are related mathematically (if yield is y, growth is the derivative dy/dt).

Peng (2000) traced the evolution of methods of measuring the growth of uneven-aged forest stands (stands of many ages) from those developed in France and Switzerland during the last century. He further notes that quantification of more detailed stand table information dates back to 1898 when De Liocourt (1898) and Meyer (1953) first noted the tendency of uneven-aged stands to exhibit a reverse J-shaped diameter distribution that could be described by geometric progression. Much progress in uneven-aged growth and yield studies has occurred since the first models were pioneered by Moser and Hall (1969). Over time, a wide variety of models have been developed to predict the growth and yield of uneven-aged stands at both the individual tree and stand level. Growth and yield methodology for uneven-aged stands not only has moved from an empirical approach to a process-based mechanistic approach, but also has incorporated a variety of techniques such as systems of equations, nonlinear stand table projection, Markov chains, matrix models, and artificial neural network techniques (Peng, 2000).

Peng (2000) further noted that compared to even-aged stands, growth and yield modelling of uneven aged stands has received very little attention due to:

i) lack of concentration and research efforts in uneven-aged management just simply following the even-aged philosophy;
ii) scarcity of suitable data and experiments including a temporal reference system in un-even-aged stands (neither stand age, nor tree age have any significance);
iii) different modelling philosophy especially as some variable such as age and site index used in even-aged models are not directly applicable to uneven-aged stands.

a) Types

According to Vanclay (1994), there are so many types of models in existence that is impossible to examine the methodology used in each. Depending on the level of details required, provided and utilised by the model, Vanclay (1994), Peng (2000) arbitrarily considered a model as a whole stand model, size class model or a single-tree model which in practice form a continuum rather than discrete classes.

i) Whole stand models. Often simple and robust, but may involve complexities not possible in other approaches. Population parameters such as stocking (number of trees per unit area), stand basal area and standing volume are used to predict the growth or yield of the forest. No details of the individual trees in the stand are determined. Stem size distributions may be inferred from existing or predicted distributions.

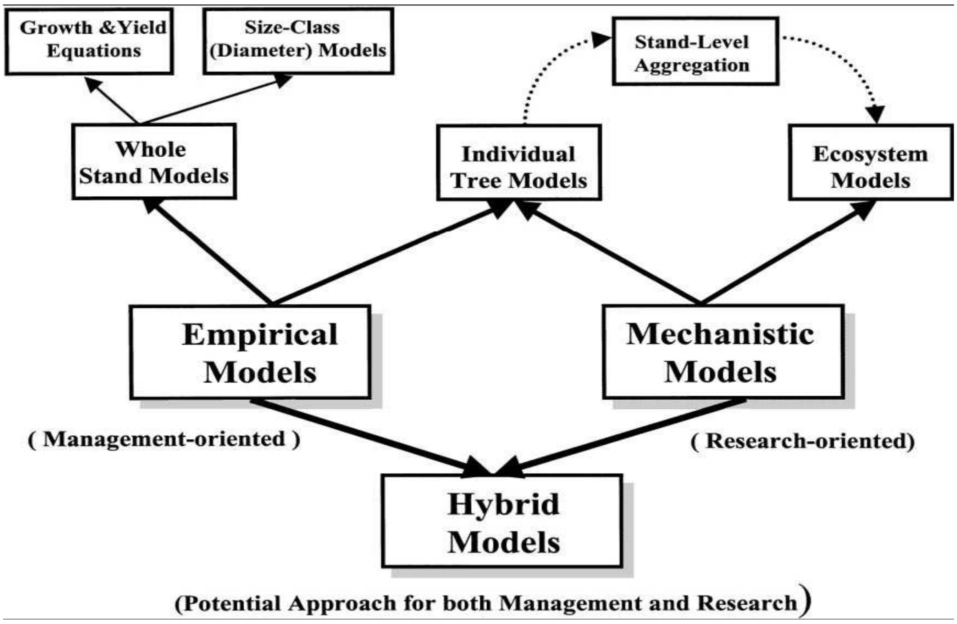


Figure 2.4. Classification of forest growth and yield models for uneven-aged stands after Peng (2000).

ii) Size class models. They provide some information regarding the structure of the stand. Several techniques are available to model stand structure, but one of the most widely used is the method of stand table projection which essentially produces a histogram of stem diameters. This approach is a compromise between whole stand models and single-tree models. When the class size is infinitely large and only one class exists, then the method is a whole stand approach. When the class width is infinitely small and each tree is considered a single class, then the method is the single-tree approach.

iii) Single-tree models. The most detailed approach is the individual tree models that simulate each individual tree as a basic modelling unit with respect to establishment, growth and mortality, and sum the resulting individual tree estimates to produce stand-level values. The minimum input required is a list specifying the size of every tree in the stand. Individual tree can further be classified into distance independent, where tree spatial locations or position of the tree, or tree height and crown class are required and distance dependent models where inter-tree spatial locations are required (e.g. Pelz, 1978). Single-tree models may be very complex, modelling branches and internal stem characteristics, and may be linked to harvesting and conversion simulators (Vanclay, 1994).

Depending on the structure and description process of their simulation system, Landsberg (1986) and others cited by Peng (2000), categorise growth and yield models into empirical, process (mechanistic) or hybrid classes (Figure 2.2). Empirical models are derived from large amounts of field data, and describe growth rate as a regression function of variables such as site index, age, tree density, and basal area. Empirical models rely on the process of production, in which a set of simulation system inputs and outputs are observed, recorded, and measured, and some or all of the mathematical models are inferred. These empirical models are based on massive experimentation or inventory where the available input and output data are accepted as the most appropriate. The major strength of the empirical approach is in describing the best relationship between the measured data and the growth-determining variables using a specified mathematical function or curve. In implementation, empirical models require only simple inputs, and are easily constructed. They are also easily incorporated into diversified management analyses and silvicultural treatments, and are able to achieve greater efficiency and accuracy in providing quantitative information for forest management. They may be an appropriate method for predicting short-term yield for time scales over which historical growth conditions are not expected to change significantly. Empirical growth and yield models may not be used, for example, to analyze the consequences of climatic changes or environmental stress (Kimmins, 1990; Shugart *et al*., 1992). Unlike empirical models, process models attempt to model the processes of growth, taking as input the light, temperature and soil nutrient levels, and modelling photosynthesis, respiration and the allocation of photosynthates to roots, stems and leaves (Vanclay, 1994). These are also known as mechanistic or physiological models. These models help to provide a better understanding of growth and stand dynamics, but have not yet successfully been used for predicting timber yields for forest management (Battaglia and Stands 1998). Ecosystem succession models (e.g. Shugart 1984, Botkin 1993) attempt to model species succession, but are generally unable to provide reliable information on timber yields. The FORCYTE model (Kimmins 1988 cited by Vanclay, 1994) uses a hybrid approach and can predict forest yields under a variety of nutrient regimes. It is useful to distinguish between models for understanding and models for prediction (Bunnell 1989). Models for understanding (e.g. process models) are useful to comprehend and link previously isolated bits of knowledge and may help to identify gaps where more work is needed. The benefits come from the insights gained while developing and exploring the model, and future uses (if any), are less important. Conversely, models for prediction may sacrifice specific details of growth processes to achieve greater efficiency and accuracy in providing information for forest management. Realism is not necessarily a virtue in a model, and it may be better to abstract just those aspects that are most relevant in each instance.

Finally, irrespective of its detail, a model may be deterministic or stochastic. A deterministic growth model gives an estimate of the expected growth of a forest stand, in the same way that the mean indicates the expected trend for a population. Given the same initial conditions, a deterministic model will always predict the same result. However, because of natural variation in the environment, real forest stands may not grow exactly the same amount each year, but may grow more or less than the expected amount. A stochastic model attempts to illustrate this natural variation by providing different predictions, each with a specific probability of occurrence. Any one of these estimates may correspond exactly to the growth under some circumstances, but may differ from the expected growth. A single estimate from a stochastic model is of little use, as a whole series of estimates is necessary to provide useful information of the variability of predictions. For instance, twenty estimates from a stochastic model will not only give a good indication of the expected growth (the mean or median), but also of its variability. The term "stochastic" is used in preference to the term "probabilistic", which is sometimes used in other contexts. Deterministic and stochastic models serve complementary purposes. Deterministic models are effective for determining the expected yield, and may be used to indicate the optimum stand condition. Stochastic models may indicate the reliability of these predictions, and the risks associated with any particular regime. Other methods such as variance propagation techniques (e.g. Gertner 1987) may provide similar information more efficiently than stochastic models. Both deterministic and stochastic predictions can be obtained from some models. Although stochastic models can provide some useful information not available from deterministic models, most of the information needs for forest planners and managers can be provided more efficiently with deterministic models.

b) Components of forest dynamics model

According to Vanclaly (1994), the more detailed approaches of forest stand modelling are not based on the overall growth of a forest stand, but need to discriminate several growth components in order to model these processes effectively. The nature of the components distinguished depends upon the forest type and the approach used. In mixed forests, an obvious requirement is to discriminate individual species or several species groups which is not often easy (Leech *et al.*, 1991). In models for intensively managed plantations, mortality and recruitment may frequently be ignored. However in many natural forests, these form an important aspect of the stand dynamics, and may have considerable influence on volume yield of the stand. In addition, the components identified in whole stand models tend to differ from those of single-tree models. In size class and single-tree models, the components usually identified are diameter (or basal area) increment, mortality and recruitment. Diameter increment is a simple concept and is relatively easy to measure and to predict. Forecasts of mortality must not only estimate the number of trees, but also the species and sizes of trees dying. Another aspect of change to be modelled is the deterioration of merchantable stems or problem trees which can be modelled in the same way as mortality. Recruitment may be predicted as ingrowth of trees reaching breast height, but some models may simulate seedlings from germination, while other models may adopt a larger threshold size such as 10 cm diameter. Each of these components will be briefly addressed individually.

i) Modelling diameter increment

Tree diameter is the easiest and most commonly measured attribute. Along with height growth and mortality data, diameter growth data are needed to estimate volume growth and to evalutate the type of product that can be obtained from individual trees and forest stands (Hann and Larsen, 1991). Therefore, tree diameter or basal area growth models have traditionally been used as one of the primary growth equations in forest growth and yield prediction systems. Over the past several decades, a number of individual-tree diameter or basal area growth models have been developed for a variety of tree species (e.g. Monserud and Sterba, 1996; Wykoff, 1990; Zhang *et al*., 2004). Since tree diameter increment and basal area increment are mathematically related, the decision to model either variable is based on convenience (Vanclay, 1994). Empirical studies offer no evidence of any difference in the precision of estimating future diameter or basal area increment equations (West, 1980). However, some authors would prefer to model basal area growth because it is more linearly related to tree volume growth than diameter growth (e.g. Hokka and Groot, 1999).

Individual tree diameter or basal area increment is often modelled using either a composite model or a potential/modifier model (Zhang *et al*., 2004). A composite model predicts tree diameter or basal area growth as a function of tree attributes (such as tree size, crown ratio, vigour and local competition) and stand level variables (such as age, site index, stand density and site characteristics) (Wykoff, 1990; Vanclay, 1994; Zhang et al., 2004). Such a generalised formulation of the individual diameter or basal area growth model has been given by Wykoff (1990) as:

$\text{In}(\Delta d^k) = a + b \times \text{SIZE} + c \times \text{COMPETITION} + s \times \text{SITE} + \varepsilon$ ……………………..2-51

Where Δd is tree diameter increment (annual or periodic); k is a constant (typically k=1 or 2); SIZE represents size variables including initial diameter and their various transformation such as lnd, 1/d, d^2; Competition describes competition among trees and is estimated from tree crown size, competition index and relative tree size, often also measured as basal area of trees larger than subject tree (one-sided competition: for above ground resources - light) and basal area (two sided competition: for below ground resources – moisture and nutrients) while SITE represents a combined effects of environmental variables that commonly include stand habitat type, location, elevation, slope and aspect. a is intercept coefficient, b is slope coefficient for size variables, c and s are vector of regression coefficients for competition and site variables respectively and ε is the model error term.

In contrast, a potential/modifier function takes the form of:

Growth = Potential Growth x Modifier……………………………………………2-52

Where the potential growth function represents the maximum growth attainable for a tree and the modifier function represents deviation from potential due to competition. Potential growth function and modifier function are usually a function of tree size, crown ratio and local competition index (Leary and Holaway, 1979). Some researchers (Zhang *et al*., 2004) consider that potential/modifier model is more biologically explainable than the composite model approach. Others find that this approach poses several difficulties (e.g. Vanclay, 1994) especially the arbitary nature of the definition of trees representing maximum attainable growth. While some authors use open-grown trees (e.g Amateis et al., 1989) others use the proportion of the fastest-growing trees present in the data (e.g. Schroder *et al*., 2002). The potential growth function and modifier function are usually constructed in separate steps using appropriate data sets (Amateis *et al*., 1989). An alternative approach of combining the potential growth and modifier functions into one model is also proposed based on Chapman-Richards or logistic functions in recent years in which the model coefficients of both functions can be estimated simultaneously (Zhang *et al.*, 2004 citing others). Comparison studies have shown that the two types (composite models and potential/modifier models) of the diameter or basal area increment models performed essentially the same over the range of conditions tested (Wykoff, 1990).

ii) Modelling mortality

Mortality is usually modelled as a binary logistic function which offers a convenient way to constrain predictions in the interval (0,1) and provides a realistic (binomial) distribution of errors (Vanclay, 1994). The logistic function can be expressed in several ways:

$P = (1+e^{-f(X)})^{-1} = 1-(1+e^{f(X)})^{-1} = [e^{f(X)}]/[1+e^{f(X)}]$ …………………………………….2-53

Where P is the probability of survival and f(X) is a function (often linear) of several explanatory variables. Probability of mortality can be obtained from 1-P. The advantage of predicting survival is that it, unlike mortality, survival is a Markov process (ie it is a transient rather than an absorbing state), so that survival over an n year period is given by the nth power of the annual probability of survival (Vanclay, 1994). Many researchers have developed mortality functions for mixed forests using the binary logistic approach (e.g. Vanclay, 1991, Zhao *et al*, 2004).

iii) Modelling recruitment

Usually a two stage procedure (Vanclay 1992, 1995) is used to model recruitment: (a) Probability of recruitment using a binary logistic model with presence or absence as dependent variable as function of environmental variables (habitat, slope, etc), distance to seed source, time since disturbance, residual G (b) Amount of recruitment - this conditional function predicts the amount of regeneration or recruitment if it is known to occur by OLS and employs stand BA, density (Nr/ha) and site index (SI) as explanatory variables.

C) Future trends

As Peng (2000) remarked citing others, traditional forestry objectives aimed at sustainable yield management are being replaced with those of sustainable ecosystem management. This paradigm shift in forest management requires an effective transfer of results from researchers to forest managers. The key to growth and yield modelling for forest planning and management in the 21st century is the extent to which the ecosystem is treated holistically. Future growth and yield efforts will face the challenges of including an increased number of silvicultural alternatives, providing expanded information on tree quality and product yields, and predicting long-term forest response to environmental stresses such as climate change, land-use, and disturbance at landscape levels. Furthermore, progress in growth and yield modelling for the 21st century centres around data collection, analysis techniques, and computing technology.

2.8. Current research on African mangrove forests

Past studies on mangrove forestry in Africa tend to have concentrated on floristic composition and distribution of species, economic utilization and regeneration strategies of the principal species (e.g. Kjerfve *et al.*, 1997; Din *et al.*, 2002; UNEP, 2007; Ajonina *et al.*, 2008). 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 (Kairo *et al.,* 2002). Many site specific biomass allometric equations have been developed across several sites in America (e.g. Smith and Whelan (2006), Australia (Komiyama, 2005) and SE Asia (Ong *et al.*, 2004) but little on any African mangrove sites (e.g. Steinke *et al.*, 1995; Slim *et al*, 1996). This study is an attempt to open up insights into allometric study of African mangroves. The mangrove research situation in Central Africa and in particular Cameroon is dismal despite the ecological and eco-morphological peculiarities of these giant mangroves of the Congo Basin, the world’s second largest rainforest. There is just mere summary description of these mangroves (Letouzey, 1968; MINEF, 1995). Though important they have been widely neglected by governments and relegated as waste lands in favour of lucrative humid inland tropical forests from which substantial revenues especially from timber is obtained to salvage their ailing economies. This has led to wanton destruction and pollution of mangrove forests with rising impacts of coastal erosion, inundations, degrading biological productivity and poverty. In Cameroon though some recent studies have been conducted (Ajonina and Usongo, 2001; Din *et al.*, 2002; Din and Ngollo, 2003; Ajonina *et al.,* 2005), large knowledge gaps still need to be filled in various aspects in understanding the dynamic nature of the resource and controlling factors in order to devise sustainable management strategies for this important forest type.

3. MATERIAL AND METHODS

3.1 Douala-Edea Wildlife Reserve

3.1.1. Location and biophysical characteristics

Location

The study site (see Figure 3.4) has been described by Ajonina and Usongo (2001). Douala-Edea Reserve (9°31' - 10°05'E, 3°14' - 3°53'N) is one of the largest and biologically rich of Cameroon nature reserves gazetted in 1932. It is situated within the Kribi - Douala basin of the coastal Atlantic Ocean and covers a greater part of the coastal plains of the Cameroon coast (160.000ha). The area has a very dense hydrological network being a meeting point of estuaries of Cameroon largest rivers (Rivers Sanaga, Nyong, Dimbamba and Wouri). Its natural boundaries are defined by this river system. River Sanaga divides the reserve into two unequal parts: the greater part is the Southern part covering more than 2/3 of the total reserve area and extends from River Sanaga in the north to River Nyong in the south with river Dipombé as the eastern limit; and the Northern part which extends from R.Kwakwa, a distributary of R.Sanaga, to the Pointe Souelaba and along the Atlantic ocean through the Manoka island to the mouth of R. Sanaga. The reserve is limited in the north by the R. Wouri estuary; east by R. Sanaga, Dipombé and Kwakwa; the south by R. Nyong; and west by the Atlantic Ocean for some 100km coastline from R. Nyong to the Wouri estuary.

Climate

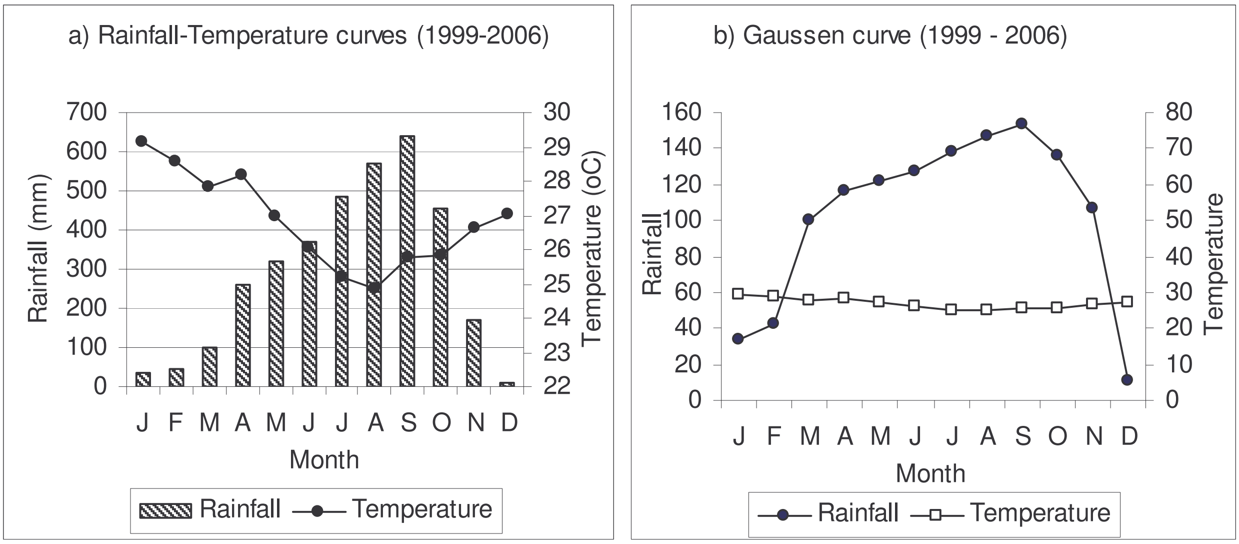


Figure 3.1. Mean monthly distribution of rainfall and temperature within the Douala-Edea Reserve (1999-2006) (from CWCS Mouanko weather station)

The climate is equatorial type characterised by abundant rains (3000 - 4000 mm) and generally high temperatures with monthly average of 24 - 29°C with a dry season spaning

November to March. The month with the heaviest rainfall is September and least December (Figure 3.1).

Vegetation and fauna

As a major wetland area encompassing two basic ecosystems (marine and humid tropical forest) the reserve has high biodiversity value. The adjoining lowland dense tropical humid forest harbours diverse fauna resources of conservation importance especially elephants, antelopes, chimpanzees, monkeys, crocodiles, manatees and sea turtles. Numerous bird species also abound especially parrots, resident and migratory palearctic waterbird species where over 60 species have been identified at the mouth of Sanaga by CWCS River Sanaga Waterbird Monthly Monitoring Program (CWCS, 2001). Over 135 fish species in 21 families with 21 endemics have been known from the River Sanaga (Ticheler, 2000).

The reserve also includes one of the country's important mangrove forests areas. These mangroves extend from Mbiako through Yoyo to Manoka within the Cameroon estuary with some patches at the mouth of the Nyong River in the southern limits of the reserve. The mangrove forests mainly consist of *Rhizophora mangle, Rhizophora harrisonii* and *Rhizophora racemosa* (red mangrove); and isolated particles of *Avicennia* sp or *Laguncularia racemosa* (white mangrove*)* in association with Nypa palms (*Nypa fruticans*). *Rhizophora* makes up more than 90% of Douala-Edea mangroves, with *Rhizophora racemosa* exceptionally big, especially at Sanaga and Wouri estuaries, where over 100cm in diameter and 50m in height have been recorded, with tree stocking rates of 911 stems/ha, 88.6m²/ha and 1315m^3/ha (for trees 5cm and above in diameter) (CWCS, 2001).

3.1.2. Socioeconomic activities

Although, the reserve acquired a protected area status since its gazettement in 1932, Government neglect through an ill-equipped conservator and one game guard to ensure the management of the reserve subsequently led to rapid encroachment into the reserve as more than 60 villages are now resident in the reserve since 1930s doing mainly fishing and trade in fisheries products with nearby cities of Douala, Edea, Kribi, etc. The mangrove area is occupied by over 20 villages and many fishing camps/hamlets (10-1000 persons) with a total mangrove population of more that 5600 (57% of the total reserve population) in some 1074 households with household size of 5.3 persons (CWCS, 2001). More than 70% of this resident mangrove population consists of foreign nationals from neighbouring countries: Nigeria, Ghana, Benin and Niger Republics with Nigeria alone having more than 60% of the total population with a greater migratory proportion following the fishing period that spans from November to April. Fish catch is mostly preserved through smoking using mangrove wood preferred for ready availability, high calorific value and flammability under wet conditions thus reducing processing costs especially drying before use. Smoked fish production within the area is estimated at between 500 - 1000 tonnes using over 180 000m^3 of mangrove wood (CWCS, 2001).

3.2 Data Collection

Data for this study is obtained from temporary and permanent sample plots undertaken by Cameroon Wildlife Conservation Society (www.cwcs-cameroon.org), a national research and conservation NGO working in the Douala-Edea Reserve since 1997 within the framework of developing a community based conservation management plan for the reserve.

3.2.1. Temporary sample plots

Temporal Sample Plots (TSP) was established between November 1999 and December 2001 to assess species composition, structure and stocking level of the mangroves in the reserve.

3.2.1.1. Site Stratification

The work started with the determination of the area of mangroves in the reserve from available maps at a scale of 1:200 000 and site stratification through several trips in the area. Generally the human settlement pattern within the mangrove zones across West and Central Africa is the same, generally inhabited by fishing communities in clustered camps or hamlets (10-1000 persons) along mangrove creeks constructed locally with mangrove materials (see Figure 3.2). With the aid of a 1:200 000 map, mangrove area (16 200 ha) in the reserve (Figure 3.4) was stratified into four more or less homogenous zones (strata) based on local biophysical factors (topography, fluvial system, influence of tides, etc) and depositional factors.

3.2.1.2. Sampling scheme

The choice of appropriate sampling scheme was consistent with a number of factors including economic (time, cost, resources), silvicultural (its peculiar silvicultural characteristics of near mono-specific stands usually referred to as natural monocultures) and site characteristics especially accessibility problems due to edaphic (very muddy, malodorous soil) and hydrological (tidal influence) peculiarities of this vegetation type yet maximizing accuracy. With due consideration to these factors, a stratified random cluster sampling scheme qualifying as single-stage clustering sampling approach (Shiver and Borders, 1996; Husch *et al.*, 2003) was adapted (see Figure 3.3) with mangrove fishing camps/hamlets identified as major cluster locations or sampling units within strata (mangrove zones). Cluster locations (mangrove camps/hamlets) were identified and allocated to the zones (strata) in direct proportion to the size (area) of the strata. Camps/hamlets for the establishment of temporal plots in transects were randomly selected using a table of random numbers.

Figure 3.2: A typical mangrove fishing camp serving as reference point for transect locations

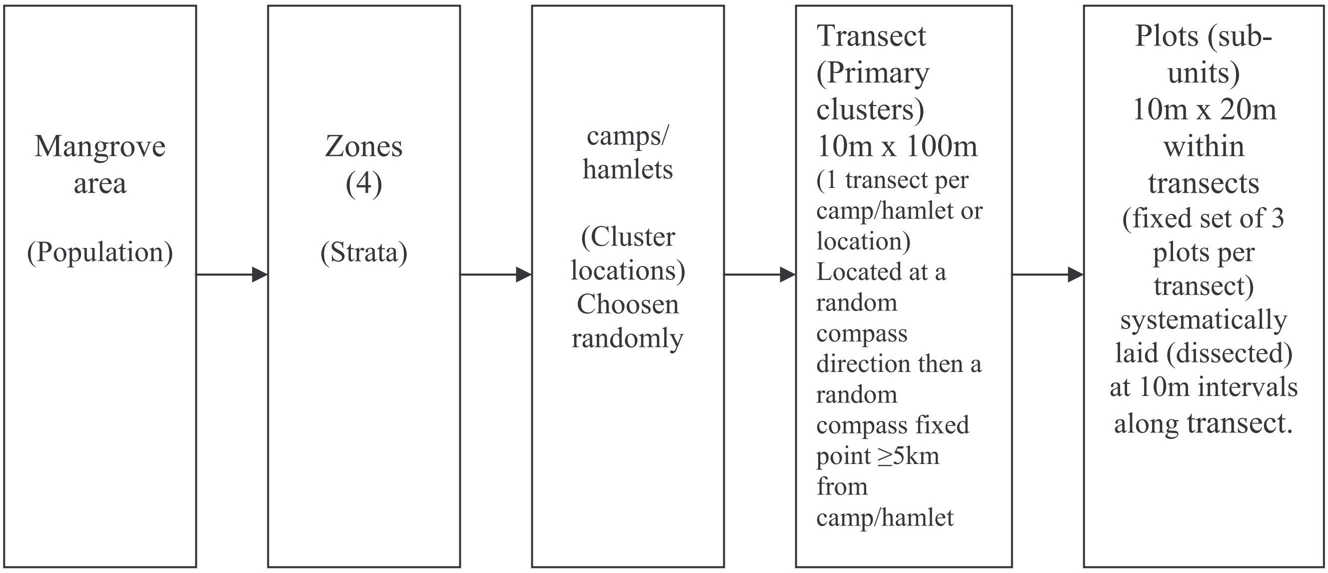


Figure 3.3: Stratified random cluster sampling (single-stage cluster sampling) scheme adapted for mangrove inventory in the Douala-Edea Reserve, Cameroon.

3.2.1.3. Pilot sampling and field location of plots

Prior to detailed sampling, pilot sampling was carried out in zone 1 with the location of a 10m x 20m plot to train the inventory team and fine tune methods. With the aid of a forest inventory team of 5 trained assistants (boat driver, cutter, diameter-height measurer, recorder and plant identifier –plates Figure 3.7), strip transects of 10m x 100 m were cut in non-exploited and well stocked mangrove sites covering the entire mangrove zone of the reserve. For the location of sample plots in the field, transects were located at least 5km in a random compass direction from the camp/hamlet's Head Residence where field camping usually took place. Once a site was identified, a random compass direction was selected (using a table of random numbers) for the location of the transect with the aid of a 100m measuring tape. Only well stocked mangrove stands not dissected by extensive water bodies were selected. Three 0.02 ha (10 m x 20 m) fixed plots per transect separated systematically at 10 m intervals were generated by pulling a 10-metre rope perpendicularly across the tape (Figure 3.7).

Table 3.1: Sampling frame- plot allocation to zones in the mangrove forest of the Douala-Edea Reserve, Cameroon

No	Name of the zone	Mangrove area (ha)	Transects (0.1ha)				Plots (10mx20m-0.02ha)				Sampling fraction (as % zone area)	
			Number			Total area (ha)	Number			Total area (ha)		
			TSP	PSP*	Total		TSP	PSP*	Total		Transects	Plots
1	Manoka Island & Malimba Creeks (Z1)	6703	12	1	13	1.3	36	3	39	0.78	0.019	0.012
2	Kwakwa Creeks & River Louanga Creeks (Z2)	2793	5	1	6	0.6	15	3	18	0.36	0.021	0.013
3	Sanaga Delta (Z3)	3352	6	1	7	0.7	18	3	21	0.42	0.021	0.013
4	Nyong Estuary (Z4)	3352	6	1	7	0.7	18	3	21	0.42	0.021	0.013
	Total	**16200**	**29**	**4**	**33**	**3.3**	**87**	**12**	**99**	**1.98**	**0.020**	**0.012**

TSP-Temporal Sample Plots PSP* - Permanent Sample Plots in undisturbed stands

3.2.1.4. Measurement protocol

Measurement protocol followed standard forest mensuration procedures (Hush *et al.,* 2003) adapted for mangrove vegetation (Pool *et al.*, 1977; Cintron and Novelli, 1984; Kjerfve *et al.*, 1997). To quicken the measurement operation without compromising accuracy, all trees were measured easily to the point (Dm) left when the metal section of the tape pierces the tree, although this underestimates the true diameter (D_0) from the zero point, this was later corrected with the regression equation $D_0 = 1,0037D_m + 3, 9347$ ($R^2 = 0, 9999$ n=134) fitted from trees later measured covering the range of diameter classes. Vascular plants and all trees greater than or equal to 2.5 cm diameter (D_m) with true diameter (D_0) of 6.4 were identified, enumerated and measured with a diameter tape to the nearest 0.1cm at breast height (1.3m above ground level). Rhizopherous species (red mangrove) with main trunk 1.3m above ground level were measured on the main trunk 30 cm above stilt root while non-rhizopherous species (white mangrove, etc) were measured at 1.3m above ground level. Height measurements (bole and top heights) were taken on 100 largest trees/ha (at least 2 trees per plot of 10m x 20m) using a Suunto clinometer but stilt root height (height from ground level up to the main stem) was measured on all trees.

A total of 1552 trees from 87 temporal sample plots in 29 transects (2.9 ha) from well stocked natural undisturbed mangrove stands covering the entire forest reserve area were enumerated and measured. Detail information on sites and tree mensuration was stored under an Excel Spread Sheet and MINITAB Release 13 packages.

3.2.2. Permanent sample plots

Three categories of Permanent Sample Plots (PSP) in transects were established in each zone under three regimes of wood exploitation as follows: heavily exploited (HE), moderately exploited (ME) and unexploited or undisturbed (UND) stands. The plots were established between June 2002 and March 2003 with the technical assistance of an expert working with the Smithsonian Institute’s network of forest dynamics plots (Condit, 1998). The aim was to monitor forest dynamics especially as affected by human use and to determine sustainable harvest levels.

3.2.2.1. Plot selection and layout

The method of establishment was similar to that described for TSP. Transects of 100m x 10m (0.1ha) were established under each regime per zone in sites where disturbance took place within the last ten years from local informants. Qualitative criteria for characterization of various perturbation were based on canopy (closure, height), tree (size and density) and undergrowth (density) characteristics and frequency of indicator species. This was later matched with a single quantitative criteria of basal area (m^2) per ha (Table 3.2).

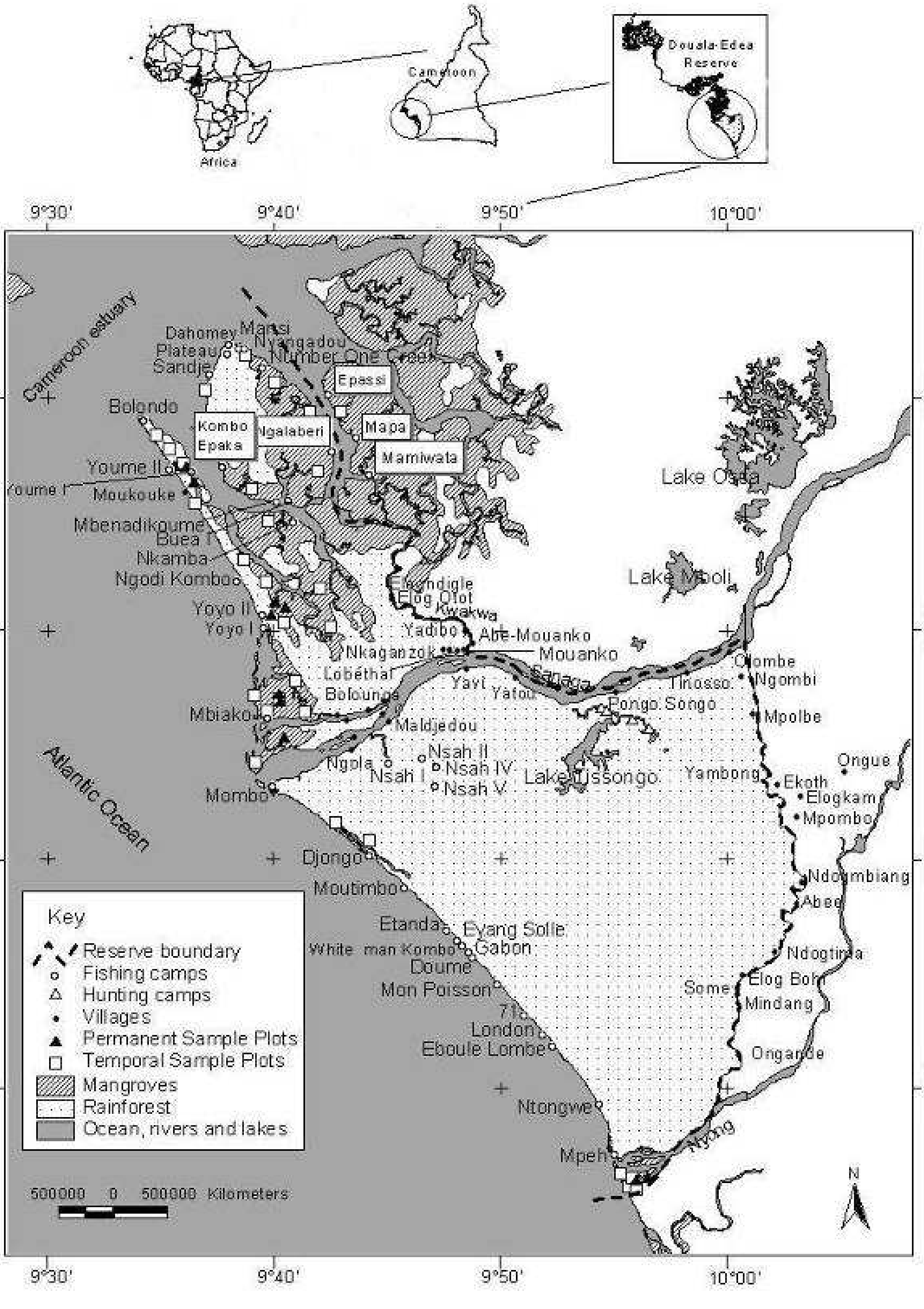


Figure 3.4: Map showing the location of Douala-Edea Reserve mangroves and the Temporal and Permanent Sample Plots

Table 3.2. Selection criteria for the perturbation regimes in mangrove stands in the Douala - Edea Reserve, Cameroon

Criteria	Characteristics	Sub-criterion	Perturbation regimes		
			Heavily exploited (HE)	Moderately exploited (ME)	Unexploited or undisturbed (UND)
Qualitative	Canopy	Closure	Open	close	Very close
		General co-dominant height	≤40m	40-50m	40-50m
	Tree	Density of trees ≥30cm dbh	Very low	low	Very high
	Under growth	Density	High	low	Very low
	Frequency of Indicator species	Mangrove fern *Acrostichum* spp	Very high	low	absent
		Mudskippers	Low/absent	high	Very high
Quantitative	Basal area/transect	Basal area Zone 1	0.339	0.581	2.329
		Basal area Zone 2	0.084	0.627	1.204
		Basal area Zone 3	0.284	0.660	2.060
		Basal area Zone 4	n.a	0.713	2.120
	Average basal area from 6 subplots per transect	Average BA Zone 1	0.057	0.097	0.338
		Average BA Zone 2	0.014	0.104	0.201
		Average BA Zone 3	0.047	0.110	0.343
		Average BA Zone 4	n.a	0.119	0.353
	Proportion of basal area removed (G_r) with UND as reference base	Average Prop Gr Zone 1	0.854	0.751	0.000
		Average Prop Gr Zone 2	0.931	0.479	0.000
		Average Prop Gr Zone 3	0.862	0.680	0.000
		Average Prop Gr Zone 4	n.a	0.664	0.000
	Total G	All transects	0.706	2.581	7.713
	Average G	All transects	0.039	0.108	0.321
	Proportion G removed (Gr)	All transects	0.870	0.665	0.000

Zone 4 - River Nyong estuary which constituted an entire uninhabited area or seasonally fishing activities with fish not smoked with mangrove wood contained no mangroves in the heavily exploited category.

Plot establishment followed Condit (1998) with some modifications. Three transect plots (10m x 100 i.e. 0.1 ha) were established in each site following a random compass direction but separately laid in 3 regimes of human wood exploitation (see Figure 3.6). As in TSP, each transect plot was divided into 3-0.02 ha (10m x 20m) plots separated at 10m intervals along the transect but this was then further subdivided into 6 square subplots of 10m x 10m. Each sub plot was divided further into two quadrats of 10m x 5m each forming 12 quadrats per transect. To facilitate tree mapping, each quadrat was again divided into 5m x 5m sub quadrats using red paint on transect baseline axis. The edges of each subplot were fixed with painted (red) plastic PVC tubes and boundaries demarcated by heavy cords. Floaters were fixed at 1.3m to the PVC tubes to facilitate plot location during high tides and its geographical positioning system points taken.

3.2.2.2. Measurement protocol

a) Measurement of disturbance

To obtain a disturbance scale, the basal area of each of the six subplots per transects (HE, ME) were compared to mean basal area of the six subplots of undisturbed transect (UND) in each zone. This generates a disturbance distribution based on proportion of basal area removed for all the sixty-six (66) plots in all the three regimes of exploitation with subplots in undisturbed transects scoring zero (Figure 3.5).

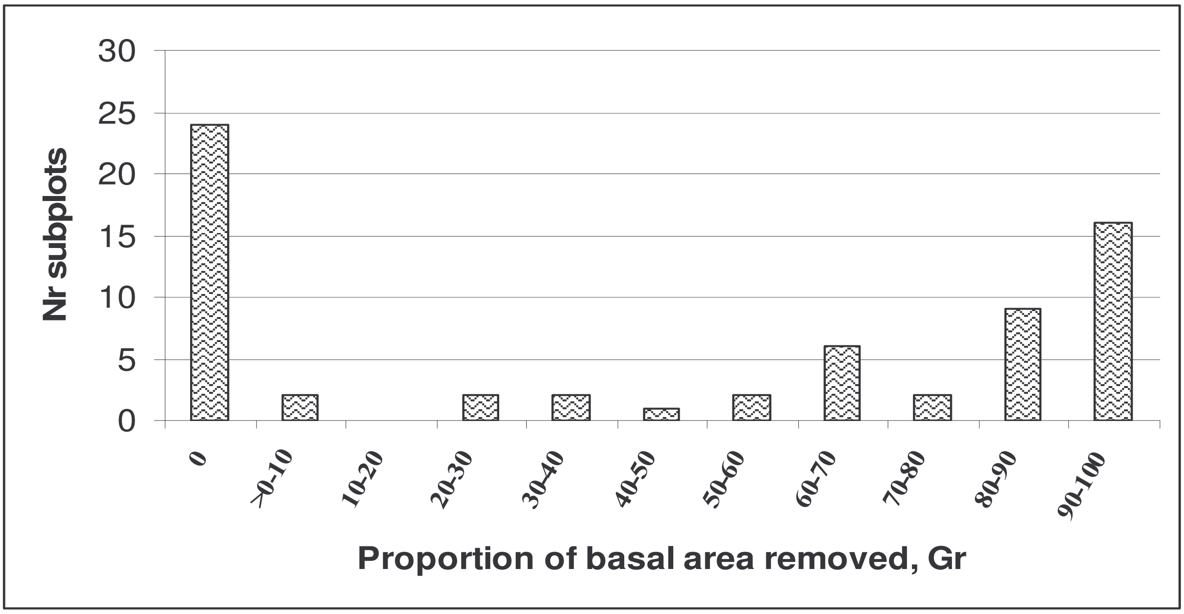


Figure 3.5. Distribution of values on a quantitative scale of mangrove forest disturbance based on proportion of basal area removed with adjacent undisturbed regimes as reference base.

b) First enumeration

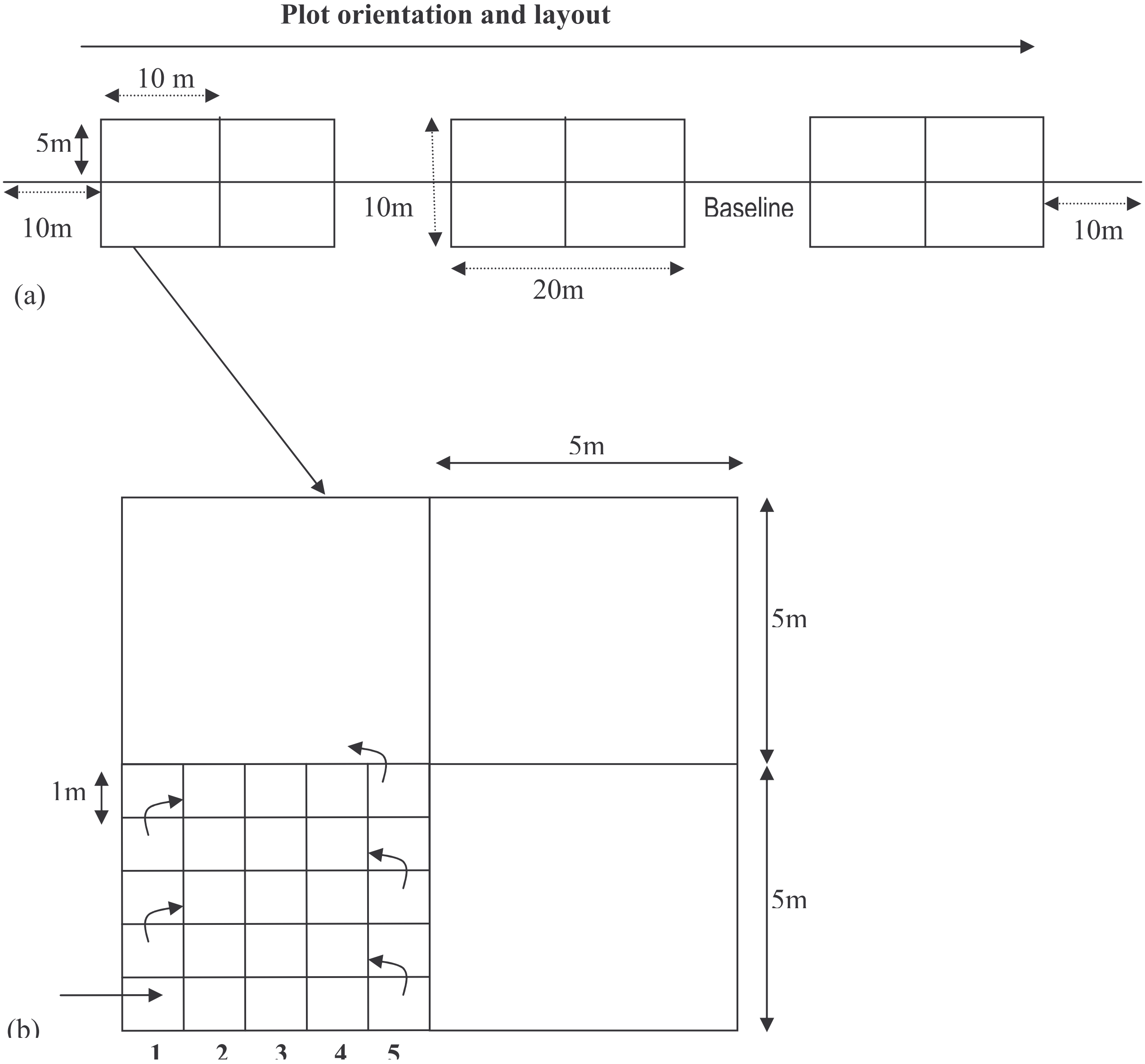


Figure 3.6 (a): Schematic layout of mangrove stands permanent sample plots (b): Field movement procedures within PSP subplot in mangrove stands in the Douala –Edea Wildlife Reserve area, Cameroon

Tree enumeration sequence and mapping followed Condit (1998) and Thomas *et al.* (2003). For each plot, the enumeration process started from the extreme south eastern end of the first 5 x 5 m sub-quadrat and swept from the bottom to the top a bandwidth of 1m, visually determined. At the top of the band, the team rotates through 180° to sweep another 1m-band width. This process covers all 5 bands per 5m x 5m quadrant. The adjacent quadrat is covered in the same manner until the entire plot is completed (Figure 3.6 b). The tree census team was made up of five persons: data recorder, mapper, mensuration technician, tag man and a paint man (also see the plates in Figure 3.7). The diameter of each tree ≥ 1cm was measured 1.3m above the ground (diameter at breast height d.b.h) .The point of measurement (POM) was marked with red paint. For trees with stilt roots, dbh was recorded at 0.3m above stilt root. Stilt root heights were also taken. For all trees of diameter < 5cm a calliper was used while a diameter tape was used for trees of diameter ≥ 5cm. Each tree was assigned a plastic number tag bearing transect number, stem number (using consecutive numbers) and mapped to the nearest 0.1m. Only trees rooted in the plot were considered. Some height measurements were taken using a Sunto Clinometer for trees ≥ 5m or a graduated pole for trees ≤ 5m. Dominant tree heights (height of 100 largest trees/ha giving at least one per subplot); dominant merchantable height (from end of stilt root to first branch) and dominant crown height were measured. Trees were classified as multiple stems (MS), problem trees (P) and Single Stemmed trees (SS or empty space). For (MS) trees, the principal stem was assigned the tree number while subsequent axial stems (secondary stems) using smaller tags, were assigned numbers (1, 2, 3, etc) in decreasing diameter order. Trees were identified morphologically while vouchers were collected and coded for identification in the near-by (at100km) Limbe Botanic-Gardens.

Summary on Data Sheets

PSP data were entered in four data types in separate Excel Sheets in a single file carrying the name of the zone. This consists of Main Data, Multi-stemmed (Multiple stemmed) Data, Height Data and Problem tree Data described below.

i) Main Data sheet

Main Data (Sheet 1) contains all the trees as entities with subsequent measured parameters.

ii) Multi-stemmed Data Sheet

This second sheet of data contain exclusively data for multi-stemmed or multiple stemmed trees. The primary stem while retaining the tree identity contained in the Main Data starts with BrNo 0 under BrNo column to denote primary branch (stem), while subsequent secondary stems though also carrying the tree identity are numbered (1,2,3, etc) in increasing diameter as described as above.

iii) Height Data sheet

This last sheet (Sheet 3) contains data with trees with their identities retained from the Main Data sheet where all types of height measurements were taken on them.

iv) Problem Tree Data sheet

This fourth and last sheet contained fallen, leaning and broken trees, trees with crocked stems and other measurational problem adequately coded and described. Tree identity as contained in Main Data sheet is still retained.

Plate 1: Field camping at Hamlet's Head Residence

Plate 2: Sign posting PSP

Plate 3: Establishment of TSP and measuring big trees

Plate 4: TSP team in degraded plots (T1)

Plate 5: Tagging trees

Plate 6: Measuring problem trees

Plate 7: Tagged and measured trees in undisturbed stands (T3)

Plate 8: Remeasurement problem: prop root growth through POM

Figure 3.7: Photo plates of mangrove forest mensuration in the Douala-Edea Reserve, Cameroon (Photos by GN Ajonina)

During the first census, the Main Data sheet contained 3894 trees, Multi-stemmed Data 1374 stems, 693 trees in Height Data and 172 trees in the Problem Tree Data.

b) Second and subsequent enumerations

The first recensus after two years of establishment started in June 2004 with the first established plots and completed in April 2005 with the last established plots. The third census (second recensus) started in June 2006 and ended in April 2007. Each renumeration corresponds at the anniversary from date of first establishment.

Remeasurement is often started by general transect inspection and plot reinforcement operations which consist of adding red paint on planted PVC's, and replacing weathered out cords. Plot procedures and mensuration followed Condit (1998) and Thomas *et al.* (2003) but only the tree diameter(s) were re-measured over bark with few complementary heights. Recruited saplings or branches ≥1cm diameters were enumerated with new numbers consecutive from the last enumerated tree during the previous tree census for the transect, tagged and mapped while dead trees or branches were noted but not remeasured. Missing tags were replaced by reference to initial plot maps and worn out tags were also replaced. If prop roots grow through point of measurement (POM), the new POM is moved 2cm below the prop root (see Plate 8- Figure 3.7).

3.3 Data Analysis

3.3.1. Data size and collation

General field data were organised into various filing systems for easy analysis and presentation. Data was disaggregated into different subsets: georeference of transects and characteristics, species, multiple trees, problem trees, dendrometric data, height data, sampling and measurement effort, etc as deemed necessary for subsequent analysis (see Table 3.3 for a summary of measurements within the various data categories.

Table 3.3: Total number of measurements during the three census periods in Douala-Edea mangrove forest, Cameroon

Transect type	Census	Tree form	Data sheet type			
			Main Data sheet	Multi-stemmed Data sheet	Height Data sheet	Problem Tree Data sheet
TSP	0	Trees/stems	1552		189	
PSP	1	Trees	3894	525	693	172
		Sec. stems		849		
		Total	3894	1374	693	172
	2	Trees	4565	554		559
		Sec. stems		971		
		Total	4565	1525	88	559
	3	Trees	5007	568		719
		Sec. stems		1077		
		Total	5007	1645	0	719

3.3.3. Tree and stand characteristics and allometry

Tree and stand parameters were estimated following standard forest mensuration procedures (Loetsch *et al.*, 1973, Cailliez, 1980; Shiver and Borders, 1996; Avery and Burkhart, 2002; Husch *et al.*, 2003).

3.3.3.1. Estimation of secondary tree parameters

Tree secondary (derived) parameters (basal area, volume) were estimated from primary (basic) tree parameters (diameter, height) including secondary stems as follows:

$$g = \pi/4d^2 \ldots\ldots (3\text{-}1)$$

$$v = g.h.f. \ldots\ldots (3\text{-}2)$$

where g = tree basal area (m^2)

v= tree volume (m^3)

d= diameter at breast or diameter above stilt root height (m)

π = constant = 3.142

h= Plot mean bole height (m)

f= form factor [0.6 from similar surveys by Ajonina and Usongo (2001)]

3.3.3.2. Tree allometry

Various relationships were fitted to combined TSP and undisturbed PSP data through regression methods (ordinary least square-OLS procedures) (Draper and Smith, 1998) to select the best equations. These equations were subsequently used to estimate plot and stand values especially volume. The following traditional equations were tried.

a) Tree/stilt root volume functions

Stilt volume was obtained from published allometric equations (Ong *et al.*, 2004).

(vi) Simple linear regression model

$$V = b_0 + b_1D^2 \ldots\ldots (3\text{-}3)$$

$$V = b_0 + b_1D^2H \ldots\ldots (3\text{-}4)$$

(vii) Multiple linear regression model

$$V = b_0 + b_1D^2 + b_2H \ldots\ldots (3\text{-}5)$$

$$V = b_0 + b_1D^2 + b_2D^2H \ldots\ldots (3\text{-}6)$$

$$V = b_0 + b_1D^2H + b_2H \ldots\ldots (3\text{-}7)$$

(viii) Quadratic model

$V = b_0 + b_1D + b_2D^2$ ....(3-8)

(ix) Logarithmic transformed model

$\text{Log } V = b_0 + b_1D$ .... ….(3-9)

$\text{Log}V = b_0 + b_1 \log D$ ....(3-10)

$\log V = b_0 + b_1\log D + b_2\log H$ ....(3-11)

$V = b_0 + b_1\log D$ ....(3-12)

(x) Weighted (by D^2 and D^2H) model

$V/D^2 = b_0 + b_1\ 1/D^2 + b_2H$ .... ……(3-13)

$V/D^2\ H = b_0 + b_1\ 1/D^2\ H + b_2\ 1/H$ ....(3-14)

Volume line:

$V = b_0 + b_1g$ .... ……..(3-15)

Where in all cases,

V = volume (in cubic metres)

D = diameter at breast height (in cm)

H = tree total height (in metres)

g= tree basal area (m^2)

b_0, b_1 and b_2 are regression constants and coefficients respectively.

Initial screening was based on high coefficient of determination, R^2; low residual standard deviation, SD; significant F-ratio, then followed by various regression diagnostic procedures through graphical examination of residuals and normal plots to ascertain the meeting of various assumptions of normality and constant variance. For equations to be useful for predictive purposes, they must have high $R^2>0.5$, minimum bias when tested with independent data set and statistical tests especially paired t-tests. This validation exercise was performed on at least one third (1/3) of the data used in the estimation of model parameters. Three types of prediction bias were variously examined: mean difference, absolute difference (expressed as % of mean observed value) and mean % bias. These biases were estimated as follows:

Mean difference %, $e = 100x\sum_{i=1}^{n}(y_i - y_{\text{i-est}})/\ \bar{y}$ ....(3-16)

Mean absolute difference % = $|e| = 100x\sum_{i=1}^{n}|(y_i - y_{\text{i-est}})|/\ \bar{y}$ ....(3-17)

Mean % bias = $\bar{e} = \sum_{i=1}^{n}100(y_i - y_{iest})/\bar{y}$ ....(3-18)

Where $\overline{y}$ = mean of observed values and y_{iest} is the estimated y –value. The predictive behaviour and accuracy of the selected models were also tested on a range of diameter classes: 1cm ≤d<10 cm, d≥10cm and d> 50 cm.

A MINITAB and SPSS softwares were used to run these regression analyses.

b) Diameter above stilt roots and stilt root height

Similarly linear relationships were tried to depict diameter above stilt roots and stilt root height.

3.3.3.3. Estimation of stand parameters

Plot values

i) Mean diameter

Arithmetic mean diameter, $\bar{d}$

$$\bar{d} = (\sum_{i=1}^{n} d_i)/n \quad \text{(3-19)}$$

Quadratic mean diameter

$$Dq = \sqrt{(\sum_{i=1}^{n} d_i^2)/n} \quad \text{(3-20)}$$

Where d= diameter at breast or diameter above stilt root height (m)

n=number of trees measured

ii) Mean height

Similarly mean height was estimated as for arithmetic mean diameter.

(iii) Plot Basal area

$$G = \sum_{i=1}^{n} g_i \quad \text{(3-21)}$$

Where G = total basal area per plot (m^2); n = total number of trees per plot

Dividing total plot basal area by the number of stems in each plot gives the mean basal area per tree per plot.

iv) Volume per plot

Similarly,

$$V = \sum_{i=1}^{n} v_i \quad \text{(3-22)}$$

Where V = total basal area per plot (m^3)

Dividing total plot volume by the number of stems in each plot gives the mean volume per tree per plot.

Plot values on per hectare basis

N-nr of stems per ha, G-basal area per ha, V-bole volume per ha were obtained on per hectare basis by using appropriate tree conversion factors as follows.

$$TF = \frac{Unit.area}{Plot.area} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3\text{-}23)$$

Where TF = tree factor; unit area = 10 000m^2 (1 ha); Plot area = 200m^2 for 20mx10m plot and 100m^2 for 10mx10m plots and 600m^2 for 3x20mx10m systematically laid plot in transect

TF$_{20m\ x10m\ plot}$ = 50, TF$_{10m\ x\ 10m\ subplot}$ = 100 and TF$_{transect}$ = 16.667

N-nr of stems per ha = TF.n

BA-basal area per ha = TF.G

V-Total volume per ha = TF.V

3.3.3.4. Stand structure

a) Spatial pattern analysis

Spatial distribution and correlation

Spatial pattern in the distribution of tree developmental stages : saplings (1cm ≤dbh<10cm), poles (10 ≤dbh<30cm) and adults (dbh>30cm) was described based on 5cmx5cm quadrats at plot level using Moristia's (1959) $I\delta$ index:

$$I_\delta = \frac{Q\sum_{i=i}^{Q} X_i(X_i - 1)}{N(N-1)} \quad \ldots\ldots\ldots\ldots\ldots\ldots (3\text{-}24)$$

Where X$_i$ is the number of individuals in each quadrat, N the total number of individuals in the 0.02ha plot, Q the number of quadrats for a given quadrat size. Morisita's $I\delta$ is 1 for a random distribution, >1 for a clumped distribution, and <1 for a regular distribution.

To evaluate patterns of spatial correlation between tree developmental stages, the spatial patterns of correlation for two populations based on Yule's (1912) index, Q cited by Pielou (1969) was used. The index is zero for spatially independent distributions, maximum of +1.0 for completely overlapping populations (i.e., attraction) and less to a minimum of 0 for completely non-overlapping populations (i.e., repulsion). The index was calculated for all tree developmental pairs (X, Y) for the same quadrat sizes as Morisita's $I\delta$.

$$Q = (ad - bc)/(mnrs)^{1/2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3\text{-}25)$$

Where a = nr of quadrats which records X presence and Y presence together, b = presence of X but Y absent, c = absence of X but Y present and d= both X and Y absent, m = a+b, n = c+d, r = a+c, s = b+d

b) Diameter distribution

The flexible Weibull function was fitted to the combined TSP and PSP undisturbed forest data. The Weibull parameters were estimated using Excel spread sheet for diameter classes with interval of 5cm. Frequency of trees in each of diameter class was plotted in a semi-logarithm scale for PSP data and the determination of the De Lieucourt (1889) ratio q of ratio between successive diameter classes to further ascertain pattern of disturbance and recovery dynamics.

3.3.3.5. Stand allometry

Regression techniques were used to fit traditional stand height curve (Height–Diameter curve), stand volume and yield models used by foresters from combined TSP and undisturbed PSP data.

a) Stand height curve (Height – Diameter curve)

To facilitate the estimation of height from diameter measurements, a Height – Diameter curve was fitted from height and diameter measurements from TSP and undisturbed PSP. The following forms were tried by regression methods and similar methods used above were employed to select the best fitted equation.

- Log: log (Stoffels and Van Soest, 1953)

$$\text{In}(h) = b_0 + b_1 \text{In } D \qquad \text{.......................(3-26)}$$

- Log : inverse linear (Avery and Burkhart, 2002)

$$\text{In}(h) = b_0 + b_1/D \qquad \text{………………..(3-27)}$$

Log linear (Hendricksen, 1950)

$$h = b_0 + b_1 \text{In } D \qquad \text{………………..(3-28)}$$

- Inverse

$$h = b_0 + b_1/D \qquad \text{……...…………...(3-29)}$$

- Power function

$$h = b_0.D^{b1}$$

- Exponential function

$$h = b_0.e^{b_1/D} \qquad \text{…………………….(3-30)}$$

- Quadratic polynomial (Trorey, 1932)
  $h = b_0 + b_1.D + b_2.D^2$ ……………..(3-31)

Petterson's Curve (Petterson 1955)

$1/(h-b)^{0.4} = b_0 + b_1/D$ …….……….(3-32)

Where h denotes height, D denotes diameter at breast height, b breast height, and b_0-b_2 denote constants.

b) Stand volume equations

The following stand volume equations were fitted to the combined TSP and undisturbed PSP data using various combination of stand volume per hectare (Vha), Basal area per hectare (G) and dominant height (H_{dom}).

$V = b_0.G.H_{dom}$ …………………………………………..(3-33)

$\text{Log } V = b_0 + b_1 \log H_{dom} + b_2 \log G$ …………………… … ...………………(3-34)

$V = b_0 \text{ SI} + b_1 \text{ SD}$ ……………………………..………..(3-35)

The variables are as previously defined.

3.3.4. Stand and biomass conversion/expansion factor equations

3.3.4.1. Stand conversion factors

Volume conversion factors were developed render the per volume estimates comparable to standard/traditional inventory minimum diameter limit of 10 cm (Husch *et al.*, 2003), 5cm and 2.5cm (Cintron-Molero and Schaeffer-Novelli, 1984) used in most tropical forest mangrove inventories. Data from 24 subplots of undisturbed mangrove forest were used to determine such conversion factors for Nr trees/ha, basal area per hectare and volume per hectare.

3.3.4.2. Biomass conversion/expansion factor equations

Available published allometric equations on biomass were accessed and their level of applicability to the study site and region was evaluated. Equations retained were based on region and diameter range covered. No equation seems to cover diameter classes above 50cm consequently biomass values above this range are extrapolations. The retained equations used are presented below (Table 3.4).

Table 3.4: Published allometric equations used in estimating mangrove tree and stand biomass density and components

Biomass component	Species	Equation	r^2	n	Diameter (cm)		Reference
					Min	Max	
Total above ground biomass excluding stilt	All species	$W_{top} = 0.251pD^{2.46}$	0.98	104	5.0	49.0	Komiyama *et al*. (2005)
Total above ground biomass including stilt	*Rhizophora mangle*	$W_{top} = 0.128DBH^{2.60}$	0.94	9	1.0	32.0	Fromard et al (1998) cited by Smith III and Whelan (2006), Komiyama *et al.* (2008)
Total above ground biomass	*Avicennia germinans*	$W_{top} = 0.140DBH^{2.40}$	0.97	45	1.0	32.0	Fromard et al (1998) cited by Smith III and Whelan (2006), Komiyama *et al.* (2008)
Stem/trunk biomass	All species	$W_{trunk} = 0.0696p(D^2H)^{0.931}$	0.99	104	5.0	48.9	Komiyama *et al*. (2005)
	Avicennia germinans	$W_{trunk} = 0.1327DBH^{2.440}$	0.97	10	1.0	10.0	Day *et al*. (1987)
	Rhizophora mangle	$W_{trunk} = 0.0116DBH^{2.412}$	0.96	10	1.0	10.0	Day *et al*. (1987)
Stiltroot biomass	*Rhizophora apiculata*	$W_{stilt}= 0.0147DBH^{2.77}$	0.96	10	5.7	47.1	Komiyama *et al*. (1988) cited by Ong *et al*. (2004)
		$W_{stilt}= 0.0209DBH^{2.55}$	0.84	42	4.8	28.0	Ong et al. (2004)
	Rhizophora mangle	$W_{stilt} = 0.0116DBH^{3.183}$	0.83	10	1.0	10.0	Day *et al*. (1987)
Below ground biomass including stiltroots	All species	$W_{root} = 0.199p^{0.899}D^{2.22}$	0.95	26	5.0	45.0	Komiyama *et al*. (2005)

For generic biomass equations, average published oven dry specific density for *Avicennia* and *Rhizophora* were used (see Table 3.5)

Table 3.5: Published stem wood density values for mangrove species

Species	Stem wood density (t/m^3)	Reference
Avicennia alba	0.506	Komiyama *et al*. (2005)
Avicennia germinas	0.677	12% mc (0.83) USDA (?), oven dry weight conversion (Brown, 1997)
Avicennia marina	0.720	Briggs (1997)
Mean *Avicennia spp*	0.634	
Rhizophora apiculata	0.770	Komiyama *et al*. (2005)
R.apiculata, R.stylosa	0.810	Clough and Scott (1989)
Rhizophora mangle	0.890	Fearnside (1997)
Rhizophora mucrona	0.701	Komiyama *et al*. 2005
Mean *Rhizophora spp*	0.793	

The same data set reserved for the development of volume equations was used to obtain biomass estimates with the above equations. Ratios of tree biomass to volume were estimated and subsequently regressed to obtain diameter dependent biomass expansion/conversion factors (BEF). Following preliminary graphical analysis of BEF and diameter plots, three distinct patterns were observed in the range D<5 cm, D>5cm and D>30cm. These were further tested through analysis of variance and contrasts tests to evaluate consistency in the range (1cm<D<5cm, 1cm <D<30cm, 30m<D<50cm, D≥50cm). Stand biomass expansion/conversion factor equations were also established using data from undisturbed PSP constituting 24 subplots (10mx10m). Stand BEF equations were developed for all trees in the stand D≥1cm, D≥ 2.5, D≥5, D≥6.4 and D≥10cm to be amenable to inventories with various diameter limits.

3.3.5. Inventory data analysis

The inventory data obtained for TSP and undisturbed PSP were analysed for basic stand parameters (N, G, V) following Shiver and Borders (1996), Husch *et al.* (2003).

3.3.5.1. Inventory and monitoring costs

Costs in terms of time (manhours) for establishment and measuring temporal and permanent sample plot were also evaluated.

3.3.5.2. Comparing the efficiency of some sampling designs

Owing to the mono-specific nature of mangrove stands, it is hypothesised if using simple random sampling design for inventory could just be adequate than complicated designs currently used in upland forests. We therefore compare the efficiency of four sampling methods (simple random sampling, stratified random sampling, cluster sampling and stratified cluster sampling) in terms of sampling error. Sampling error (SE) is also the indicator of the precision of the estimates. At a given confidence level (95% in this study), SE depicts the probability of estimates deviating from what has been estimated if sampling were repeated a number of times. Thus the lower the SE, the more reliable is the estimate and vice versa.

a) Stratified sampling estimators

Define following Shiver and Borders (1996):

L = number of strata into which the population will be divided
N_h = number of sampling units in stratum h

N = number of sampling units in entire population; $N = \sum_{h=1}^{L} N_h$ …………(3-36)

n$_h$ = number of sampling units from stratum *h* included in the sample
n = total number of sampling units from all strata included in the sample;

$$n = \sum_{h=1}^{L} n_h \qquad \text{…………...(3-37)}$$

$y_{h,i}$ = an observed value of the variable *y* on sampling unit *I* in stratum *h*

The sample mean for stratum *h* is denoted $\bar{y}_h$:

$$\bar{y}_h = \frac{1}{n_h}\sum_{i=1}^{n_h} y_{h,i} \qquad \text{…………..…(3-38)}$$

The variance of the sample mean for stratum *h* is denoted $S^2_{\bar{y}_h}$:

$$S^2_{\bar{y}_h} = \frac{S^2_{y_h}}{n_h}\left(\frac{N_h - n_h}{N_h}\right) \qquad \text{……………..…(3-39)}$$

Where:

$S^2_{y_h}$ = sample variance among sampling units within stratum *h*

$$S^2_{y_h} = \frac{1}{n_h - 1}\left[\sum_{i=1}^{n_h} y^2_{h,i} - \frac{\left(\sum_{i=1}^{n_h} y_{h,i}\right)^2}{n_h}\right] \qquad \text{……………………………………..…(3-40)}$$

The sample total for stratum *h* is denoted $\hat{T}_h$:

$$\hat{T}_h = N_h \bar{y}_h \qquad \text{………………………………………(3-41)}$$

The variance of the sample total for stratum h is denoted $S^2_{\hat{T}_h}$

$$S^2_{\hat{T}_h} = (N_h)^2 S^2_{\bar{y}_h} \qquad \text{…………………………………………………(3-42)}$$

The sample mean for the entire population, denoted $\bar{y}_{ST}$,

$$\bar{y}_{ST} = \sum_{h=1}^{L}\frac{N_h}{N}\bar{y}_h = \frac{1}{N}\sum_{h=1}^{L} N_h \bar{y}_h \qquad \text{………………………………………………….…(3-43)}$$

Variance of the overall sample estimate of the population mean, denoted $S^2_{\bar{y}_{ST}}$ is

$$S^2_{\bar{y}_{ST}} = \sum_{h=1}^{L}\left(\frac{N_h}{N}\right)^2 S^2_{\bar{y}_h} \qquad \text{……………………………………………………..(3-44).}$$

The sample total for the entire population, denoted $\hat{T}_{ST}$, is

$$\hat{T}_{ST} = N\,\overline{y}_{ST} = N\left(\frac{1}{N}\sum_{h=1}^{L} N_h \overline{y}_h\right) = \sum_{h=1}^{L} \hat{T}_h \quad \text{……………………………………………(3-45)}$$

Variance of the overall sample estimate of the population total, denoted $S^2_{\hat{T}_{ST}}$, is

$$S^2_{\hat{T}_{ST}} = N^2 S^2_{\overline{y}_{ST}} = \sum_{h=1}^{L} N_h^2 S^2_{\overline{y}_h} = \sum_{h=1}^{L} S^2_{\hat{T}_h} \quad \text{…………………………………………………...(3-46)}$$

b) Cluster sampling estimators

Cluster sampling is a type of multistage sampling that consists of selecting primary sample points or locations and establishing a number of closely located secondary sampling units as a group or cluster at each selected primary point. The clusters can take a multitude of different configurations depending on the subplots, the distance between units and the geometric configuration. Hush *et al*., (2003) has illustrated some of the common cluster configurations. The configuration used in any fixed situation depends largely on the nature of sampling problem and universe of interest. If fixed secondary units are selected from a set of primary clusters it is referred to as simple, one stage, or single-stage cluster sampling and two stage cluster sampling when secondary units are sub-sampled randomly or systematically. In this study fixed plots (3) (clusters) (10mx20m) were laid systematically at 10m intervals within transects (Primary clusters). Many reasons have been provided by Hush *et al*., (2003) for use of cluster sampling in forest inventory including: large areas with dispersed sampling units difficult or impossible to identify or locate single sampling units and prohibitive time and cost associated with travelling between and location of single sampling units.

Hush *et al*., (2003) provide statistics for single-stage cluster of equal size as follows:

Let n = number of clusters

M = number of subunits per cluster

y_{ij} = value of parameter (e.g basal area, volume) for the jth subunit of the ith cluster

$y_i = \sum_{j=1}^{M} y_{ij}$ = total for jth cluster ………………………………………………(3-47)

$\overline{y}$ = y_i/M = $\sum_{j=1}^{M} y_{ij} / M$ = mean of sub unit of ith cluster …………………(3-48)

$\overline{y} = \sum_{i=1}^{n} y_i / n$ = estimated sample mean cluster …………………………(3-49)

$\overline{\overline{y}} = \sum_{i=1}^{n} y_i / n\,M = \overline{y}/M$ = estimated mean subunit………………………(3-50)

The variance among subunits has two components and is estimated by:

$s^2 = [(n-1)s^2_b + n(M-1)s^2_w]/(nM-1)$ ………………………………………(3-51)

where s^2_b is the variance between clusters and is estimated by:

$s^2_b = \sum_{i=1}^{n} (\overline{y_i} - \overline{\overline{y}})^2 / n-1$ …………………………………………………(3-52)

and s^2_w within clusters

$s^2_w = \sum_{i=1}^{n} \sum_{j=1}^{M} (y_{ij} - \overline{y_i})^2 / n(M-1)$ ………………………………………..(3-53)

Statistical efficiency in cluster sampling can be achieved by using sampling units that include within themselves as much of the heterogeneity of the population as possible to minimise the differences between sampling units. Intra-cluster correlation coefficient has been used to measure the degree of homogeneity within clusters and is an important statistics to determine the efficiency of cluster sampling or optimal cluster size (Schabenberger, 1991). Low homogeneity within clusters compared to between clusters results to high intra-cluster correlation while heterogeneous elementary units will yield a low or sometimes negative intra-cluster correlation.

3.3.6. Stand dynamics

3.3.6.1. Estimating basic demographic parameters

The following basic demographic parameters were estimated from PSP data:

Mortality rate = $TF.N_{dead}/\Delta t$ ………………………………….(3-54)

Also Annual Mortality, $M = 1 – [1-(N_0 – N_1)/N_0]^{1/\Delta t}$ …………………..(3-55)

Recruitment rate= $TF.N_{recruit}/\Delta t$ ………………………………….(3-56)

Growth (Current increment-CI)= ΔC (census 2)= $P_{t2} - P_{t1}$

or ΔC (census 3)= $P_{t3} - P_{t2}$ ……………………………………………(3-57)

Growth (Periodic increment-PI)= $\Delta P = P_{t3} - P_{t1}$ ………………………...(3-58)

Current Annual Increment (CAI) = $\Delta C/\Delta t$ …………………………(3-59)

Periodic Annual Increment (PAI) = $\Delta P/\Delta t$ …………………………(3-60)

Where the terms are as earlier defined except:

N_0 and N_1 are population counts at the beginning and end of each growth period

N_{dead} = number of dead trees during the period

$N_{reccuit}$ = Number of trees entering the 1cm class during the period

Δt = number of years

P_{t1}, P_{t2} are values of a parameter (diameter, basal area, volume, etc) measured at times t_1 and t_2 respectively. In our case t corresponds to census periods: t_1=2002-2003, t_2=2004-2005, t_3=2006-2007, and Δt=2 or 4 years

Basal area and volume increments were expressed on per hectare basis using:

$PAI,_{V,G} = TF.\ \Delta P_{V,G}/\Delta t$ …………………………(3-61)

3.3.6.2. Assessing human impacts on mangrove forest structure and dynamics

Using data from PSP, relevant statistical methods (descriptive statistics e.g. use of tables, figures, percentages, etc; inferential statistics e.g. use of analysis of variance, χ^2-test, t-test, etc) and packages (MINITAB release 13 and SPSS) were used to test hypotheses relating to human impact on stand structure and dynamics especially: spatial tree distribution patterns, diameter distribution, incidence of multi-stemmed trees, incidence of deformed trees, mortality, recruitment, growth and changes in species composition. A 2-factor (Treatments: site-4 x disturbance regimes-3) or 3-factor (including time-3) analysis of variance (ANOVA) technique using completely randomized design with 3 (plot level) or 6 replications (subplot level), or unreplicated (transect level –for two way analysis) (Akindele, 1989; Mean and Curnow, 1983) were used where appropriate with F-tests carried out to determine the main effects and interactions of treatments on most of the above parameters that were significant. Means were subsequently separated where necessary using post-ahoc tests using least significant difference (LSD) at p= 0.05.

3.3.6.3. Growth and yield of Avicennia germinans and Rhizophora spp in balanced mixed stands.

The mangroves across West and Central Africa are largely dominated by the *Rhizophora* species (red mangrove) (UNEP, 2007) which constitute more than 90% frequencies while *Avicennia* (white mangrove) made up less than 10%. In some cases *Avicennia* is not present. There are rising concerns about the continued disappearance of the species *Avicennia germinans* and possible extinction in the mangrove landscape (UNEP, 2007). Though *Avicennia germinans* presents favourable coppicing characteristics than *Rhizophora* that does not coppice, there is need to step up efforts to restore this species through appropriate silvicultural techniques in order to forestall its extinction. Balanced mixed stands of *Avicennia germinans* and *Rhizophora* spp were found in heavily exploited regime of zone 1 (Youme) with stand heights of 15.4m and 17.2m for *Avicennia* and *Rhizophora* respectively. This presents an opportunity to study the growth and yield of these species in balanced associations in order to explore silvicultural methods to regenerate the species and maintain the species composition of the West and Central African mangroves. Various statistical comparisons were made of the growth and yield characteristics of these species in this balanced mixed stands.

3.3.7. Modelling stand dynamics following mangrove forest exploitation

Data from PSP were exclusively used to model stand dynamics under different exploitation regimes where a disturbance scale based on proportion of basal area removed (Gr) was used. Both ordinary least squares (OLS) and binary logistic regressions based on maximum likelihood approaches were used where appropriate to model stand dynamics. Matrix models were also used to model changes in multi-stemmed tree status and stand structure. Stand dynamics model considered include individual tree basal area increment, mortality functions, recruitment functions, stand volume projection models, modelling some eco-morphological phenomena, changes in multi-stemmed status and structural dynamics through matrix models.

3.3.7.1 Individual tree basal area growth model

A generalised composite model proposed by Wykoff (1990) modified by Zhang *et al*. (2004) was used,

$$\text{In}(\Delta g+1)= a + b \times \text{SIZE} + c \times \text{COMPETITION} + s \times \text{SITE} + \varepsilon \;\ldots\ldots\ldots\ldots\ldots\ldots\ldots(3\text{-}62)$$

We add the management variable component representing human impacts on the forest. The basal area growth equation becomes:

$$\text{In}\ (\Delta G+1) = a + b \times \text{SIZE} + c \times \text{COMPETITION} + s \times \text{SITE} + m \times \text{Management} + \varepsilon \;\ldots(3\text{-}63)$$

Where In ($\Delta g+1$) is the response variable representing four year basal area increment plus 1 to offset negative growth and with the following potential explanatory variables being measurements at the beginning of the four year growth interval:

a) SIZE effects: initial diameter (D), reciprocal diameter (1/D), D^2, relative diameter, ($D/\overline{D}$), relative size interaction term ($D^2/\overline{D}$), stand quadratic diameter, QMD/D
b) COMPETITION effects: Basal area (G), Larger basal area (BAL), BAL/D
c) SITE effects: Top height (H_{dom}), Top crown ratio (CR_{dom})
d) Management/human impacts: Proportion of basal area removed (Gr), ($0 \leq Gr < 1$)

ε is the model error term

Data containing 2204 trees from 66 subplots of PSP were used in developing the model while 1224 trees were retained for model validation. Several combinations of predictor variables were tried in a weighted regression approach. Based on statistical screening criteria such as R^2, SE, significant t-value ($p<0.05$) for coefficients, variance inflation factors (VIF) less than 5, further regression diagnostic procedures through graphical residual and normal plots; the following form of the model was retained:

$$\ln(\Delta g+1) = b_0 + b_1 1/D + b_2 D^2/\overline{D} + b_3 Gr + b_4 G.Gr \quad \ldots\ldots (3\text{-}64)$$

Validation tests based on mean % difference, mean % absolute bias and mean % bias as predictive bias and student t-paired sample test were conducted to test the predictive accuracy of the model against observed values in independent data set following procedure given by Vanclay and Skovsgaard (1998).

3.3.7.2. Mortality functions

The probability of four year survival was modelled with the same independent variables used for the diameter growth model in addition to relative tree status expressed as the relative position on the cumulative basal area distribution (i.e. the biggest tree in the stand has RS = 0, and the smallest tree has RS = 1). Several combinations of these predictor variables were tried in binary logistic regression approach using the method of maximum likelihood to determine the parameters. The same data set used for the calibration of individual tree basal area growth models were used to obtain the maximum likelihood estimates of the parameter using SPSS. Based on statistical screening criteria such as χ^2-goodness-of-fit statistics (which must not be significant at p=0.05) and Wald statistics (significant at p=0.05) for coefficients, the following form of the model was retained:

$P = (1+ e^{-(b_0 + b_1 1/D + b_2 D/AMD + b_3 SI + b_4 Gr)})^{-1}$ ……………………………..…(3-65)

Four year survival can be converted to an annual mortality function by using the equation:

$M(x) = 1 - S(x)^{1/n}$ ………………………………………………………(3-66)

Where M(x) is the annual mortality rate function, S(x) the 4 year survival function and n the number of years, four in this case.

Validation was based on chi square goodness-of-fit test on survival frequencies of the seven diameter classes against expected survival obtained by the model.

3.3.7.3. Recruitment functions

The logistic and regression approach of modelling recruitment (Vanclay, 1994) were applied to 66 subplots split into two with 33 plots used to validate the model.

a) <u>Logistic model</u>

The final binary logistic function retained for four year recruitment was of the form:

$P = (1+ e^{-(b_0 1/Nr + b_2 SI + b_3 Gr)})^{-1}$ ……………………………………………(3-67)

Validation tests were based on a chi-square frequency (nr of plots) with recruits against expected obtained by the model.

b) <u>Linear regression model</u>

The final form of linear regression model retained was:

$Ln\ (4yr\ Recr) = b_0 ln(Nr/Gr+1) + b_1 Gr$ ………………………………………(3-68)

Where Nr is Nr trees per ha and Gr as earlier defined

3.3.7.4. Stand volume projection models

Data from the 66 PSP subplots on stand volume recorded for three census periods facilitated the development of stand volume projection and yield equations following different disturbance regimes. Three equations were fitted using OLS procedures: time dependent volume equation for short-term prediction and two yield equations (time independent) following various disturbance systems.

$V_t = b_0 + b_1 G_t + b_2 Gr + b_3 T$ …………………………………………………(3-69)

$V = b_0 + b_1 G + b_2 Gr$ ……………………………………………………..…(3-69)

$\ln V = b_0 + b_1 \ln SI + b_2 Gr + b_3 SI/G + b_4 G^2$ ……………………………………..(3-70)

Where V_t is stand volume at time period, T, T is period elapsed after disturbance and the rest of the variables are as earlier defined.

3.3.7.5. Modelling eco-morphological phenomena

The large data set collected on multi-stemmed and problem trees greatly facilitated insights into hypothesing if eco-morphological phenomena such as probability of tree branching, tree damage, root sprouts in Rhizophora and species invasion could be modelled. Binary logistic regression approach was employed. The presence or absence of phenomena as independent variable and all set of predictor variables earlier described and their various combinations were tested. Statistical screening criteria such as χ^2-goodness-of-fit statistics (which must not be significant at p=0.05) and Wald statistics (significant at p=0.05) for coefficients were used to select the most appropriate form of the model. Finally, only incidence of multi-stemmed trees and root sprout in Rhizophora could successfully be modelled. The form of equations is presented below:

a) Incidence of multi-stemmed trees (probability of tree branching)

$P = (1 + e^{-(b_0 + b_1 D + b_2 \ln D + b_3 RS + b_4 Gr + b_5 G.Gr + b_6 T)})^{-1}$ ………………………(3-72)

b) Incidence of root sprouts in *Rhizophora*

$P = (1 + e^{-(b_0 + b_1 RS + b_2 RS.Gr + b_3 T)})^{-1}$ ………………………………………...(3-73)

The variables are as earlier defined.

Validation was based on chi square goodness-of-fit test on incidence (frequencies) within the seven diameter classes against expected incidence obtained by the model.

3.3.7.6. Modelling dynamics of multi-stemmed trees

Observations on the change on multi-stemmed (MS) status within the tree population were made. Some trees were gaining MS status while some were losing this status i.e. becoming single stemmed trees (SS) after every census period following the first. It becomes apparent if this process could be represented as a simple two-state (SS = state 1, MS = state 2) Markov chain process summarised in a 2x2 matrix thus:

$$A = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix}$$

Where a_{11} represents proportion of trees that survived but remained SS; a_{12}, survived but moved from MS to SS; a_{21}, survived but moved from SS to MS; and a_{22} survived but remained MS after a time interval t. The entries are thus calculated:

a_{ij} = P(State Survival).P(change of state) ……………………………………(3-74)

If we denote recruitment during the second census period to be a column vector:

$$B = \begin{bmatrix} NR_{SS} \\ NR_{MS} \end{bmatrix}$$

The evolution of the stand could then be projected over some period using:

$N_{Ti} = A^T N_{0i} + B_{2i}$ ……………………………………………………..(3-75)

Where

N_{Ti} = the projected population structure at the end of the growth period

N_{0i} = Population structure during the first tree census (i=1 for SS, and i=2 for MS)

N_{0i} can be modified to $N_{0i,j}$ to structure the population into j diameter classes

A = the population projection matrix

B_{2i} = State specific recruitment during the second period assumed to be constant throughout projection period.

T = time step for the matrix which is equal to 2 years.

The stability of the SS:MS distribution can be investigated through eigenvector analysis (Usher, 1966). Data from the first two censuses were used to develop the parameters of the model then predictions were made for the third census (T=2) with which the validity of the model was assessed through chi-square goodness-of-fit tests.

3.3.7.7. Modelling stand structural dynamics with population growth matrix model

Leslie-Lefkovich type matrix models were adapted and used to study the dynamics of tree population of the site. Transitory matrix models were constructed to describe stand structure and stable states for various disturbed conditions, sites and pooled situations. Five diameter classes commensurate with the various tree developmental stages or wood utility classes were used as follows (the samplings being divided into classes at an interval of 2cm to take advantage of large number of stems in this category): ≥1cm to <3cm (code 1), ≥3cm to <5cm (code 2), (≥5cm to <7cm code 3), saplings; ≥7cm to <10cm (code 4) large saplings (posts); ≥10cm to <30cm (code 5) poles; ≥30cm to <50cm (code 6) standards; and ≥50+cm (code 7), veterans.

The population growth matrix of type

$$P = \begin{bmatrix} m_{11} & c_{12} & c_{13} & .... & c_{17} \\ m_{21} & m_{22} & m_{23} & .... & m_{27} \\ . & . & . & . & . \\ . & . & . & . & .. \\ m_{51} & m_{52} & m_{53} & & m_{57} \end{bmatrix}$$

was adopted where m_{ij} is the contribution over a unit time interval of trees in size class j to size class i (i, j = 1,2…,7) and c_{ij} is the average recruitment per individual tree in class j.

Matrix models use the equation $\mathbf{n}(t+1) = \mathbf{P} \times \mathbf{n}(t)$, where $\mathbf{n}(t)$ and $\mathbf{n}(t+1)$ are column vectors that contain the population structure at time t and $t+1$, and **P** is a square matrix containing transition probabilities among categories during growth period. In this equation, the population structure at time $t+1$ is obtained by multiplying the structure at time t with the transition matrix that contains information on the dynamics of the population. When repeating this multiplication many times, the population structure (in relative terms) and population growth rate become stable. In that situation, the rate at which the population grows (the asymptotic population growth rate) is equal to the dominant eigenvalue (λ) of matrix **P**, which is an inherent characteristic of the transition matrix. The stable population structure is also equal to a characteristic of matrix **P**: the right eigenvector. Further theoretical documentation on matrix models are presented by Caswell (1989). Elements m_{ij} of transition matrix **P** can be grouped according to their position in the matrix (Zuidema and Boot, 2002): growth elements (*G*) represent an individual's probability to grow from one category to the next (they are positioned in the sub-diagonal of the matrix); stasis elements (S) represent the probability of remaining in the same category (elements in the diagonal) and fecundity elements (*F*) represent the number of offspring produced by an individual in a certain category (elements in the upper row, except for the top-left element).

a) Assumptions of the Model

Any tree in the population could make one and only one of these moves:

(i) Move to a higher diameter class;
(ii) Remain in class i, or die in class i;
(iii) That no tree moves backwards, i.e. no shrinkage would be allowed during the growth period;
(iv) That no tree be deemed to have moved up more than one class during the growth period; and
(v) That the growth conditions during the projection periods do not change significantly.

b) Model Construction

First, all trees were assigned to their respective diameter classes using the first tree census data. The data of the second census were used to determine the proportion of life trees that remained or moved to the next higher class.

Thus the diagonal elements (Growth elements) of the matrix **P** were calculated as:

$$m_{jj} = (1 - P_j)S_j \qquad \text{...(3-76)}$$

Where

S_j = the survival rate of the trees in class j

P_j = the probability of trees moving from class j to class j+1 at the end of the growth period.

$(1 - P_j)$ = the probability of trees remaining in class j at the end of the growth period.

Then the subdiagonal elements (stasis elements) as:

$$(m_{j+1,j}) = P_j S_j \qquad \text{...(3-77)}$$

The fecundity elements, C_{1j} are elements of the first row of **P**, j = 2, 3, …,7 representing the average contribution of trees in each of the diameter size classes to the recruitment of the stand during the growth period. The estimation of C_{ij} was based on the assumption of uniform contribution to the lowest diameter class by the reproductive classes 10cm and above, but weighted proportionality to trees present in each diameter class. In this case, individual stem's contribution to seedling production was proportional to the stem's diameter.

The fecundity elements were then calculated as: F = P(Si)P(fi).nj (Zuidema and Boot, 2002) where P(fi) is the proportion of the trees in the class i that are fecund (diameter classes D≥ 7cm) and nj is the number of offsprings produced by individual in class j in the fecundity category being weighted proportion of survived individuals in the class.

Stages (diameter classes) which recorded no individual moving to the next higher stage were assigned a probability of movement to the next stage of 0.001 following Pinero *et al.* (1984). Therefore except for the diagonal and the sub-diagonal elements and the first row of the matrix **P**, all other elements would be zero. This is in accordance with our assumption which neither allowed for shrinkage nor movement more than one size class during the growth period.

Parameters of the matrix model were estimated from a spreed sheet programme developed for the purpose.

c) Predictions with the model

The evolution of the stand was then projected over some period using:

$$N_{Ti} = P^T N_{0i} \qquad \text{..(3-78)}$$

Where

N_{0i} = Population structure during the first tree census

N_{Ti} = the projected population structure at the end of the growth period

P = the population projection matrix

T = time step for the matrix which is equal to 2 years.

d) Testing of the model

The accuracy of the matrix model in estimating the population structure of the stand was tested by comparing model prediction of expected diameter distribution for the period t_3 with the actual third tree recensus diameter distribution data using the chi-square goodness-of-fit test as follows (Spiegel, 1981):

$$X^2 = \sum_{i=1}^{n} \frac{(o_i - e_i)^2}{e_i} \qquad \text{(3-79)}$$

Where

o_i = observed frequency in class i (i.e. by third tree recensus data)

e_i = expected frequency in class i (predicted by the model for third tree recensus).

The null hypothesis was then tested at 95 % confidence interval

e) Stability studies

The stable state and stable stage distribution were respectively determined by finding the eigenvalue and eigenvector associated with each of the population projection matrices. The nature and magnitude of the dominant eigenvalue and associated eigenvector was examined for stability. Eigen values and vectors were extracted using the PC – MATLAB software.

The construction of matrices for different regimes across the various sites and various pooled situations of sites and regimes offer wide range of possibilities to appreciate the sensitivity of the model to different perturbation situations and sites.

3.3.8. Comparing the modelling approaches

The efficiencies of various models developed were assessed through a stand table projection approach. Data for the first and third census were used to make projections over four years using survival, recruitment and the growth models developed, the expected total population given by the models was verified against observed population through chi-square goodness-of-fit test.

3.3.9. Determining sustainable harvest limits

The various models developed can be used to develop sustainable harvest limits.

Rotation ages are determined from different product classes through the time of “passage” approach by dividing the class interval of each product class by the mean annual increment of the product class (Devoe and Cole, 1998). A practical approach in forestry is also to equilibrate growth rate (productivity) with harvest rate. That is the allowable cut is simply equal to the growth rate. Other methods include the determination of dominant eigen value (λ) associated with the population projection matrix (Usher, 1966; Osho and Ajonina, 1998) which enables the harvests to be either concentrated to some diameter classes or spread evenly depending on the objectives of such harvests. The established tree volume equations and tables drawn from such equations will facilitate practical field determination of actual harvests from annual coupes to avoid wastes.

4. RESULTS

The results of this study are presented in six sections. The first section presents the various allometric relationships, the second, inventory data analysis, the third impact assessments, fouth section on the dynamics of *Avicennia* and *Rhizophora* species in balanced mixed stands while models of stand dynamics following different exploitation pressures are presented in section five. A comparison is made of different modelling methods in section six. The results are presented in tables and graphs. Greater details or supplementary information are presented in appendices available at the Department of Forest Biometry, University of Freiburg, Germany.

4.1. Allometric relationships

Allometric relationships to guide sustainable exploitation of mangrove forest are presented in Tables 4.1 to 4.4 and Figures 4.1 - 4.10. This includes height partitioning relationships, stand curves, tree and stand volume equations including their statistical and graphical fit tests Where-ever appropriate various predictive accuracies of the models within given diameter range (1-10cm, 10-50cm, >10cm, 50+cm, ≥1cm) are further tested. Volume reduction/conversion factors to render stand volume estimates comparable to other inventories with varying diameter limits are also presented. Biomass expansion/conversion factors equations or constants have been developed based on ratios of tree volumes to total biomass obtained from relevant published generic biomass equations.

Table 4.1: Diameter and height class distribution of trees used in the development of allometric models for Douala-Edea coastal Atlantic mangrove forest, Cameroon

Diameter class (cm)	Species	Total height class (m)							
		1-10	10-20	20-30	30-40	40-50	50+	Total	**% All trees**
1-10	Red mangrove (Rhizophora)	540	31					571	**64.7**
	White mangrove (Avicennia)	33	8					41	**4.6**
	Total	573	39					612	**69.4**
10-20	Red mangrove (Rhizophora)		12	10	6	1		29	**3.3**
	White mangrove (Avicennia)		1		2	1		4	**0.5**
	Total		13	10	8	2		33	**3.7**
20-30	Red mangrove (Rhizophora)		1	18	7	3		29	**3.3**
	White mangrove (Avicennia)		2	1	2			5	**0.6**
	Total		3	19	9	3		34	**3.9**
30-40	Red mangrove (Rhizophora)			14	22	8	1	45	**5.1**
	White mangrove (Avicennia)			1	1			2	**0.2**
	Total			15	23	8	1	47	**5.3**
40-50	Red mangrove (Rhizophora)		2	4	23	8	4	41	**4.6**
	White mangrove (Avicennia)			1	5	2	1	9	**1.0**
	Total		2	5	28	10	5	50	**5.7**
50+	Red mangrove (Rhizophora)		1	3	52	17	18	91	**10.3**
	White mangrove (Avicennia)			1	9		5	15	**1.7**
	Total		1	4	61	17	23	106	**12.0**
Total Red mangrove (Rhizophora)		540	47	49	110	37	23		
%		**94.2**	**81.0**	**92.5**	**85.3**	**92.5**	**79.3**		
Total White mangrove (Avicennia)		33	11	4	19	3	6		
%		**5.8**	**19.0**	**7.5**	**14.7**	**7.5**	**20.7**		
Total		573	58	53	129	40	29	882	**100.0**
% All trees		**65.0**	**6.6**	**6.0**	**14.6**	**4.5**	**3.3**	**100.0**	

4.1.1. Height partitioning relationships

The relationship between total height, bole height and crown length seem to be weak in these mangrove trees (Figures 4.1 to 4.3).

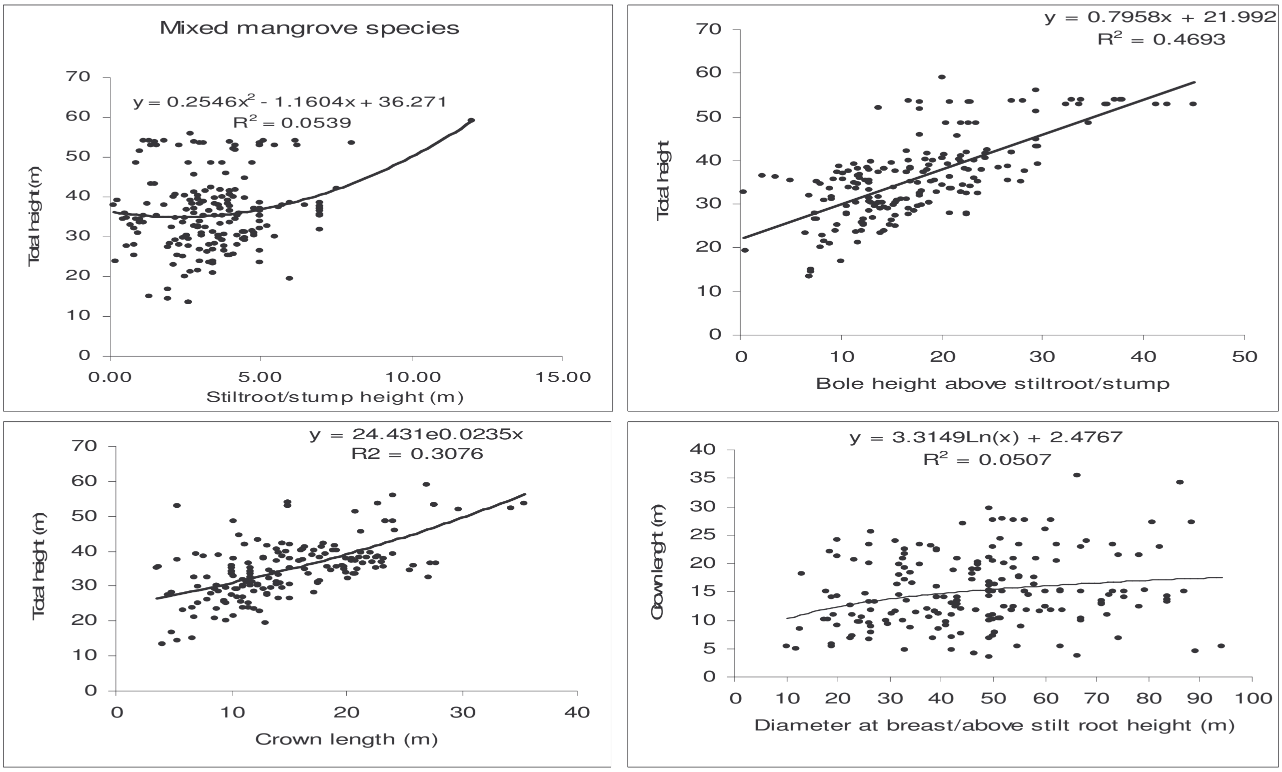


Figure 4.1. Stem height dimensional relationships in mixed species in Douala-Edea mangrove forest, Cameroon

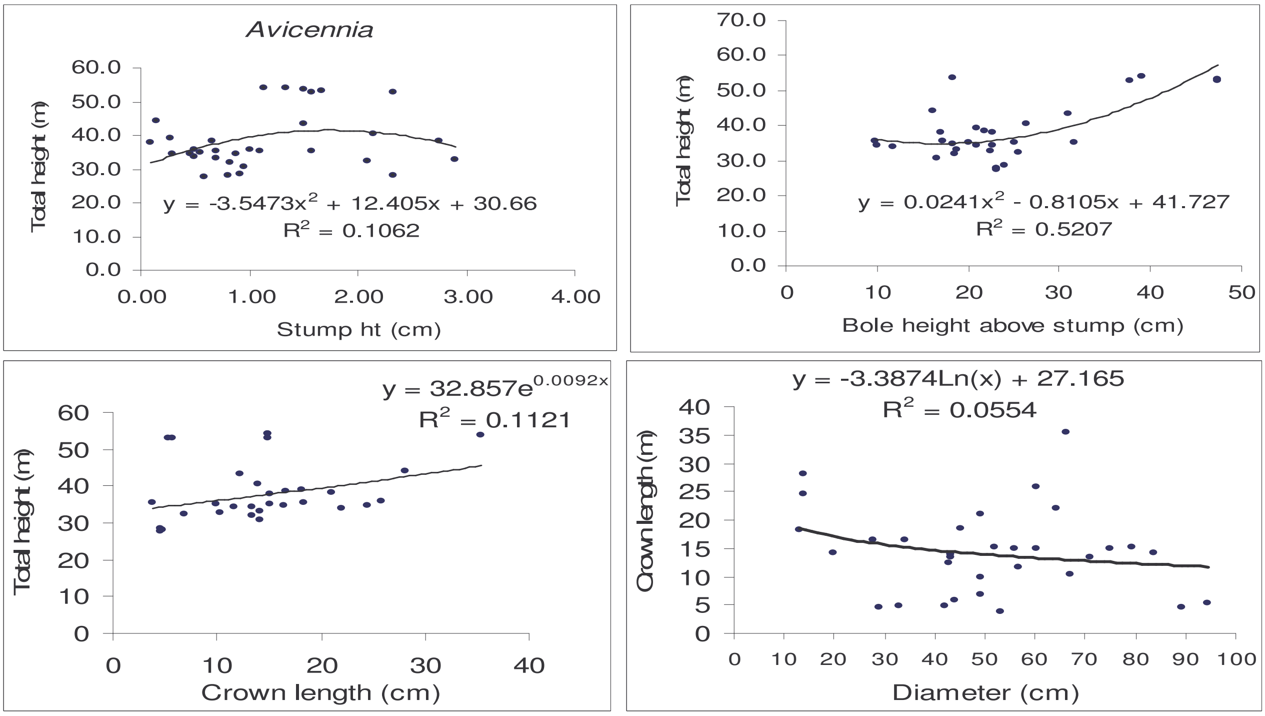


Figure 4.2. Stem height dimensional relationships in *Avicennia* species in Douala-Edea Cameroon

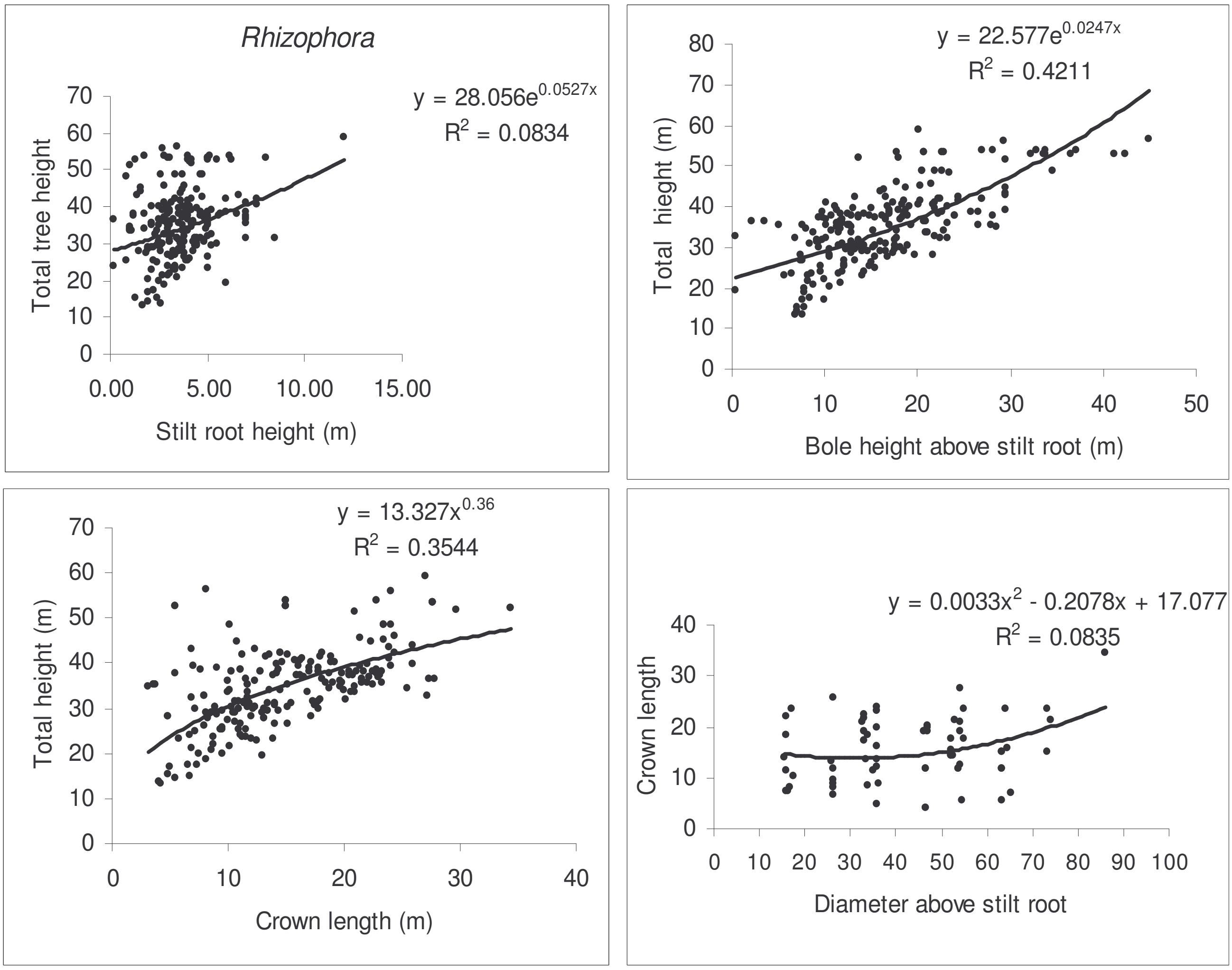


Figure 4.3. Stem height dimensional relationships in *Rhizophora* species in Douala-Edea Cameroon

4.2.2. Height-Diameter curves

Statistical and fit properties of the height diameter models are presented (Tables 4.2). All the models were consistent in describing the heights of *Avicennia* but not for *Rhizophora* and mixed species. The different types of model display various predictive accuracies within given diameter range (1-10cm, 10-50cm, >10cm, 50+cm, ≥1cm). The quadratic model seems the best and robust for individual and joint species of mangroves.

Table 4.2: Statistical properties of selected Height- Diameter equations for Douala-Edea coastal Atlantic mangrove forest, Cameroon

Species	Type	Independent variable	n	Model summary				Coefficients							
				SE	R^2-adj	F-ratio	Sig	Coef	Unstandardised		Standardised	t	Sig	95% CI for B	
									B	SE	Beta			Lower	Upper
Avicennia	Stoffels and Van Soest, 1953 (power)	lnH	51	0.356	0.850	285.069	0.000	Constant	1.048	0.111		9.456	0.000	0.825	1.271
								lnD	0.649	0.038	0.924	16.884	0.000	0.572	0.726
	Avery and Burkhart, 2002 (exponential)	lnH	51	0.520	0.681	107.910	0.000	Constant	3.418	0.099		34.514	0.000	3.219	3.617
								1/D	-4.513	0.434	-0.829	-10.388	0.000	-5.385	-3.640
	Inverse	H	51	11.327	0.532	57.798	0.000	Constant	32.98	2.160		15.271	0.000	28.640	37.319
								1/D	-72.015	9.472	-0.736	-7.602	0.000	-91.050	-52.979
	Trorey, 1932 (Quadratic polynomial)	H	51	7.727	0.782	90.756	0.000	Constant	4.179	1.827		2.288	0.027	0.506	7.852
								D	1.02	0.140	1.676	7.292	0.000	0.739	1.301
								D^2	-6.67E-03	0.002	-0.857	-3.730	0.001	-0.010	-0.003
	Petterson,1955	$1/H^{0.4}$	51	.0.0885	0.723	131.578	0.000	Constant	0.259	0.013		19.180	0.000	0.031	0.286
								1/D	0.678	0.059	0.854	11.471	0.000	0.559	0.797
	Linear	H	51	8.685	0.725	132.637	0.000	Constant	7.933	1.714		4.629	0.000	4.489	11.377
								D	0.52	0.045	0.855	11.517	0.000	0.429	0.611
	Hendricksen,1950	H	51	7.500	0.795	194.594	0.000	Constant	-7.261	2.335		-3.109	0.003	-11.954	-2.567
								lnD	11.292	0.809	0.894	13.950	0.000	9.665	12.900
Rhizophora	Stoffels and Van Soest, 1953 (power)	lnH	606	0.269	0.928	7780.466	0.000	Constant	0.853	0.016		53.856	0.000	0.822	0.884
								lnD	0.72	0.008	0.963	88.207	0.000	0.704	0.736
	Avery and Burkhart, 2002 (exponential)	lnH	606	0.472	0.777	2111.900	0.000	Constant	3.105	0.033		93.790	0.000	3.040	3.170
								1/D	-2.942	0.064	-0.882	-45.955	0.000	-3.067	-2.816
	Trorey, 1932 (Quadratic polynomial)	H	606	4.231	0.906	2901.916	0.000	Constant	1.676	0.225		7.457	0.000	1.235	2.118
								D	1.294	0.032	1.880	40.443	0.000	1.231	1.957
								D^2	-1.08E-02	0.000	-1.004	-21.604	0.000	-0.012	-0.010
	Petterson,1955	$1/H^{0.4}$	606	0.074	0.816	2689.154	0.000	Constant	0.302	0.005		58.079	0.000	0.292	0.313
								1/D	0.522	0.010	0.904	51.857	0.000	0.502	0.542
	Linear	H	606	5.631	0.833	3013.467	0.000	Constant	3.86	0.267		14.442	0.000	3.335	4.385
								D	0.628	0.011	0.913	54.895	0.000	0.606	0.651
	Hendricksen,1950	H	606	4.688	0.884	4615.979	0.000	Constant	-2.147	0.276		-7.771	0.000	-2.689	-1.604
								lnD	9.668	0.142	0.940	67.941	0.000	9.388	9.947
Mixed species	Stoffels and Van Soest, 1953 (power)	lnH	602	0.286	0.922	7141.383	0.000	Constant	0.878	0.019		45.832	0.000	0.840	0.916
								lnD	0.71	0.008	0.960	84.507	0.000	0.694	0.727
	Avery and Burkhart, 2002 (exponential)	lnH	602	0.476	0.786	2207.636	0.000	Constant	3.222	0.030		108.346	0.000	3.163	3.280
								1/D	-3.346	0.070	-0.887	-46.985	0.000	-3.486	-3.206
	Trorey, 1932 (Quadratic polynomial)	H	602	5.216	0.880	2213.013	0.000	Constant	1.904	0.298		6.379	0.000	1.318	2.490
								D	1.288	0.033	1.883	38.834	0.000	1.223	1.353
								D^2	-1.07E-02	0.001	-1.040	-21.439	0.000	-0.012	-0.010
	Petterson,1955	$1/H^{0.4}$	602	0.072	0.827	2868.888	0.000	Constant	0.287	0.004		63.926	0.000	0.278	0.296
								1/D	0.576	0.011	0.909	53.562	0.000	0.555	0.597
	Linear	H	602	6.929	0.789	2248.071	0.000	Constant	4.895	0.350		13.967	0.000	4.206	5.583
								D	0.608	0.013	0.888	47.414	0.000	0.583	0.633
	Hendricksen,1950	H	602	5.635	0.860	3706.780	0.000	Constant	-3.468	0.377		-9.201	0.000	-4.209	-2.728
								lnD	10.071	0.165	0.928	60.883	0.000	9.746	10.396

4.2.3. Tree and stand volume equations

Statistical and fit properties of the tree volume models are presented (Tables 4.3). All the models were consistent in describing the volumes of *Rhizophora* and mixed species but not for *Avicennia*. Like the H-D models, the different types of model display various predictive accuracies within given diameter range. The logarithm model seems the best and robust for volume prediction for individual and joint species of mangroves.

Table 4.3: Statistical properties of selected tree volume equations for Douala-Edea coastal Atlantic mangrove forest, Cameroon

Species	Type	Independent variable	n	Model summary				Coefficients								Durbin - Watson	Residual statistics			
				SE	R^2-adj	F-ratio	Sig	Coef	Unstandardised		Standardised	t	Sig	95% CI for B			Min	Max	Mean	SD
									B	SE	Beta			Lower	Upper					
Avicennia	Simple linear	VH(st)	51	1.10054	0.952	1010.032	0.000	D^2	1.92E-03	0.000	0.976	31.781	0.000	0.002	0.002	2.48	-2.54	3.71	-0.143	0.989
	Quadratic	VH(st)	51	1.03908	0.957	570.073	0.000	D	-3.59E-02	0.013	-0.272	-2.663	0.010	-0.063	-0.009	2.68	-3.25	2.81	0.062	0.988
								D^2	2.43E-03	0.000	1.237	12.117	0.000	0.002	0.003					
	log	logVH(st)	51	0.1553	0.989	4627.864	0.000	constant	-3.875	0.049		-79.620	0.000	-3.973	-3.778	1.70	-2.45	2.92	0.000	0.990
								logD	2.643	0.039	0.995	68.028	0.000	-2.564	2.721					
	Volume line	VH(st)	51	1.10054	0.952	1010.032	0.000	g	24.434	0.769	0.976	31.781	0.000	22.890	25.978	2.48	-2.54	3.71	-0.143	0.989
Rhizophora	Simple linear	Vsr	606	0.03901	0.902	5720.917	0.000	D^2Hsr	5.52E-05	0.000	0.951	75.637	0.000	0.000	0.000	1.58	-6.90	7.67	0.050	0.999
	Multiple linear	Vsr	606	0.09958	0.904	2760.823	0.000	constant	2.42E-02	0.005		4.996	0.000	0.015	0.034	1.62	-7.37	7.41	0.000	0.998
								Hsr	-3.25E-02	0.004	-0.167	-8.147	0.000	0.040	0.025					
								D^2Hsr	6.24E-05	0.000	1.075	52.362	0.000	0.000	0.000					
	Simple linear	VH(sr)	606	0.54665	0.947	10826.334	0.000	D^2	1.65E-03	0.000	0.973	104.050	0.000	0.002	0.002	1.72	-5.10	9.22	0.061	0.998
	Multiple linear	VH(sr)	606	0.5286	0.943	4993.168	0.000	constant	-0.154	0.029		-5.247	0.000	-0.212	-0.097	1.53	-4.35	9.73	0.000	0.998
								D^2	1.52E-03	0.000	0.886	54.711	0.000	0.001	0.002					
								H(sr)	1.86E-02	0.003	0.104	6.422	0.000	0.013	0.024					
	Quadratic	VH(sr)	606	0.5377	0.949	5603.750	0.000	D	-1.55E-02	0.003	-0.153	-4.596	0.000	-0.022	-0.009	1.78	-5.77	8.62	0.034	0.999
								D^2	1.90E-03	0.000	1.120	33.713	0.000	0.002	0.002					
	log	logVH(sr)	606	0.1236	0.994	98599.221	0.000	constant	-3.975	0.007		-548.468	0.000	-3.989	-3.961	1.45	-4.19	4.44	0.000	0.999
								logD	2.699	0.009	0.997	314.005	0.000	2.683	2.716					
	Volume line	VH(sr)	606	0.5466	0.947	10826.334	0.000	g	21.046	0.202	0.973	104.050	0.000	20.649	21.443	1.72	-5.10	9.22	0.000	0.998
Mixed species	Simple linear	VH(sr/st)	602	0.7033	0.935	8708.284	0.000	D^2	1.63E-03	0.000	0.967	93.318	0.000	0.002	0.002	1.59	-7.10	9.40	0.050	0.999
	Multiple linear	VH(sr/st)	602	0.66349	0.930	3969.839	0.000	constant	-0.252	0.039		-6.476	0.000	-0.328	-0.176	1.38	-6.42	10.72	0.000	0.998
								D^2	1.46E-03	0.000	0.853	51.912	0.000	0.001	0.062					
								H(sr/st)	2.58E-02	0.003	0.142	8.628	0.000	0.020	0.032					
	Quadratic	VH(sr/st)	602	0.7003	0.936	4395.296	0.000	D	-8.91E-03	0.004	-0.088	-2.500	0.013	-0.016	-0.002	1.60	-7.15	9.40	-0.050	0.999
								D^2	1.77E-03	0.000	1.051	29.845	0.000	0.002	0.002					
	log	logVH(sr/st)	602	0.1325	0.993	90568.349	0.000	constant	-3.968	0.009		-447.695	0.000	-3.986	-3.951	1.48	-3.92	3.70	0.000	0.999
								logD	2.695	0.009	0.997	300.946	0.000	2.678	2.713					
	Volume line	VH(sr/st)	602	0.7033	0.935	8708.284	0.000	g	20.763	0.222	0.967	93.318	0.000	20.326	21.200	1.59	-7.15	9.40	-0.050	0.999

4.2.4. Stand volume equations

Statistical and fit properties of the selected stand volume models are presented (Tables 4.4a). The selected models were consistent in describing stand volume. The logarithm model is still very appropriate in predicting stand volume.

4.1.5. Validation of the allometric models with data from another region

The models display various statistical behaviours when tested with data collected for a climate change project from another mangrove region - Ntem transborder mangrove region some 300 km away. It is not surprising that the data related to *Rhizophora* were a fit to data in the region since the mangroves in the region compose entirely of *Rhizophora* species. Quadratic volume model was a fit to the data set while the log model was a good fit at diameters lower than 10cm where most of the trees (81%) lie. The Hendrickson's height model –was a fit to the data set.

4.1.6. Volume reduction factors

To render volume estimates comparable to other inventories with varying diameter limits, volume expansion factors were developed. Other stand parameters such as nr/ha and basal area per ha were also considered (Table 4.4 b).

Table 4.4: Statistical properties of selected stand volume equations and conversion factors for Douala-Edea coastal Atlantic mangrove forest, Cameroon

a) Statistical properties of selected volume equations

Category	Type	Independent variable	n	Model summary				Coefficients								Durbin - Watson	Residual statistics			
				SE	R^2-adj	F-ratio	Sig	Coef	Unstandardised		Standardised	t	Sig	95% CI for B			Min	Max	Mean	SD
									B	SE	Beta			Lower	Upper					
All stems above 6.4 cm (from TSP)	Simple Linear	$Vha_{d>=6.4cm}$	66	307.500	0.976	2669.440	0.000	Constant	-437.707	58.332		-7.504	0.000	-554.239	-321.175	1.39	-3.18	4.54	0.000	0.920
								G	26.086	0.505	0.988	51.667	0.000	25.078	27.095					
	Multiple linear	$Vha_{d>=6.4cm}$	66	289.300	0.989	2869.802	0.000	G	26.368	0.484	1.123	54.487	0.000	25.401	27.335	1.68	-3.35	4.33	0.10	0.992
								H_{dom}	-12.381	1.460	-0.175	-8.482	0.000	-15.297	-9.465					
	Log	$lnVha_{d>=6.4cm}$	66	0.167	0.972	2266.651	0.000	Constant	1.964	0.110		17.917	0.000	1.745	2.184	1.71	-1.95	3.95	0.000	0.992
								lnG	1.227	0.026	0.986	47.609	0.000	1.175	1.278					
Trees >=1.0 cm (from PSP)	Simple Linear	$Vha_{d>=1.0cm}$	16	113.600	0.952	297.106	0.000	Constant	-222.361	56.287		-3.950	0.001	-343.084	-101.637	1.94	-1.63	2.09	0.000	0.966
								G	25.087	1.455	0.977	17.237	0.000	21.965	28.208					
	Log	$lnVha_{d>=1.0cm}$	16	0.159	0.986	1045.696	0.000	Constant	0.973	0.159		6.115	0.000	0.632	1.315	1.59	-1.67	1.72	0.000	0.966
								lnG	1.527	0.047	0.993	32.337	0.000	1.426	1.628					
All stems >=1.0 cm (from PSP)	Simple Linear	$Vha_{d>=1.0cm}$	16	175.800	0.967	468.419	0.000	G	20.368	0.941	0.984	21.643	0.000	18.363	22.374	1.82	-1.24	2.41	-0.223	0.972
	Log	$lnVha_{d>=1.0cm}$	16	0.242	0.972	521.512	0.000	Constant	0.976	0.228		4.282	0.001	0.487	1.465	2.38	-1.87	1.71	0.000	0.966
								lnG	1.515	0.066	0.987	22.832	0.000	1.373	1.658					

b) Tree, basal area and volume conversion factors (mean ±SE) for different inventory minimum diameter limits

Component	Minimum diameter[a]				10[b]
	2.5cm	5.0cm	6.4cm	10.0cm	
Tree (Nr/ha)	0.448 ± 0.064	0.271 ± 0.075	0.248 ± 0.070	0.197 ± 0.054	0.877 ± 0.039
Basal area (m^2/ha)	0.948 ± 0.016	0.847 ± 0.057	0.839 ± 0.057	0.824 ± 0.057	0.981 ± 0.009
Volume (m^3/ha)	0.980 ± 0.010	0.900 ± 0.057	0.900 ± 0.060	0.889 ± 0.057	0.991 ± 0.005
[a] base diameter limit D = 1.0cm		[b]Base diameter limit D = 6.4			

4.1.7. Biomass expansion/conversion factor equations

Results are presented of size dependent biomass partitioning and expansion/conversion factor equations for mangrove trees and stands from published generic allometric equations (Figures 4.4 to 4.10). Tables based on these factors were produced.

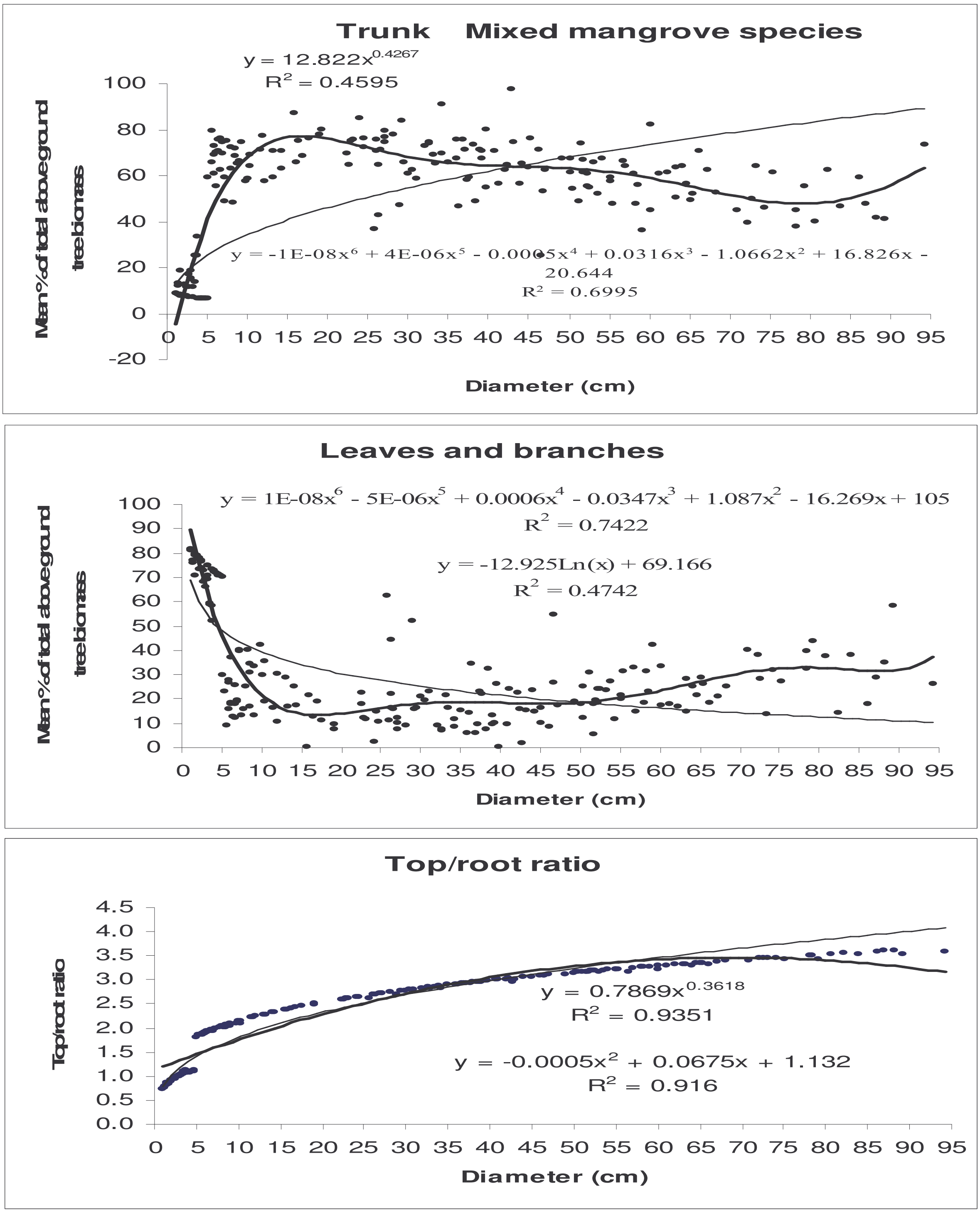


Figure 4.4: Size dependent pattern of tree biomass partitioning in mixed mangrove species in Douala – Edea Atlantic coast, Cameroon

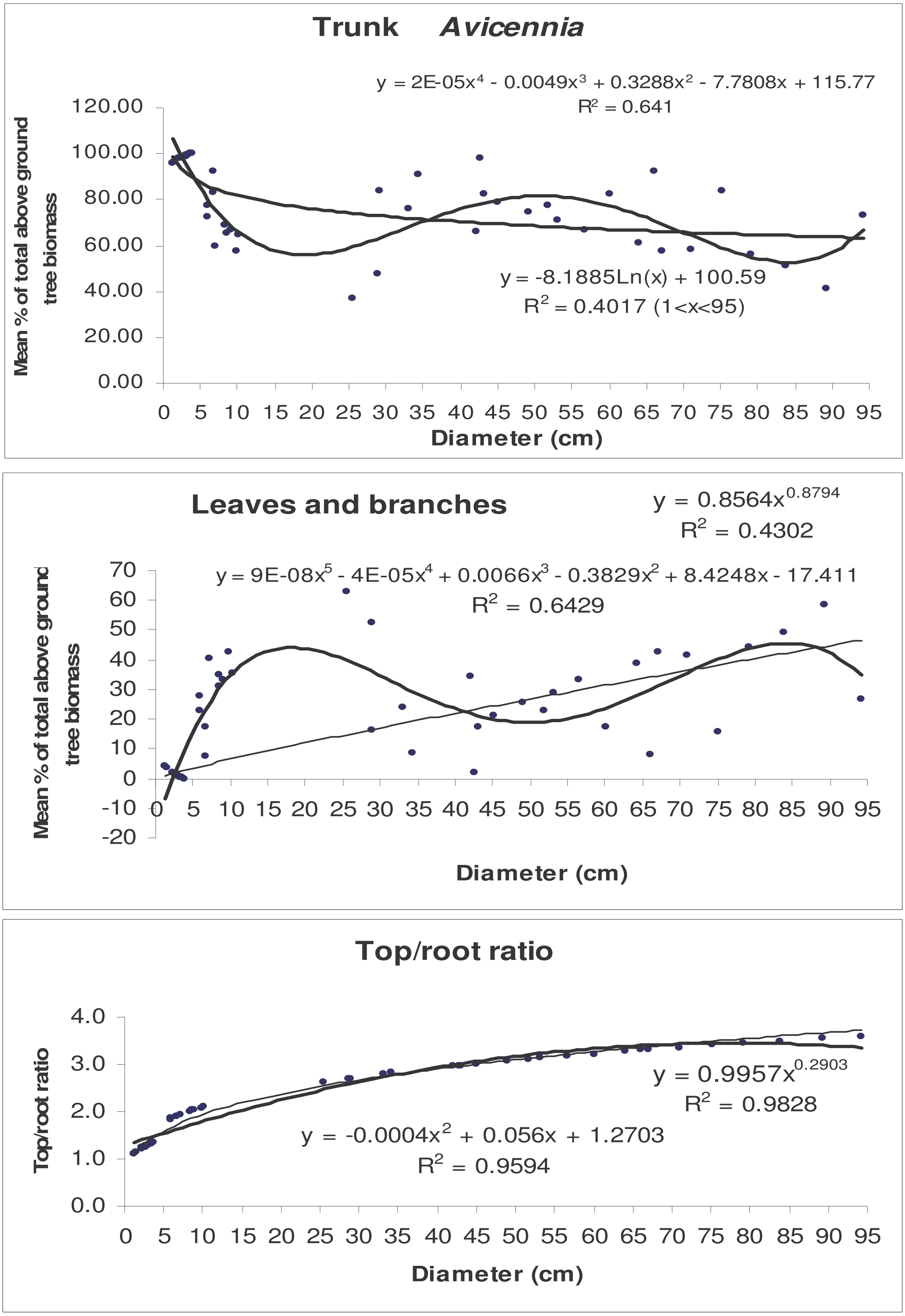


Figure 4.5: Size dependent pattern of tree biomass partitioning for *Avicennia* in Douala-Edea coastal Atlantic mangrove forest, Cameroon

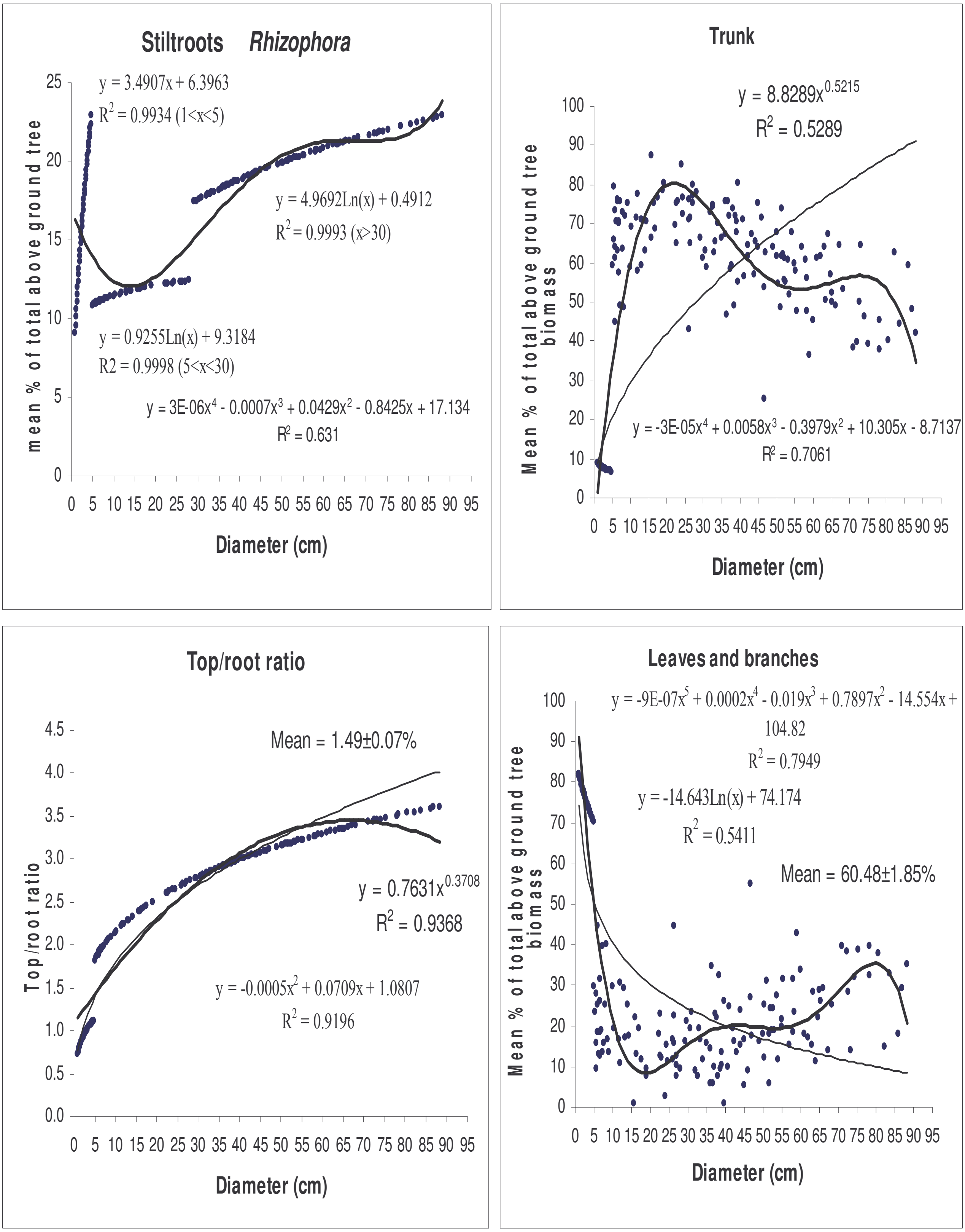


Figure 4.6: Size dependent pattern of tree biomass partitioning for *Rhizophora* in Douala-Edea coastal Atlantic mangrove forest, Cameroon

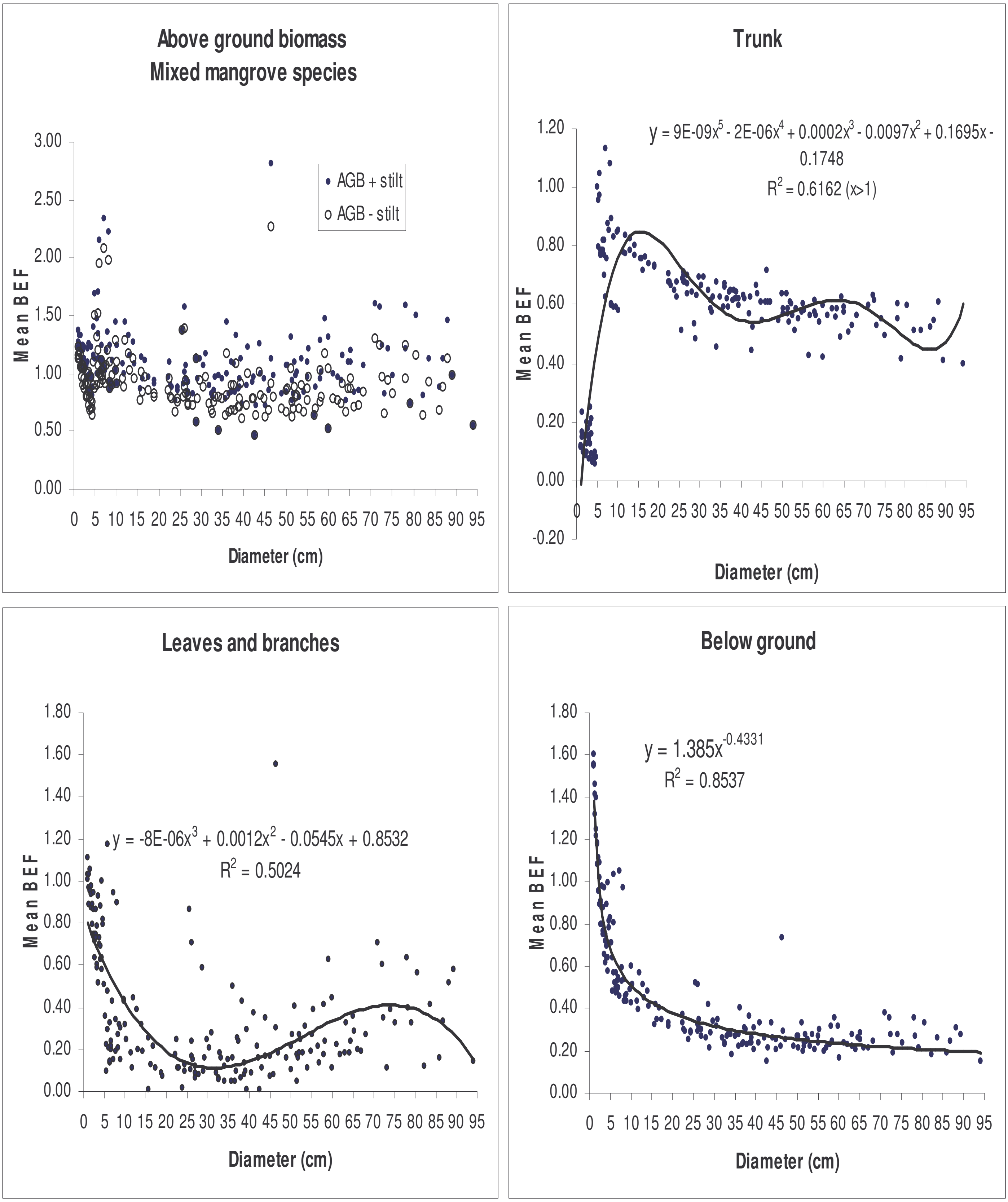


Figure 4.7. Tree biomass expansion factor equations for mixed mangrove species of Douala-Edea Atlantic coast, Cameroon

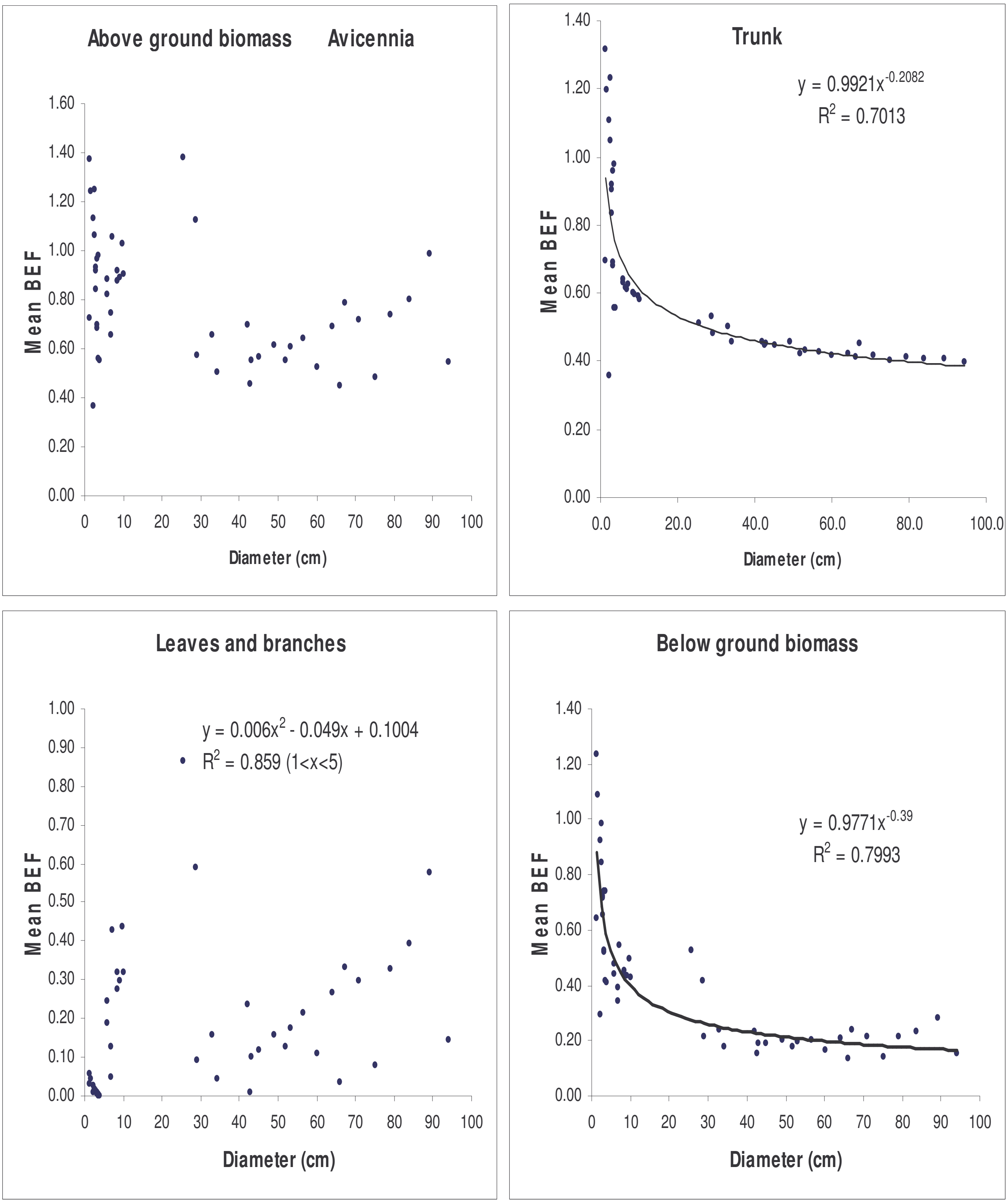


Figure 4.8. Tree biomass expansion factor equations for *Avicennia* mangrove species of Douala-Edea Atlantic coast, Cameroon

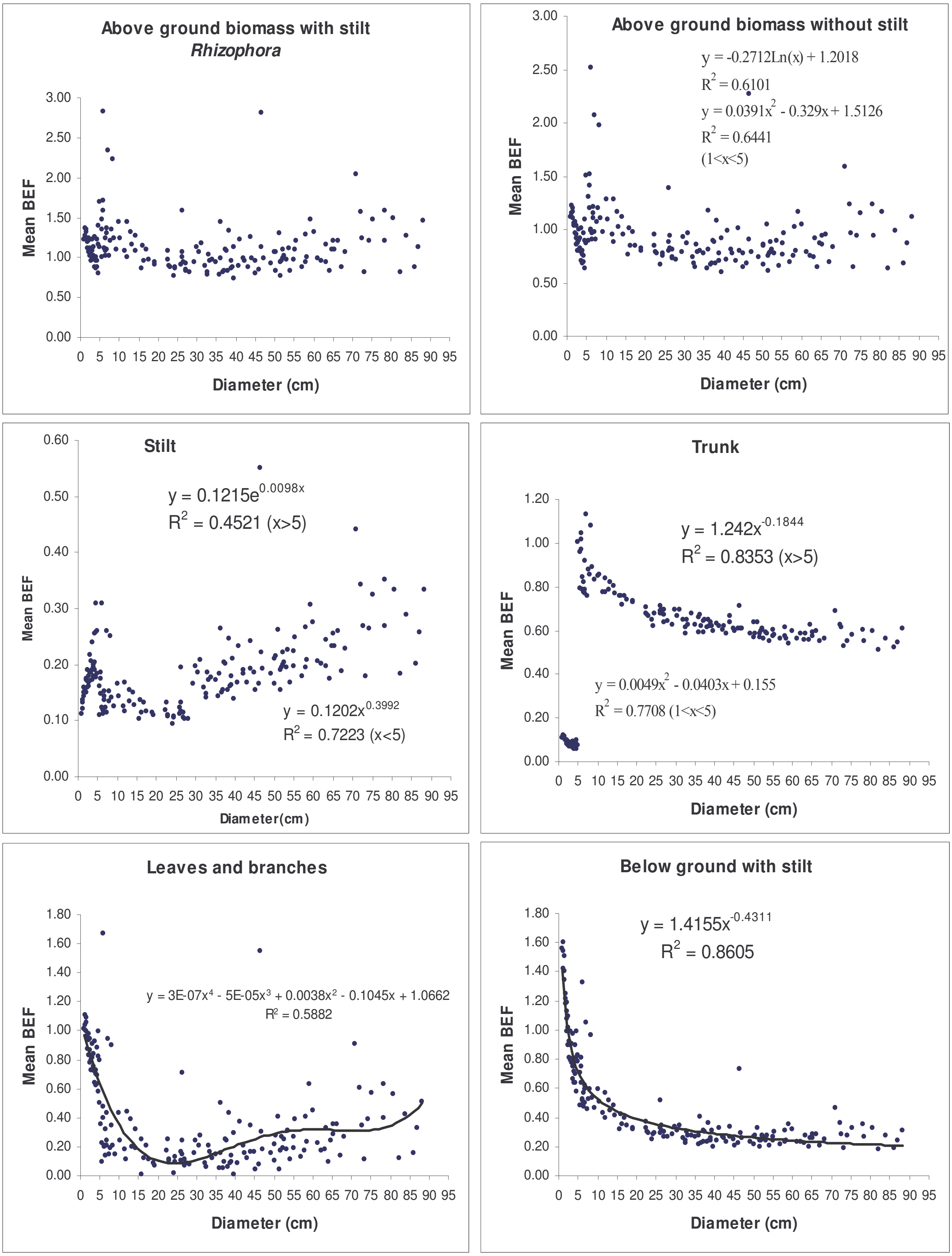


Figure 4.9. Tree biomass expansion factor equations for *Rhizophora* mangrove species of Douala-Edea Atlantic coast, Cameroon

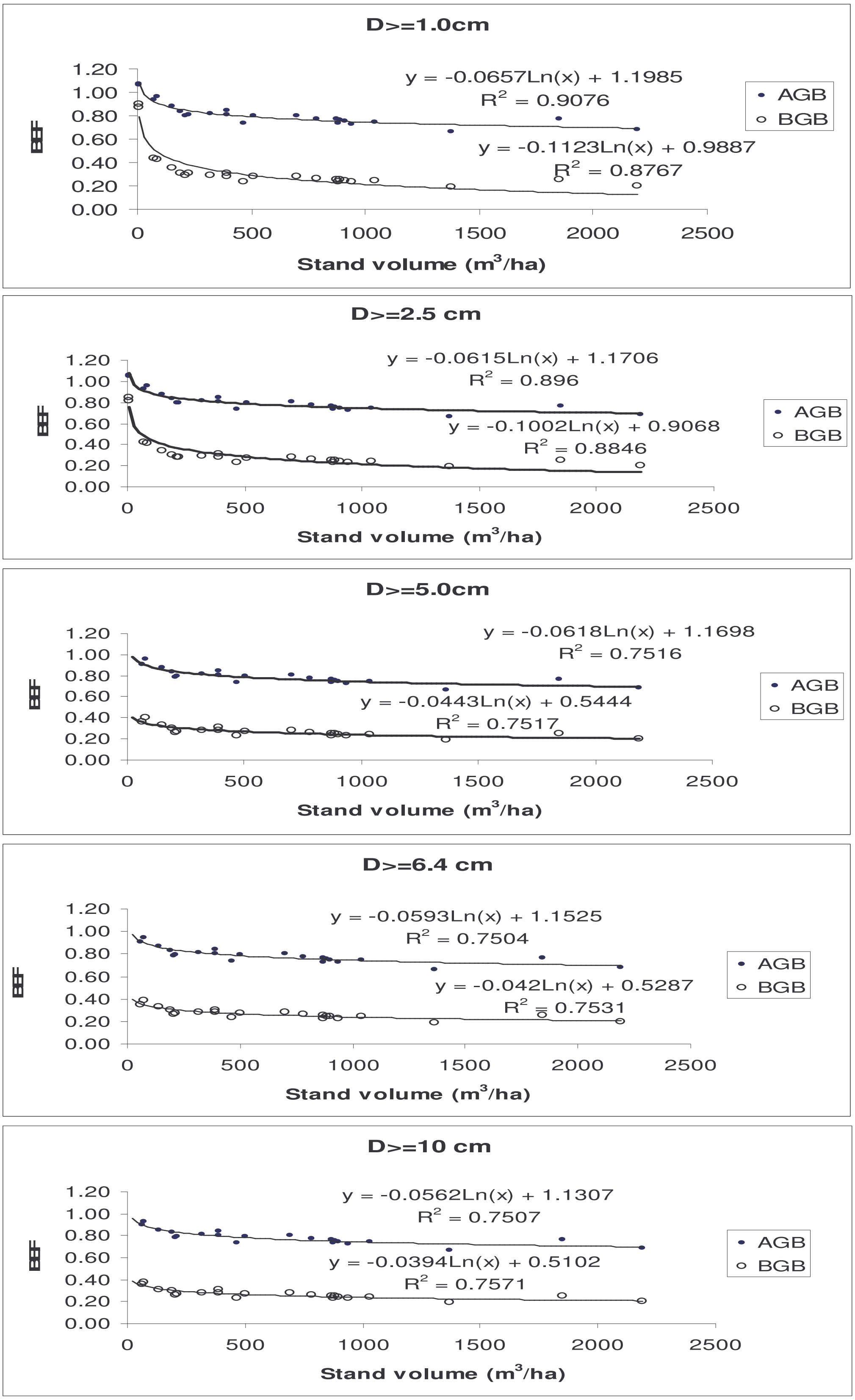


Figure 4.10: Stand biomass expansion factor equations for Douala-Edea Coastal Atlantic mangrove forest, Cameroon

4.2. Inventory data analysis

Results of inventory of stocked mangrove forest undertaken mainly to obtain a wide range of parameters for the development of allometric relationship together with the stock assessments are presented. A comparison of inventory and monitoring costs in terms of man/hours in the establishment and measuring TSP and PSP are provided with efficiency of some sampling techniques for mangrove inventory.

4.2.1. Inventory and monitoring costs

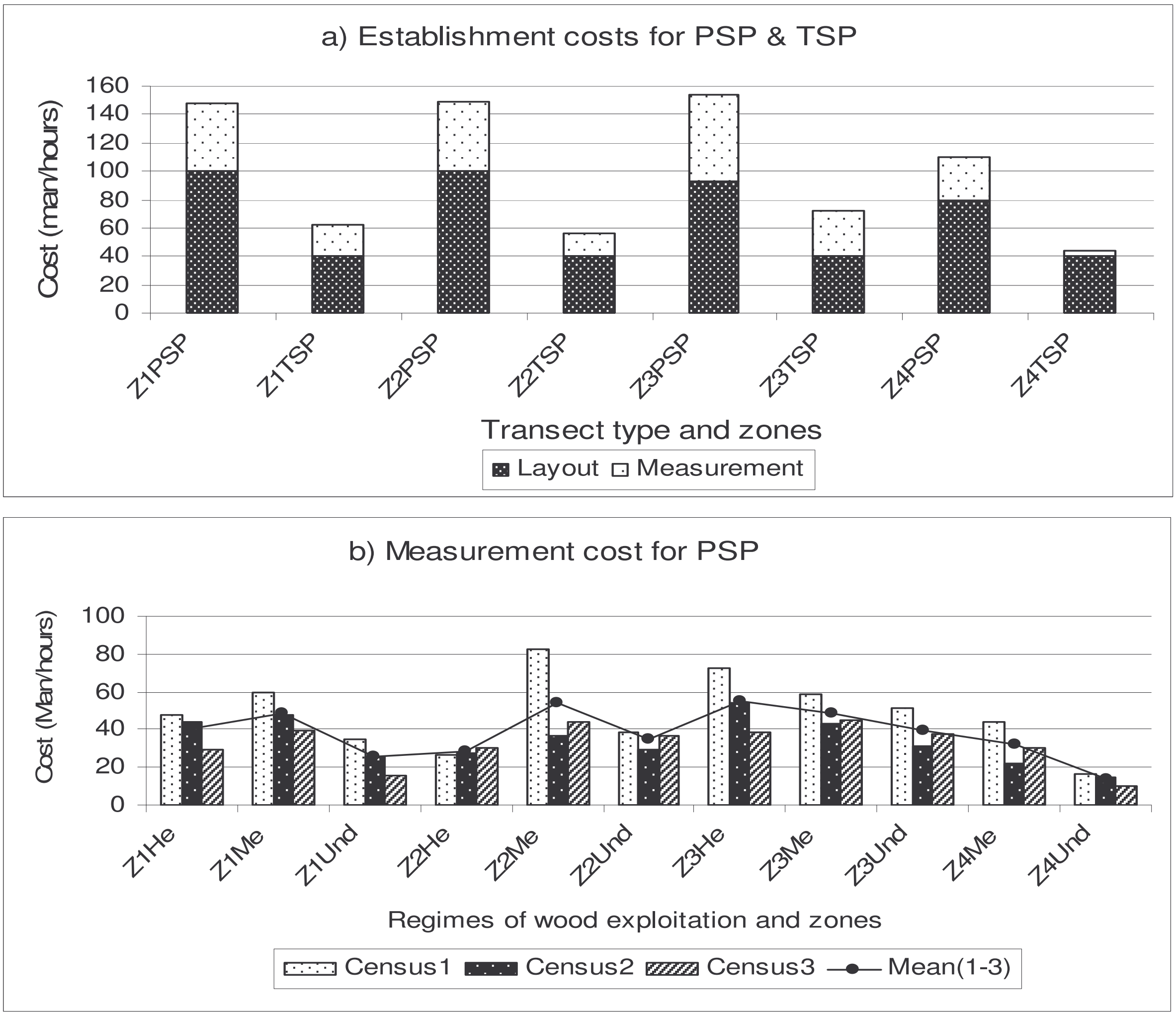


Figure 4.11: Economics (in terms of comparative duration and labour) of establishment and measurement of 100m x 10m temporal and permanent transects in the Douala-Edea mangroves, Cameroon

The cost of establishing or measuring PSP was significantly higher than for TSP being three times over (Figure 4.11). This is largely due to the large number of trees measured in PSP with minimum diameter limit of 1 cm while it was 6.4 cm in TSP.

4.2.2. Inventory Data

4.2.2.1. Species composition and stocking level

The mangroves of the Douala-Edea Reserve of the Cameroon Atlantic coast where the inventory of stocked mangrove stands were concentrated appear to be dominated like the mangroves of the rest of Cameroon coast, by *Rhizophora* spp (rel. freq. 89.9%) and to some extent *Avicennia germinans* (rel. freq. 0.25 %) tree species. Nipa palms (*Nypa fruticans* rel. freq. 28.3%) *Ficus* sp (rel. freq. 3.0%) and *Raphia* sp 2.0 (Table 4.5). *Rhizophora* attains a maximum height of 59m and diameter of 131.7 cm in these well stocked stands while *Avicennia* attains maximum height of 54m with diameter of 81.3cm. Mean stand volume (1879m^3/ha) are exceedingly higher than those obtained in undisturbed PSP (min 223 m^3/ha, max 611 m^3/ha, mean 403 m^3/ha). This may be largely due to inventory procedure that selected well stocked and undissected mangrove forests in order to obtain a wide range of parameters for the development of allometric relationships. Moreover these stands are frequently preferred and attacked for exploitation. Except for species, there were significant zonal (site) differences in most of the tree and stand parameters.

4.2.2.2. Stand structure

Descriptive statistics of all diameter measurements are provided in Table 4.6 with a stand table in Table 4.8. The diameter distribution tends to approximate the log-normal type with Weibull shape parameters ranging from 1.43 to 2.62 for zones and pooled zones 1.66 and scale parameters from 25.06 to 39.57 for zones and pooled zones 36.07 (Table 4.7) . De Liocourt q-ratios (Table 4.9) were variable with minimum values ranged from 0.3 – 0.6 for zones and 0.3 for pooled zones; maximum: 2.5 – 5.0 for zones and 3.0 pooled zones; mean 1.4 – 1.5 for zones, 1.4 for pooled zones; and CV of 40.8-81.6% for zones and 49.1% for pooled zones.

Table 4.5: Floristic composition, relative frequencies, densities, domimance and important values (I.V.) of stocked mangrove forests of the Douala-Edea Reserve, Cameroon

Zone	No. plots (10mx20m)	Species	Habit	Freqency (%)	Trees/ha	Stems/ha	Mean clump size	Diameter (cm) measurements						Height (m) measurements				Basal area (m^2/ha)	Volume(m^3/ha)	Relative values (%)			Importance value (IV)	Association index
											Diameter distribution (N/ha)													
								Max diam.	Arithm.mean diam.	Quad. mean diam	Saplings (6.4-<10)	Poles (10-<30)	Adults (≥30)	Stilt root (stump) ht	Min dom. Ht	Max dom. Ht	Mean dom.Ht			Frequency	density	Dominance (BA)		
I	39	*Rhizophora* spp	Tree	92.31	567	677	1.2	131.7	38.3	42.5	2.6	256.4	417.9	3.13	19.4	59	37.7	95.93	2148.43	92.31	87.85	85.15	265.3	-0.44
		Avicennia spp	Tree	0.33	82	94	1.1	96.3	41.5	47.7	3.8	32.1	57.7	0.55	27.6	44.2	35.6	16.73	409.8	0.33	12.15	14.85	27.3	
		Ficus	shrub	0																				
		Nypa fruticans	palm	30.77																				
		Raphia spp	palm	0																			0.0	
		Total (mean)			**649**	**771**	1.2	**131.7**	**38.6**	**43.1**	**6.4**	**288.5**	**476.9**	**2.81**	**19.4**	**59**	**37.3**	**112.66**	**2558.23**				0.0	
II	18	*Rhizophora* spp	Tree	77.78	672	756	1.1	66.2	21.4	25	200	375	180.6	2.92	22.8	54	37.2	37.19	608.8	77.78	86.9	83.03	247.7	-1.93
		Avicennia spp	Tree	0.28	94	114	1.2	53.1	26	29.1	22.2	52.8	38.9	1.31	28	35.6	31.8	7.6	131.3	0.28	13.1	16.97	30.3	
		Ficus	shrub	0																			0.0	
		Nypa fruticans	palm	16.67																			0.0	
		Raphia spp	palm	0																			0.0	
		Total (mean)			**767**	**869**	**1.1**	**66.2**	**22**	**25.6**	**222.2**	**427.8**	**219.4**	**2.71**	**22.8**	**54**	**36.1**	**44.79**	**740.09**				0.0	
III	21	*Rhizophora* spp	Tree	85.71	519	686	1.3	82.2	36.9	40.5	78.6	133.3	473.8	3.43	13.5	56.4	44.2	88.49	1811.62	85.71	72.54	73.85	232.1	-1.36
		Avicennia spp	Tree	0.33	179	260	1.4	94.3	34.5	39.2	35.7	66.7	157.1	1.31	32.4	54	47.9	31.33	665.26	0.33	27.46	26.15	53.9	
		Ficus	shrub	4.76																			0.0	
		Nypa fruticans	palm	61.9																			0.0	
		Raphia	palm	0																			0.0	
		Total (mean)			**698**	**945**	**1.4**	**94.3**	**36.2**	**40.2**	**114.3**	**200**	**631**	**2.85**	**13.5**	**56.4**	**45**	**119.82**	**2476.88**				0.0	
IV	21	*Rhizophora* spp	Tree	100	510	574	1.1	84.2	28	33.1	0	78.6	276.2	3.38	20	39.3	31.5	49.45	999.41	100	100	100	300.0	-
		Avicennia spp	Tree																					
		Ficus	shrub	9.52																				
		Nypa fruticans	palm	0																				
		Raphia spp	palm	9.52																				
		Total (mean)			**510**	**574**	**1.1**	**84.2**	**28**	**33.1**	**0**	**78.6**	**276.2**	**3.38**	**20**	**39.3**	**31.5**	**49.45**	**999.41**					
All the zones	99	*Rhizophora* spp	Tree	89.9	567	673	1.2	131.7	31.15	35.275	78.6	276.2	219	3.215	13.5	59	37.4	67.765	1392.07	89.9	85.9	76.6	252.4	-0.84
		Avicennia spp	Tree	0.25	84	111	1.3	96.3	34	38.667	13.1	36.4	63.1	1.0567	27.6	54,0	38.2	20.665	487.675	0.25	13.1	23.4	36.8	
		Ficus	shrub	3.03																				
		Nypa fruticans	palm	28.28																				
		Raphia spp	palm	2.02																				
		Total (mean)			**651**	**784**	1.2	**131.7**	**33**	**37.9**	**84.3**	**291.4**	**408.1**	**2.89**	**13.5**	**59**	**37.5**	**88.43**	**1879.74**					

Table 4.6: Descriptive statistics of all diameters at breast height or above stilt root (cm) for all trees enumerated in stocked Douala-Edea mangrove forests, Cameroon

Parameter	**Site I**			**Site II**			**Site III**			**Site IV**			**All sites combined**		
	Species			Species			Species			Species			Species		
	Avicennia sp	*Rhizophora* sp	Mixed	*Avicennia* sp	*Rhizophora* sp	Mixed	*Avicennia* sp	*Rhizophora* sp	Mixed	*Avicennia* sp	*Rhizophora* sp	Mixed	*Avicennia* sp	*Rhizophora* sp	Mixed
Count	73	528	601	41	272	313	109	288	397	-	241	241	223	1329	1552
Minimum	6.9	6.4	6.4	6.4	6.4	6.4	6.4	6.4	6.4	-	6.4	6.4	6.4	6.4	6.4
Maximum	96.3	131.7	131.7	53.1	66.2	66.2	94.3	82.2	94.3	-	84.2	84.2	96.3	131.7	131.7
Range	89.3	23.6	125.3	46.7	59.7	59.7	87.8	75.8	87.8	-	77.8	77.8	89.8	23.6	125.3
Mean	41.07	38.25	38.6	26.02	21.43	22.03	34.46	36.86	36.20	-	28.04	28.04	35.07	32.66	33.02
Median	35.9	34.2	34.25	23.0	19.0	20.0	35.0	39.1	39.1	-	22.8	22.8	33.0	31.0	31.0
Mode	21.0	35.9	35.9	22.0	22.0	22.0	10.0	47.1	47.1	-	19.0	19.0	21.0	22.0	22.0
Standard deviation	23.88	18.47	19.2	13.30	12.96	13.08	18.78	16.88	17.43	-	17.67	17.67	20.39	18.27	18.60
Standard error	2.80	0.80	0.78	2.08	0.79	0.74	1.80	0.99	0.87	-	1.14	1.14	1.37	0.50	0.47
Sample Variance	570.32	341.30	368.38	177.02	167.96	170.98	352.59	284.92	303.80	-	312.19	312.19	415.55	333.69	345.86
Kurtosis	-0.85	1.67	1.12	-0.89	0.36	0.07	-0.29	-0.54	-0.49	-	0.39	0.39	-0.12	0.84	0.66
Skewness	0.45	1.12	1.00	0.26	0.95	0.85	0.31	-0.17	-0.03	-	1.00	1.00	0.61	0.81	0.78

Table 4.7: Weibull parameters for the mangrove forest of Douala-Edea, Cameroon

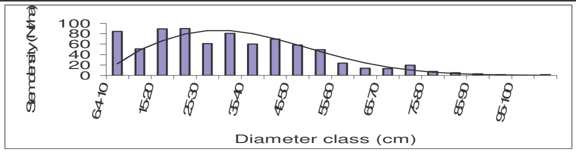
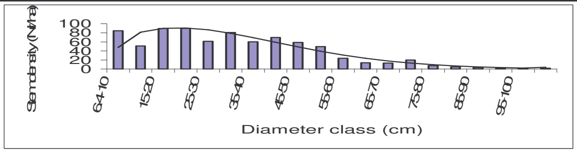
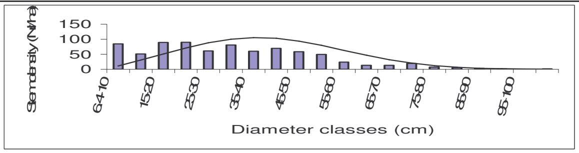
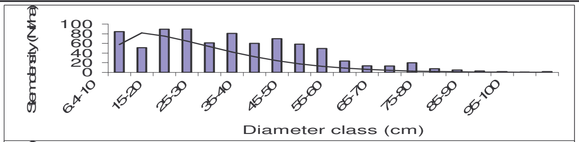
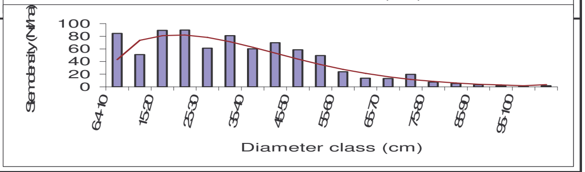
Zone	Parameters		Fit-statistics (KS-test)					Graph
	Shape	Scale	Absolute	+ve	-ve	KS	Signif 2 tailed)	
1	2.18	39.57	0.100	0.150	-0.100	0.474	0.978	
2	1.66	36.07	0.400	0.150	-0.400	1.265	0.082	
3	2.62	45.98	0.150	0.150	-0.150	0.474	0.978	
4	1.43	25.06	0.200	0.200	-0.200	0.632	0.819	
Whole Forest	1.66	36.07	0.150	0.150	-0.100	0.474	0.978	

Table 4.8: Stand table for stocked mangrove forest stands in Douala-Edea Atlantic coast, Cameroon

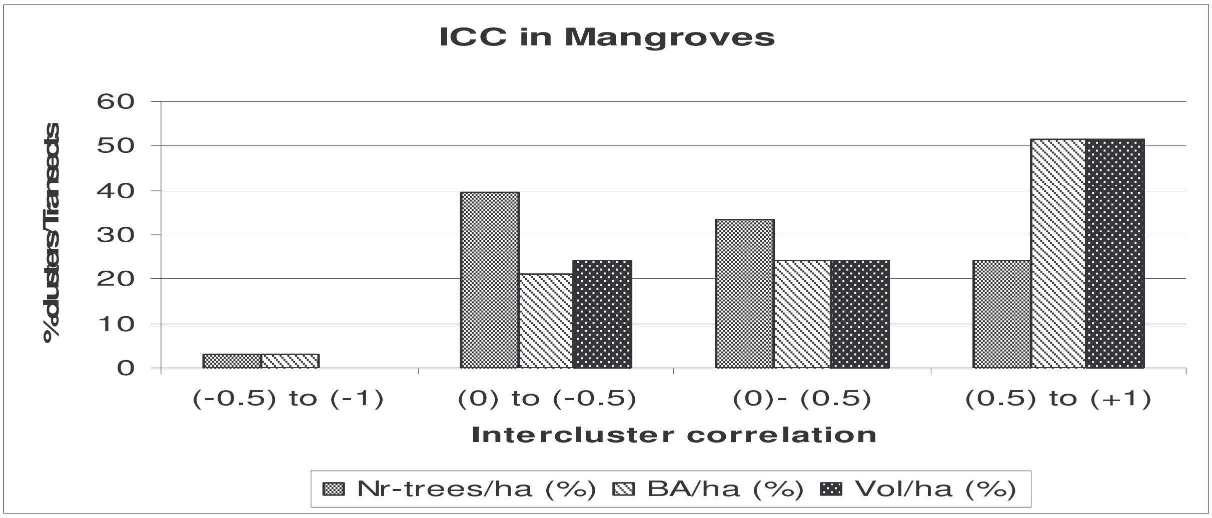
Stem Diameter class[1]	**Zone**																											
	I						**II**						**III**					IV					**All combined**					
	Species						**Species**						**Species**					**Species**					**Species**					
	Avicennia sp		*Rhizophora* sp		Mixed		*Avicennia* sp		*Rhizophora* sp		Mixed		*Avicennia* sp		*Rhizophora* sp		Mixed	*Avicennia* sp	*Rhizophora* sp		Mixed		*Avicennia* sp		*Rhizophora* sp		Mixed	
	N/ha	%	N/ha	%	N/ha	%	N/ha	%	N/ha	%	N/ha	%	N/ha	%	N/ha	%	N/ha	N/ha	N/ha	%	N/ha	%	N/ha	%	N/ha	%	N/ha	%
6.4 -<10	3.8	**4.1**	2.6	**0.4**	7.7	**1.0**	22.2	**19.5**	200.0	**26.5**	222.2	**25.6**	35.7	**13.8**	78.6	**12.8**	114.3	0.0	78.6	**13.4**	78.6	**13.7**	13.1	**11.6**	70.7	**9.6**	84.3	10.8
10 - <20	16.7	**17.8**	97.4	**14.4**	111.5	**14.5**	11.1	**9.8**	205.6	**27.2**	216.7	**24.9**	42.9	**16.5**	52.4	**8.6**	95.2	0.0	173.8	**29.7**	173.8	**30.3**	17.7	**15.7**	123.7	**16.8**	140.4	17.9
20 - <30	15.4	**16.4**	159.0	**23.5**	174.4	**22.6**	41.7	**36.6**	169.4	**22.4**	211.1	**24.3**	23.8	**9.2**	8.0	**1.3**	104.8	0.0	102.4	**17.5**	102.4	**17.8**	18.7	**16.6**	132.3	**18.0**	151.0	19.3
30 - <40	14.1	**15.1**	151.3	**22.3**	166.7	**21.6**	13.9	**12.2**	100.0	**13.2**	113.9	**13.1**	45.2	**17.4**	133.3	**21.8**	178.6	0.0	78.6	**13.4**	78.6	**13.7**	17.7	**15.7**	122.7	**16.7**	140.9	18.0
40 - <50	7.7	**8.2**	111.5	**16.5**	119.2	**15.5**	22.2	**19.5**	55.6	**7.4**	77.8	**8.9**	59.5	**22.9**	190.5	**31.1**	250.0	0.0	78.6	**13.4**	66.7	**11.6**	19.7	**17.5**	108.6	**14.8**	128.3	16.4
50 - <60	14.1	**15.1**	71.8	**10.6**	84.6	**11.0**	2.8	**2.4**	22.2	**2.9**	25.0	**2.9**	33.3	**12.8**	97.6	**15.9**	131.0	0.0	35.7	**6.1**	35.7	`	13.1	**11.6**	60.6	**8.2**	73.2	9.3
60 - <70	6.4	**6.8**	21.8	**3.2**	29.5	**3.8**	0.0	**0.0**	2.8	**0.4**	2.8	**0.3**	11.9	**4.6**	40.5	**6.6**	52.4	0.0	16.7	**2.8**	16.7	**2.9**	5.1	**4.5**	21.2	**2.9**	26.8	3.4
70 - <80	10.3	**11.0**	41.0	**6.1**	51.3	**6.7**	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	4.8	**1.8**	9.5	**1.6**	14.3	0.0	19.0	**3.3**	19.0	**3.3**	5.1	**4.5**	22.2	**3.0**	27.3	3.5
80 - <90	2.6	**2.7**	15.4	**2.3**	17.9	**2.3**	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	2.4	**0.4**	2.4	0.0	2.4	**0.4**	2.4	**0.4**	1.0	**0.9**	71.1	**9.7**	8.1	1.0
90 - <100	2.6	**2.7**	1.3	**0.2**	3.8	**0.5**	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	2.4	**0.9**	0.0	**0.0**	2.4	0.0	0.0	**0.0**	0.0	**0.0**	1.5	**1.3**	0.5	**0.1**	2.0	0.3
≥100	0.0	**0.0**	3.8	**0.6**	3.8	**0.5**	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	0.0	0.0	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	1.5	**0.2**	1.5	0.2
Total	**93.6**	**100.0**	**676.9**	**100.0**	**770.5**	100.0	**113.9**	**100.0**	**755.6**	**100.0**	**869.4**	**100.0**	**259.5**	**100.0**	**612.8**	**100.0**	**945.2**	**0.0**	**585.7**	**100.0**	**573.8**	**100.0**	**112.7**	**100.0**	**735.1**	**100.0**	**783.9**	100.0
1	Diameter at breast height for *Avicennia* and Diameter at breast height or above stilt root in *Rhizophora*																											

Table 4.9: Estimation of q-ratios between successive diameter classes for stocked mangrove forests in Douala-Edea Atlantic coast, Cameroon

D-class Interval	D-Class	Zone									
		1		2		3		4		Whole forest	
		Stems/ha	q-ratio	Stems/ha	q-ratio	Stems/ha	q-ratio	Stems/ha	q-ratio	Stems/ha	q-ratio
5cm	6.4-10	7.7	0.32	222.2	2.50	114.3	2.29	78.6	1.14	84.3	1.65
	10-15	24.4	0.28	88.9	0.70	50.0	1.11	69.0	0.66	51.0	0.57
	15-20	87.2	0.83	127.8	0.92	45.2	0.86	104.8	1.83	89.4	0.99
	20-25	105.1	1.52	138.9	1.92	52.4	1.00	57.1	1.26	89.9	1.47
	25-30	69.2	0.73	72.2	1.04	52.4	0.59	45.2	0.79	61.1	0.76
	30-35	94.9	1.32	69.4	1.56	88.1	0.97	57.1	2.67	80.8	1.34
	35-40	71.8	1.04	44.4	1.07	90.5	0.72	21.4	0.56	60.1	0.86
	40-45	69.2	1.38	41.7	1.15	126.2	1.02	38.1	1.33	69.7	1.19
	45-50	50.0	0.80	36.1	2.17	123.8	1.49	28.6	1.50	58.6	1.18
	50-55	62.8	2.88	16.7	2.00	83.3	1.75	19.0	1.14	49.5	2.09
	55-60	21.8	1.89	8.3		47.6	1.43	16.7	1.75	23.7	1.74
	60-65	11.5	0.64	0.0		33.3	1.75	9.5	1.33	13.6	1.04
	65-70	17.9	0.42	2.8		19.0	2.67	7.1	1.00	13.1	0.67
	70-75	42.3	4.71	0.0		7.1	1.00	7.1	0.60	19.7	2.60
	75-80	9.0	0.88	0.0		7.1	3.00	11.9	5.00	7.6	1.50
	80-85	10.3	1.33	0.0		2.4		2.4		5.1	1.67
	85-90	7.7	3.00	0.0		0.0		0.0		3.0	2.00
	90-95	2.6	2.00	0.0		2.4		0.0		1.5	3.00
	95-100	1.3	0.33	0.0		0.0		0.0		0.5	0.33
	100+	3.8		0.0		0.0		0.0		1.5	
Min			0.3		0.7		0.6		0.6		0.3
Max			4.7		2.5		3.0		5.0		3.0
Mean			1.4		1.5		1.4		1.5		1.4
SD			1.1		0.6		0.7		1.1		0.7
CV%			81.6		40.8		50.1		73.9		49.1
10 cm	6.4-10	7.7	0.07	222.2	1.03	114.3	1.20	78.6	0.45	84.3	0.60
	10-20	111.5	0.64	216.7	1.03	95.2	0.91	173.8	1.70	140.4	0.93
	20-30	174.4	1.05	211.1	1.85	104.8	0.59	102.4	1.30	151.0	1.07
	30-40	166.7	1.40	113.9	1.46	178.6	0.71	78.6	1.18	140.9	1.10
	40-50	119.2	1.41	77.8	3.11	250.0	1.91	66.7	1.87	128.3	1.75
	50-60	84.6	2.87	25.0	9.00	131.0	2.50	35.7	2.14	73.2	2.74
	60-70	29.5	0.58	2.8		52.4	3.67	16.7	0.88	26.8	0.98
	70-80	51.3	2.86	0.0		14.3	6.00	19.0	8.00	27.3	3.38
	80-90	17.9	4.67	0.0		2.4	1.00	2.4		8.1	4.00
	90-100	3.8	1.00	0.0		2.4		0.0		2.0	1.33
	100+	3.8		0.0		0.0		0.0		1.5	
Min		3.8									
Max			4.7		9.0		6.0		8.0		4.0
Mean			1.7		2.9		2.1		2.2		1.8
SD			1.4		3.1		1.8		2.4		1.2
CV%			84.7		105.7		86.9		110.1		65.4

4.2.2.3. Comparing inventory methods

Due to the mono-cultural nature of mangrove forest couple with very difficult accessibility under muddy conditions, it is hypothesized if simple random sampling methods may just be economically adequate to other more advanced sampling schemes. The results show that this is not far from the truth given comparatively low sampling efficiency though stratified random sampling schemes are relatively better (Table 4.10), but a trade-off is necessary. Generally in determining stand parameters (Nr/ha, BA/ha, Vol/ha) stratified random sampling was just 1.1 times efficient than simple random sampling in turn 4-8 times more efficient than strafified cluster sampling which was 7-10 times more efficient than cluster sampling while simple random sampling was 3-7 times more efficient than stratified cluster sampling and 7-9 times more efficient than cluster sampling. Stratified cluster sampling was 1.2 – 2 times more efficient than cluster sampling. The apparently variable sampling errors could be due to low to negative level of intra-cluster correlation indicating high heterogeneity between clusters in most of the zones (Figure 4.12). As mentioned earlier sampling adequacy was not the primary objective of this study.



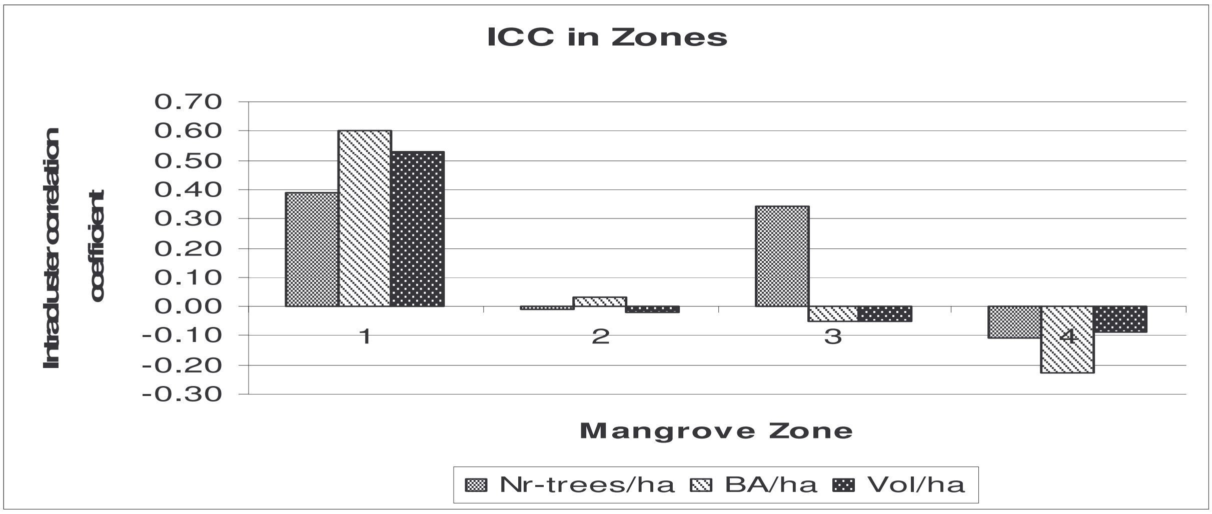


Figure 4.12. Intra-cluster correlation coefficients within sampling zones in the Douala-Edea Mangrove forest, Cameroon

Table 4.10: Comparing population estimates of some sampling designs for mangrove forest inventory in Douala-Edea Atlantic coast, Cameroon

Sampling Unit	Parameter Per ha	Stratified sampling (SRS)			Stratified cluster sampling (SCS)			Cluster sampling (CS)			Simple random sampling (RS)			Relative efficiency				
		Estimate	CI[a]	E%	Estimate	CI	E%	Estimate	CI	E%	Estimate	CI	E%	RS/ SRS	SCS/ SR	CS/ RS	SCS/ SRS	CS/ SCS
Transects	Nr-stems (Nr/ha)	783.80	689.48 - 878.12	12.03							783.40	683.06 - 1466.46	12.80	1.06				
	Basal Area (m^2/ha)	88.43	66.02 - 110.84	25.34							88.43	64.40 - 152.83	27.20	1.07				
	Volume (m^3/ha)	1879.74	1279.89 - 2479.59	31.91							1879.74	1250 - 3130.55	33.46	1.05				
Plots	Nr-stems (Nr/ha)	783.80	722.50 - 845.10	7.82	783.80	335.63 - 1241.97	58.45	783.80	230.17 - 1337.43	70.63	783.80	718.13 - 1501.93	8.38	1.07	8.43	6.98	8.43	1.21
	Basal Area (m^2/ha)	88.43	74.57 - 102.29	15.67	88.43	0 - 179.26	102.71	88.43	0 - 186.03	110.37	88.43	73.53 - 161.96	16.85	1.08	6.10	6.55	6.10	1.07
	Volume (m^3/ha)	1879.74	1506.53 - 2252.95	19.85	1879.74	498.45 - 3261.03	73.48	1879.74	0 - 4472.66	137.94	1879.74	1487.29 - 3367.0	20.88	1.05	3.52	6.61	3.52	1.88
Relative efficiency Transects/Plots	Nr-stems (Nr/ha)			1.54									1.53					
	Basal Area (m^2/ha)			1.62									1.61					
	Volume (m^3/ha)			1.61									1.60					

[a] 95% Confidence Interval

4.3. Human impacts on mangrove forests

Results of various univariate and multivariate analysis of variance and other inferential statistical tests with graphical illustrations are provided on the impacts of various wood extraction regimes on stand parameters; stand spatial patterns; mortality, recruitment, growth and yield; tree form and plant invasion.

4.3.1. Stand parameters

Pattern of variations in tree and stand parameters are shown in Figures 4.13 – 4.19. There were significant zonal differences in all of the stand parameters (nr-trees, nr-multi-stemmed trees, stand basal area), except incidence of problem trees. Regimes were significantly different in all stand parameters as expected (being set from the beginning). The only interaction effects noted was between regimes and zones in incidence of multi-stemmed trees.

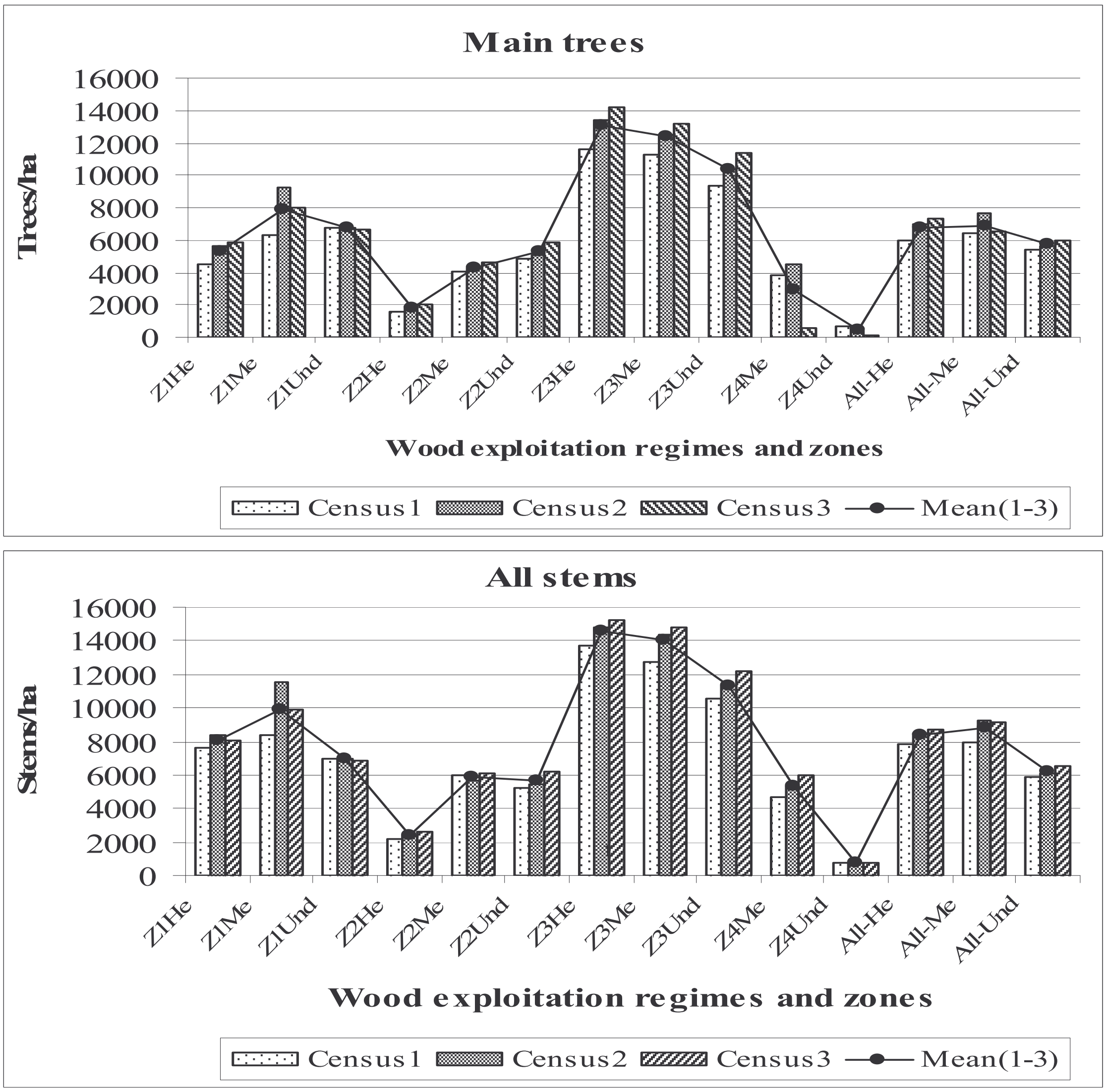


Figure 4.13 Trends in stand density of mangrove forest under different wood exploitation regimes in Douala-Edea, Cameroon during three census periods

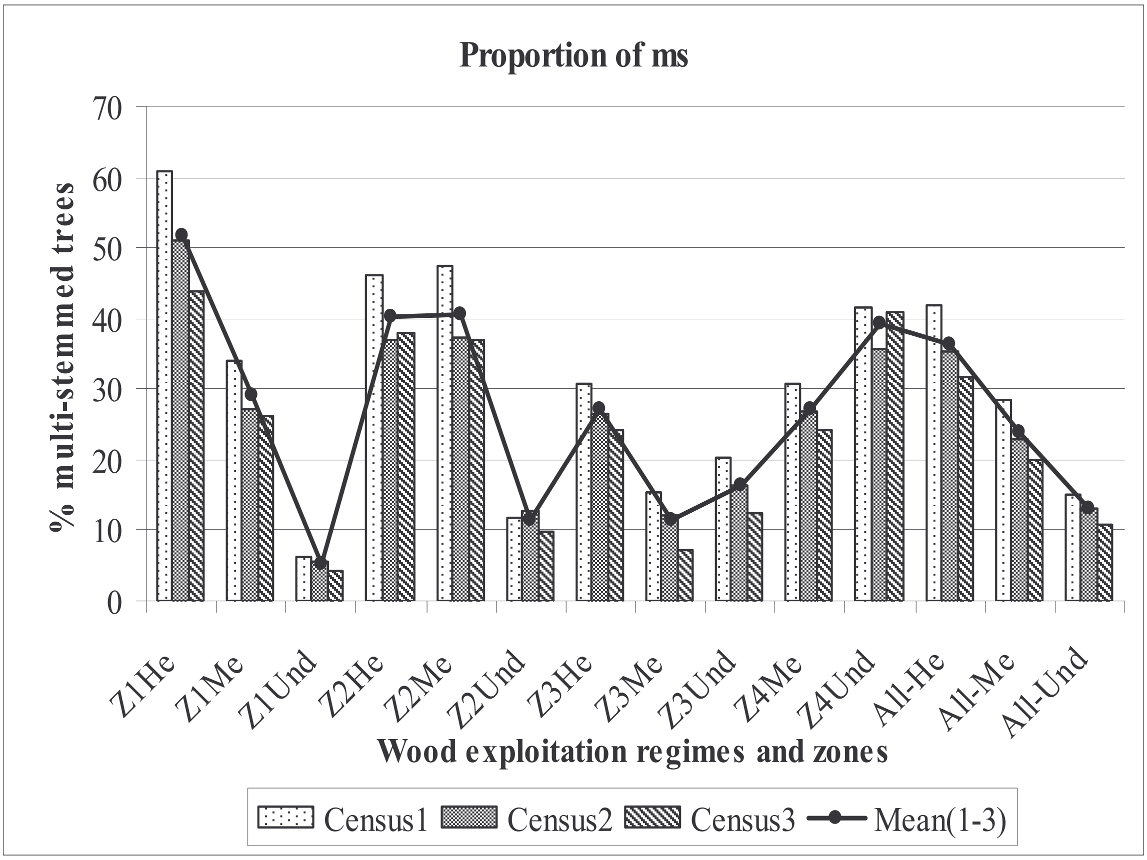


Figure 4.14: Trends in the contribution of multi-stemmed trees to total stems in mangrove forest stands under different wood exploitation pressures in Cameroon

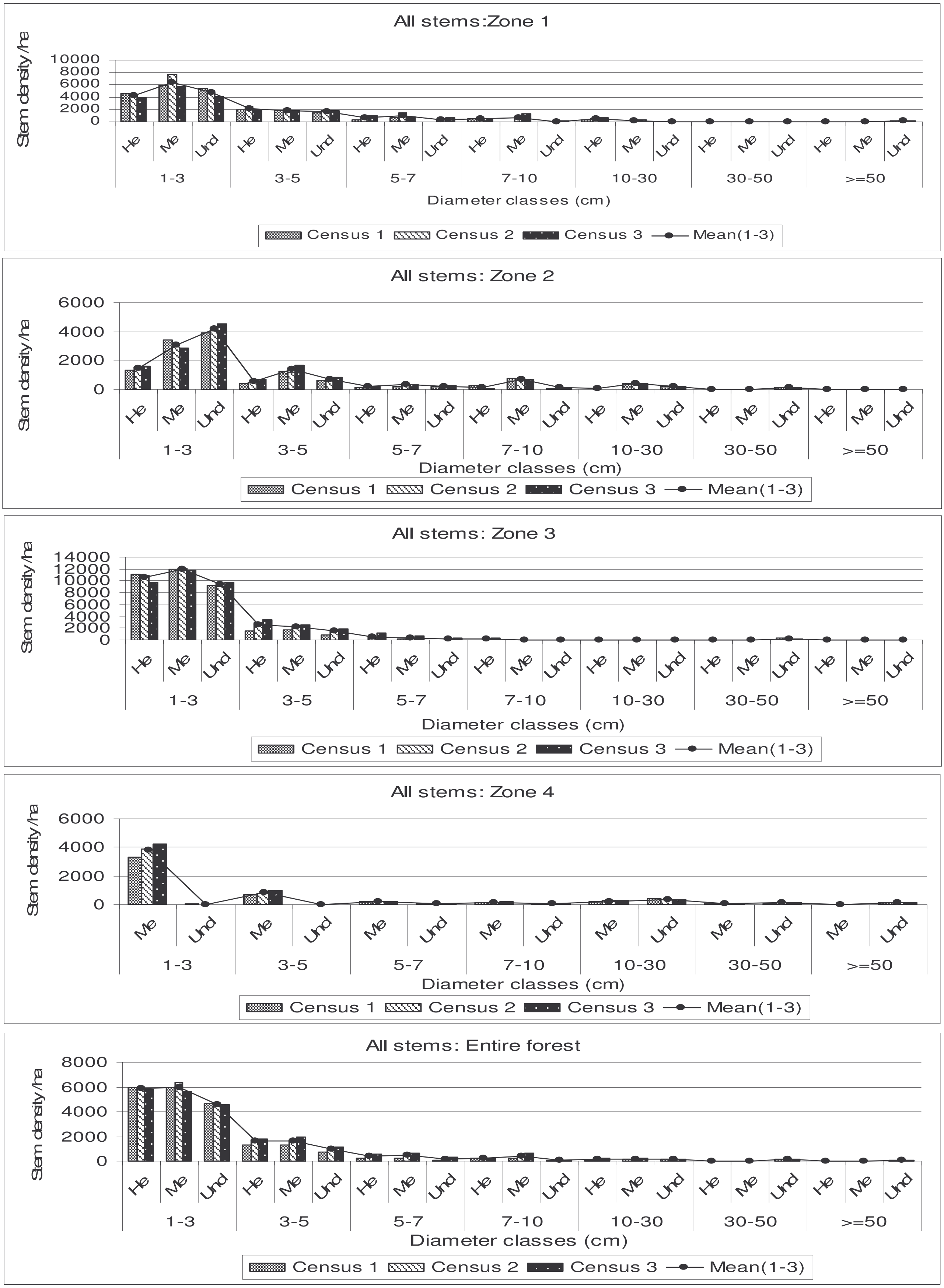


Figure 4.15: Trends in stem size class distribution following different wood exploitation regimes in Douala-Edea coastal Atlantic mangrove forest, Cameroon

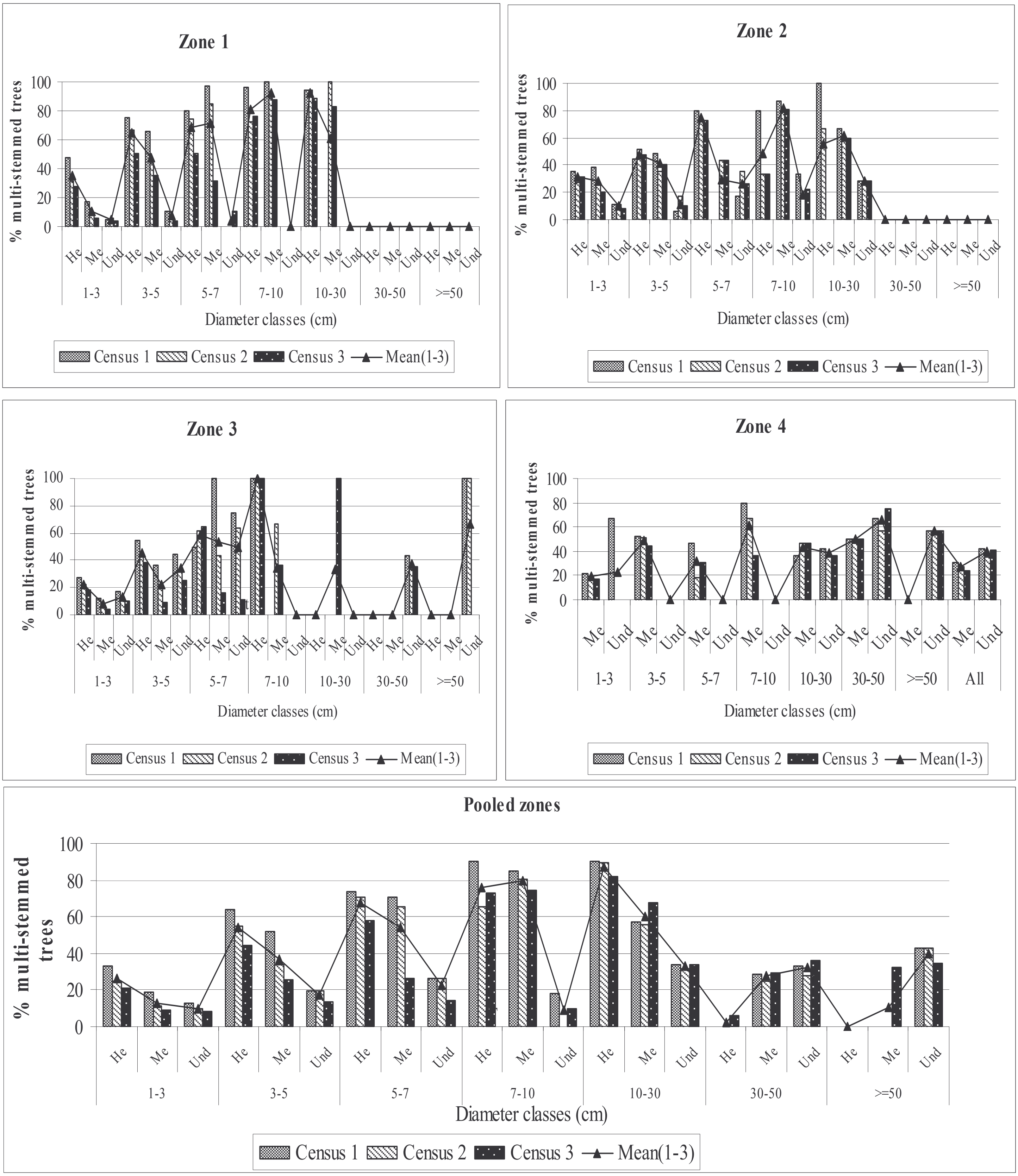
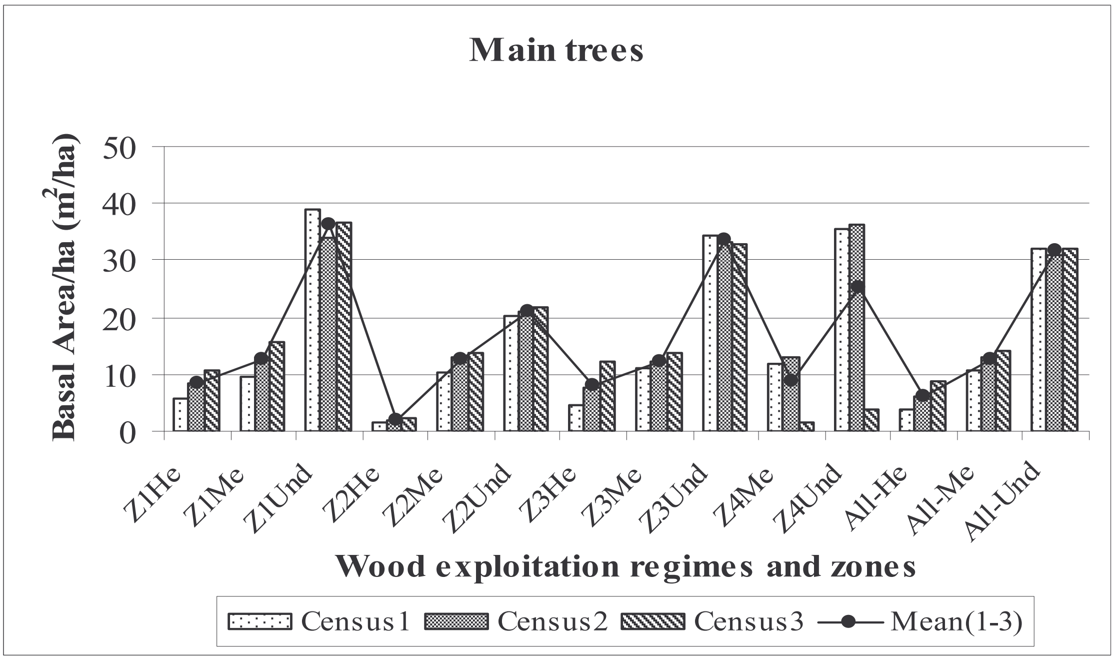


Figure 4.16: Trends in size class distribution of contribution of multi-stemmed trees to total stem population in mangrove forest under different wood exploitation regimes in Douala-Edea Cameroon during three census period.



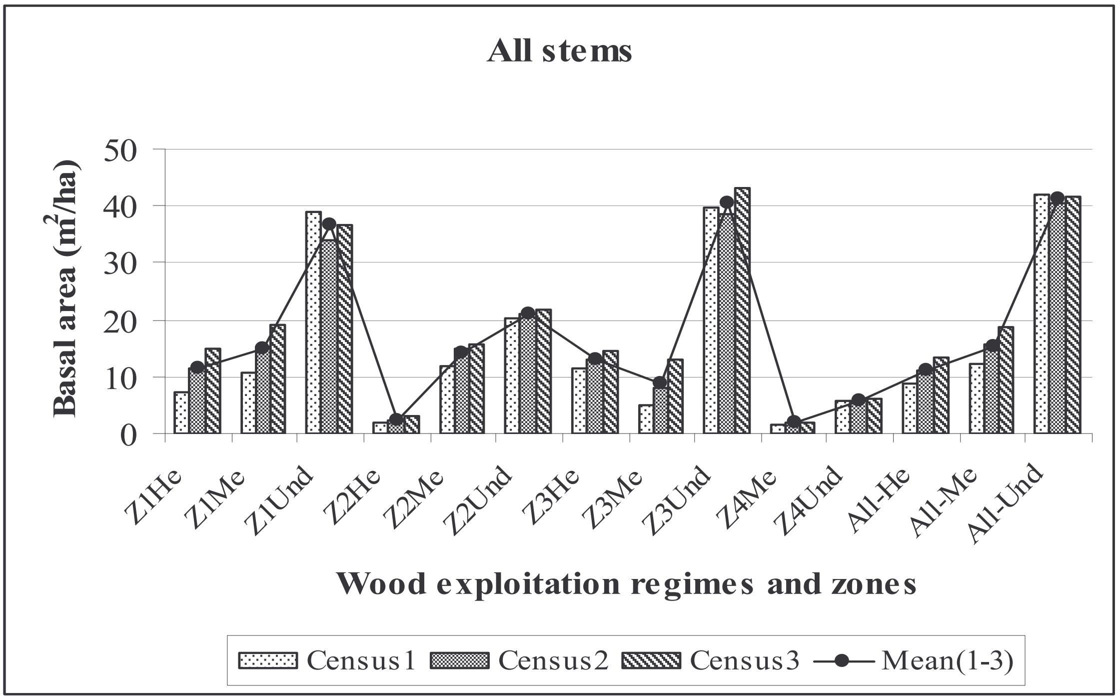


Figure 4.17: Trends in basal area of mangrove forest under different wood exploitation regimes in Douala-Edea, Cameroon during three census periods

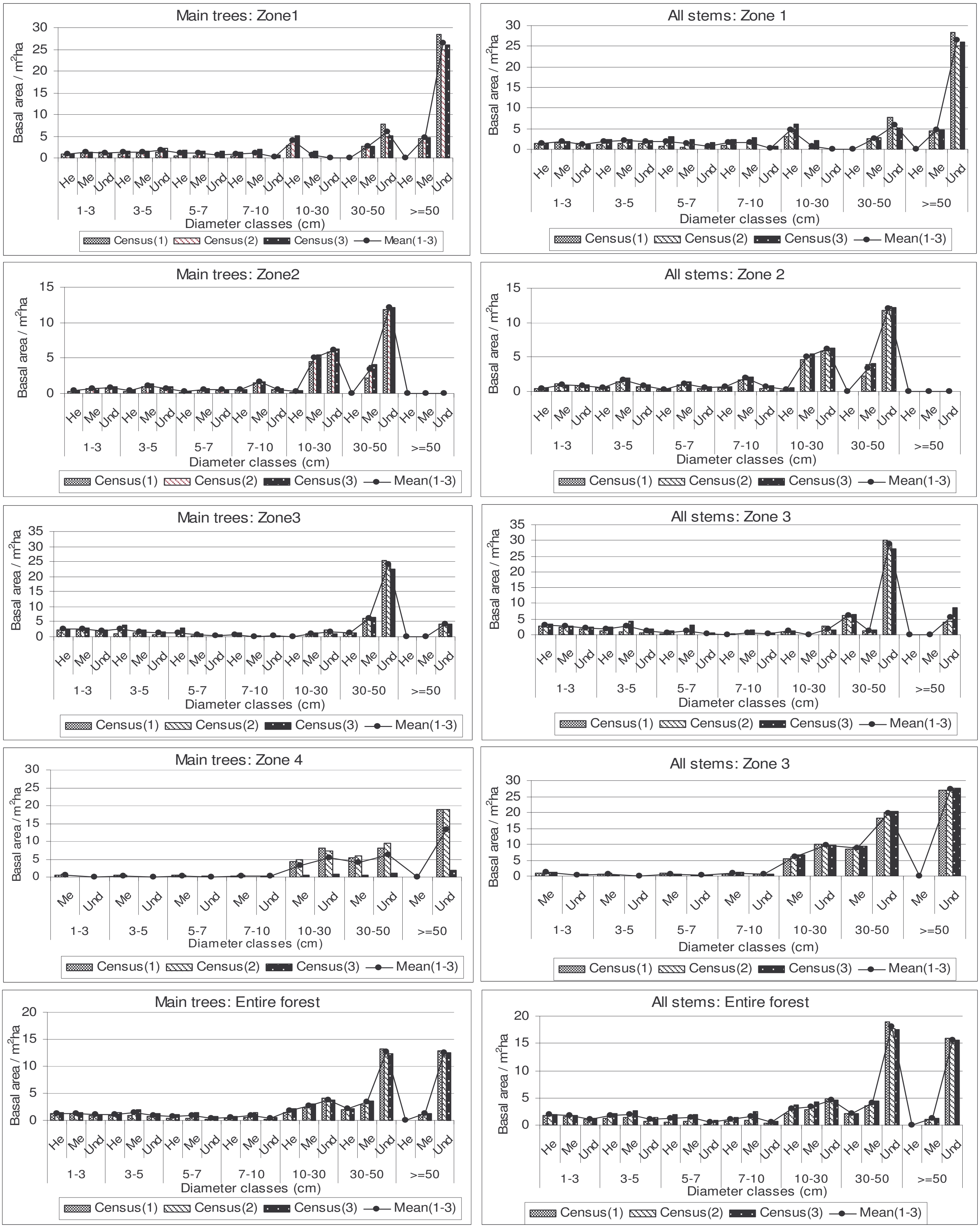


Figure 4.18: Trends in basal area distribution by diameter classes in mangrove forest under different wood exploitation regimes in Cameroon Atlantic coast during three census periods

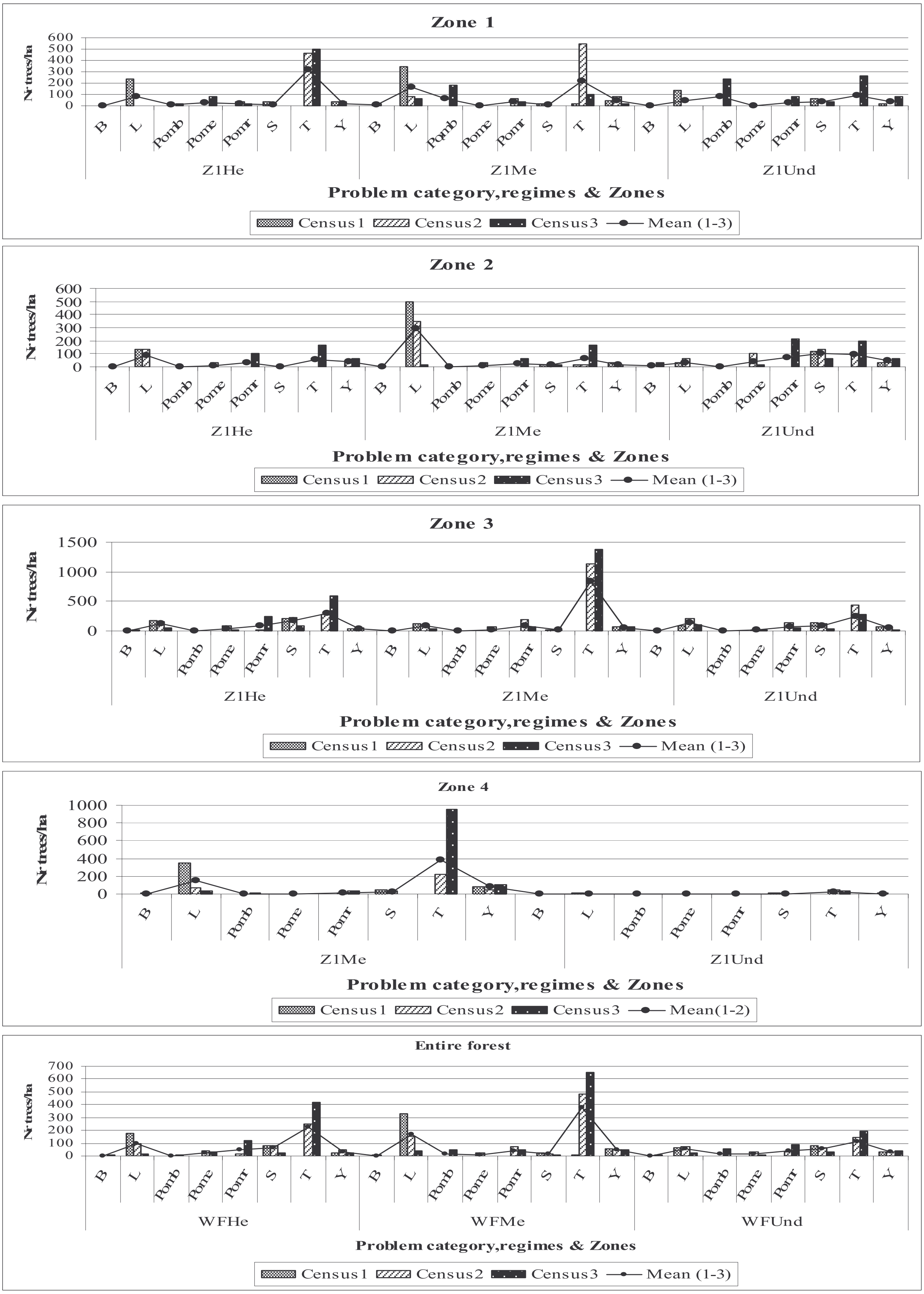


Figure 4.19. Trends in incidence of problem trees in Douala-Edea coastal Atlantic mangrove forest, Cameroon under different regimes of exploitation

4.3.2. Stand spatial patterns

Values of Morisita's coefficient were varied generally above unity in most cases revealing different patterns of dispersion of tree developmental stages and mortality and recruitment which in a most situations exhibit clumped habits (Figures 4.20 – 4.21).

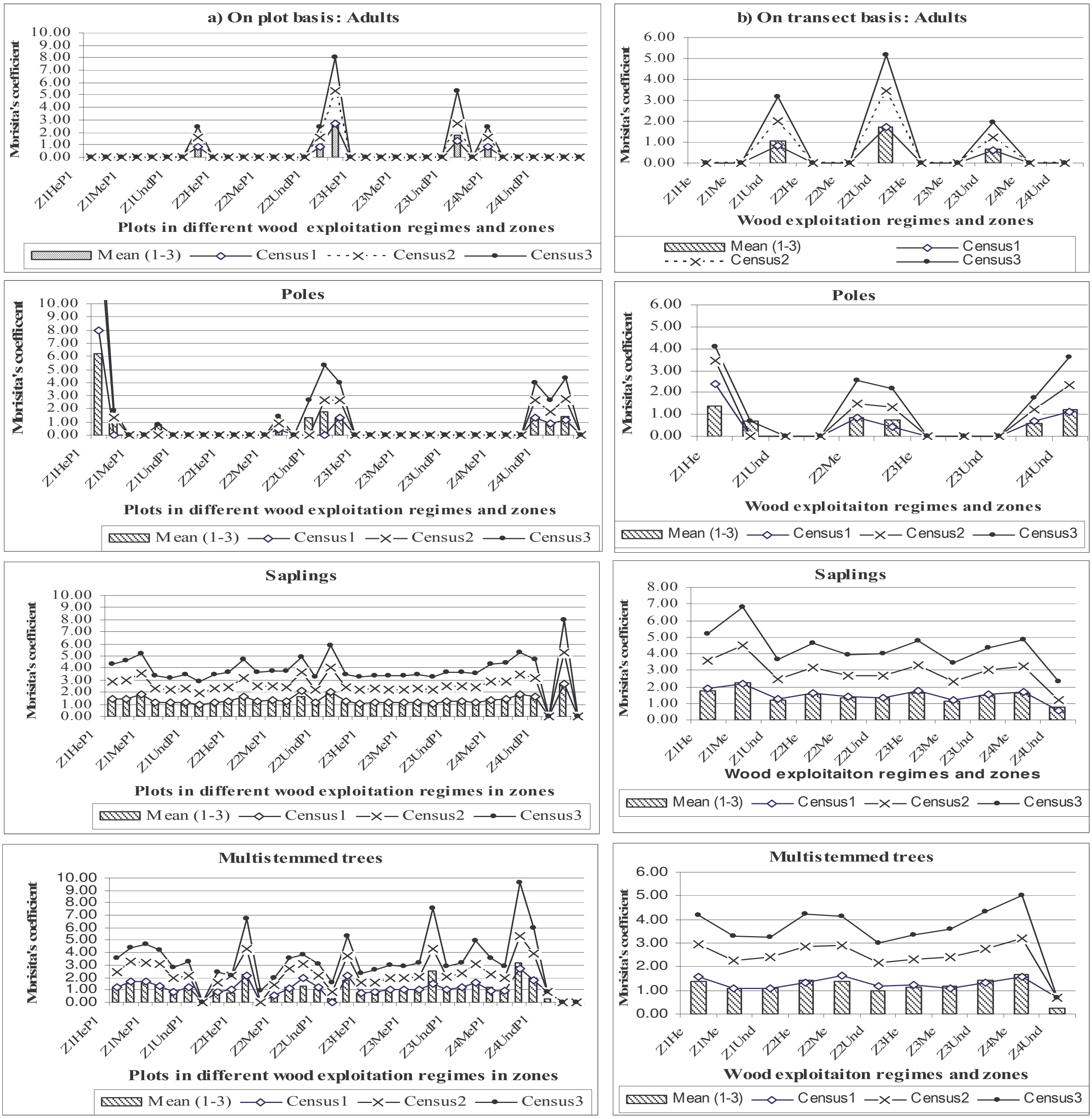


Figure 4.20: Trends in values of Morisita's coefficient in tree developmental stages along transects in different wood exploitation regimes in mangrove forest in Douala-Edea, Cameroon during three census periods

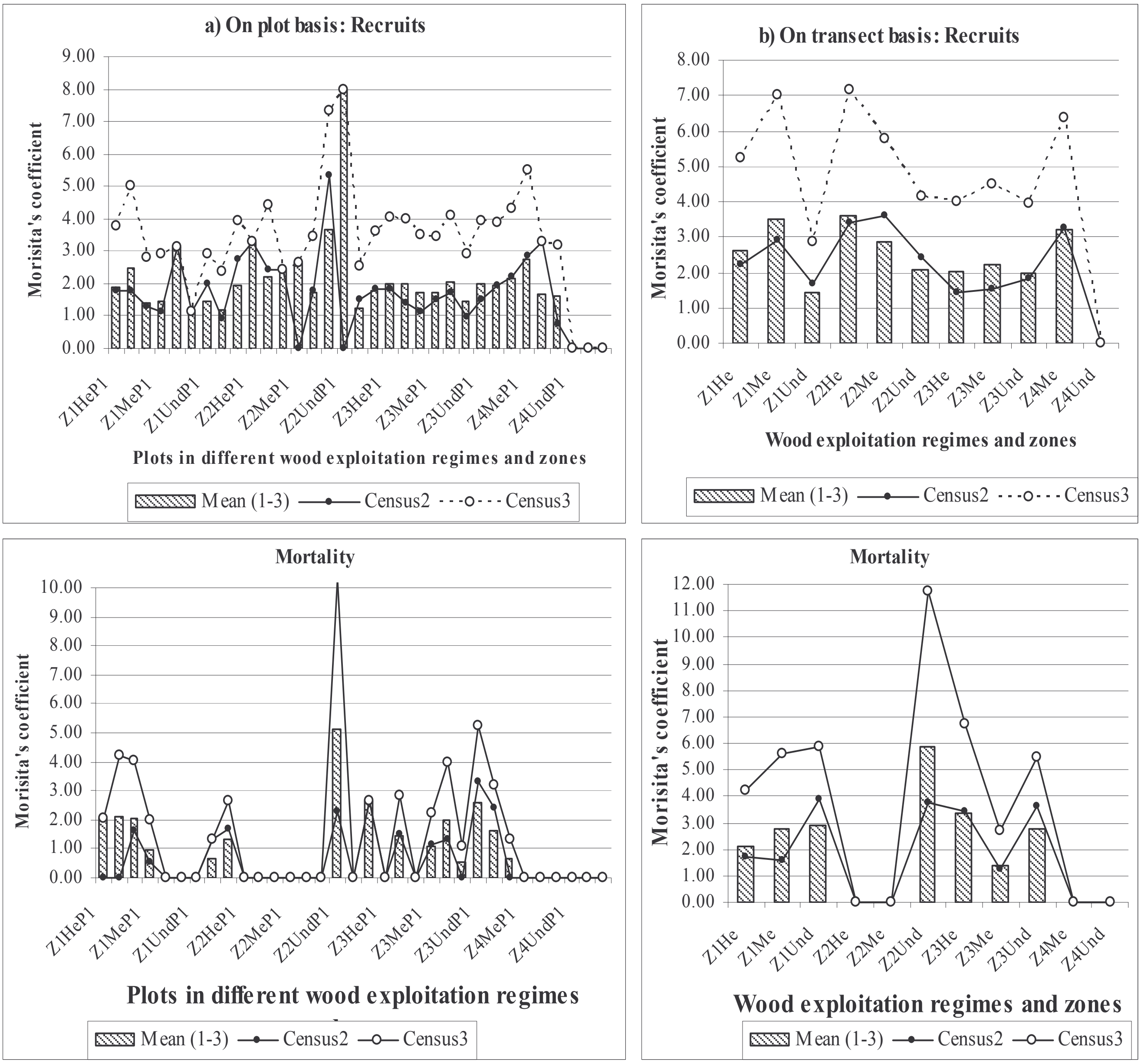


Figure 4.21: Trends in values of Morisita's coefficient in tree recruits and mortality along transects in different wood exploitation regimes in mangrove forest in Douala-Edea Cameroon during three census periods.

There were no significant site, wood exploitation regime and time or their interaction effects on spatial patterns in all the tree developmental stages. However, spatial pattern of mortality was significant for site, wood exploitation regime and time and their interactions except regime x census interaction. Spatial pattern for multi-stemmed trees were only significant at the site x wood exploitation regime interaction level. Like values of Morisita's coefficient, values of spatial correlation indices with mortality and recruits usually indicate more attractive repulsive tendencies with recruits than deads with other tree developmental stages (Table 4.11).

Table 4.11: Spatial correlation of tree recruits and mortality with other tree Developmental stages under different disturbance regimes in Douala-Edea mangrove, Cameroon

Zone	Wood exploitaiton regimes	Association index values						
		Dead Vs Adults	Dead Vs multiple stem	Dead Vs Poles	Recruits Vs Adults	Recruits Vs Dead	Recruits Vs Multiple stem	Recruits Vs Poles
1	He	-0.10	0.40	0.35	-	-0.03	0.18	0.13
	Me	0.26	-0.25	-0.14	0.16	0.36	-0.28	-0.08
	Und	-0.37	0.08	-	-0.07	-0.07	-0.16	-
2	He	-	-0.26	-0.13	-	0.12	0.12	0.11
	Me	0.31	0.01	0.17	0.18	0.19	0.06	-0.33
	Und	-0.12	0.20	-0.19	-0.07	-0.12	-0.04	-0.23
3	He	-0.21	-0.65	0.13	0.04	0.00	-0.16	-0.05
	Me	-	0.04	0.21		-0.24	0.08	-0.23
	Und	-0.01	0.14	-0.22	-0.17	0.11	0.40	-0.21
4	Me	-0.10	-0.18	-0.25	-0.19	-0.23	0.11	0.05
	Und	0.30	0.12	-0.10	-	-	-	-

4.3.3. Mortality, recruitment, growth and yield parameters

There were only significant zonal differences in recruitment and regime differences in basal area increment. No interaction effects were noted. Though mortality was not significant during the period, except for the natural undisturbed forest in zone 4, mean recruitment over the period was generally above mortality (Figure 4.22, Figure 4.23). There was almost normal distribution in diameter growth categories (Figure 4.24) with most trees being of the average growth category (0.11-0.50cm/yr) less at the lowest extreme negative or nil performance (-ve - 0.00) and at highest extreme that consists of excellent performance (over 1.00 cm/yr). Basal area growth was highest in moderate exploited forests ranging from 0.00 – 0.11m^2/ha/yr, mean 0.02 m^2/ha/yr, then followed by heavily exploited forests that range from 0.00 – 0.04 m^2/ha/yr, mean 0.01 m^2/ha/yr; then lastly by undisturbed forests in the range -0.46 – 0.05 m^2/ha/yr with mean -0.001 m^2/ha/yr.

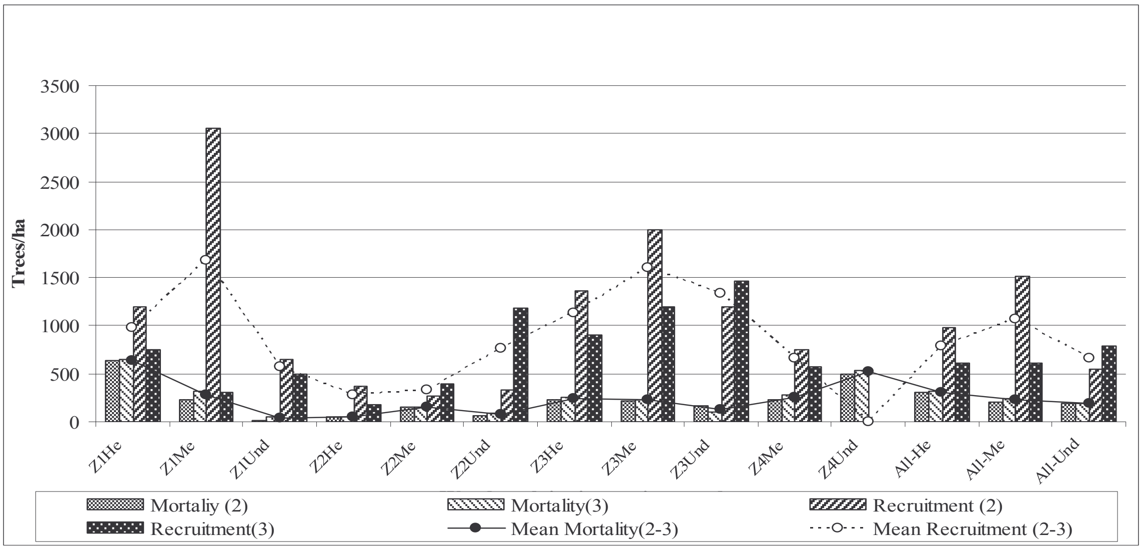


Figure 4.22: Spatio-temporal trends in mortality and recruitment in Douala-Edea coastal Atlantic mangrove forest, Cameroon under different wood exploitation regimes.

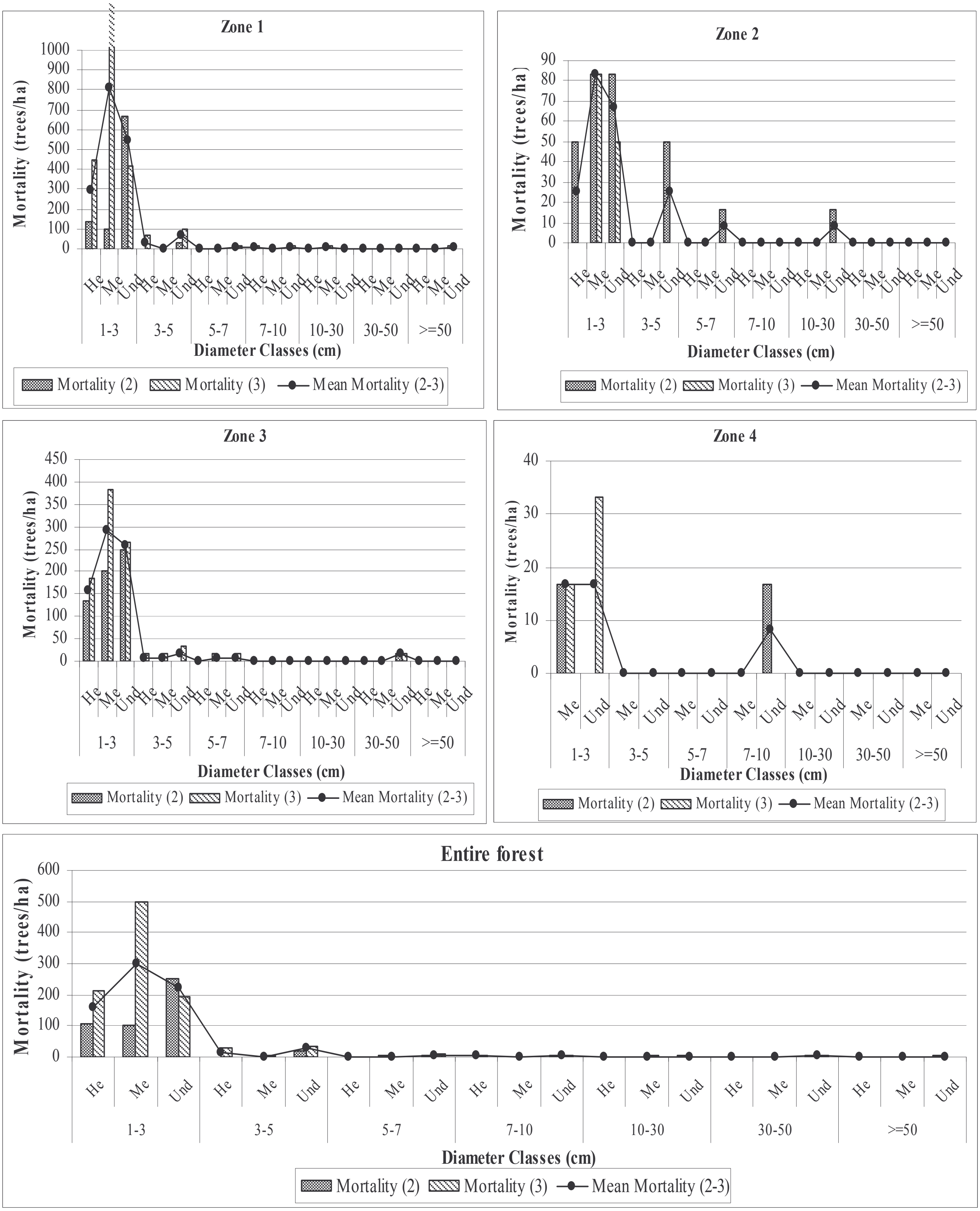
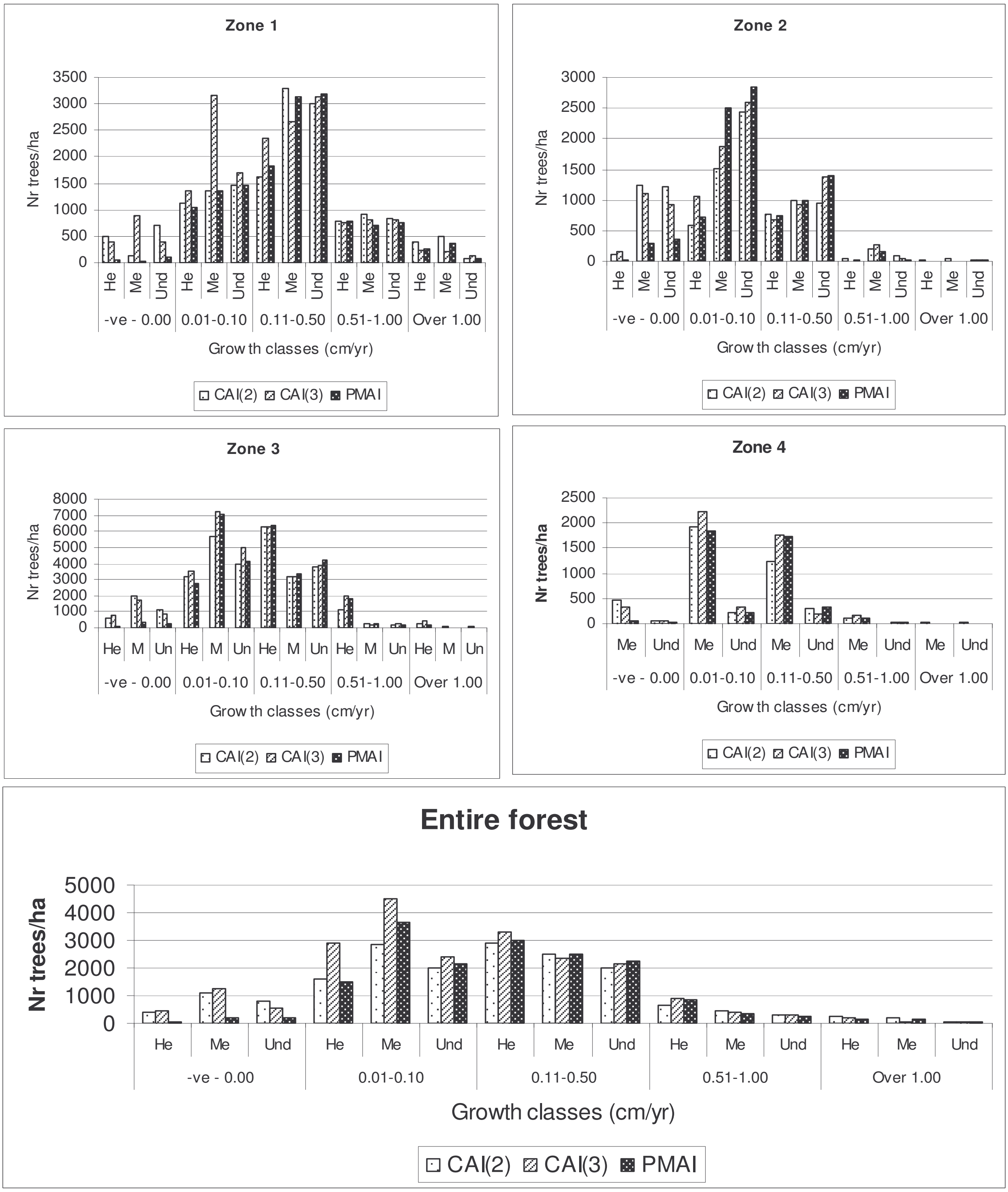


Figure 4.23: Size specific mortality in Douala-Edea coastal Atlantic mangrove forest, Cameroon following different wood exploitation levels.


Zone 1

Zone 2

Zone 3

Zone 4

Entire forest

Figure 4.24. Distribution of growth categories in Douala-Edea coastal Atlantic mangrove forest, Cameroon following different levels of wood exploitations (Growth categories after Kariuki et al. (2006): -ve - 0.00 – negative and nil (non performance); 0.01 -0.10 - below average; 0.11-.50-average; 0.51 – 1.00 above average and over 1.00-excellent.

4.3.4. Tree form

The results obtained permit us to understand if mangrove wood exploitation has any impact on whether a tree is single stemmed or multi-stemmed. Whether it is justifiable to consider stems as separate entities or isolate tree individuals.

4.3.4.1. Stems per tree (branching intensity)

Stand tree density decreases with increasing stem density per tree in an L-shape fashion (Figure 4.25).

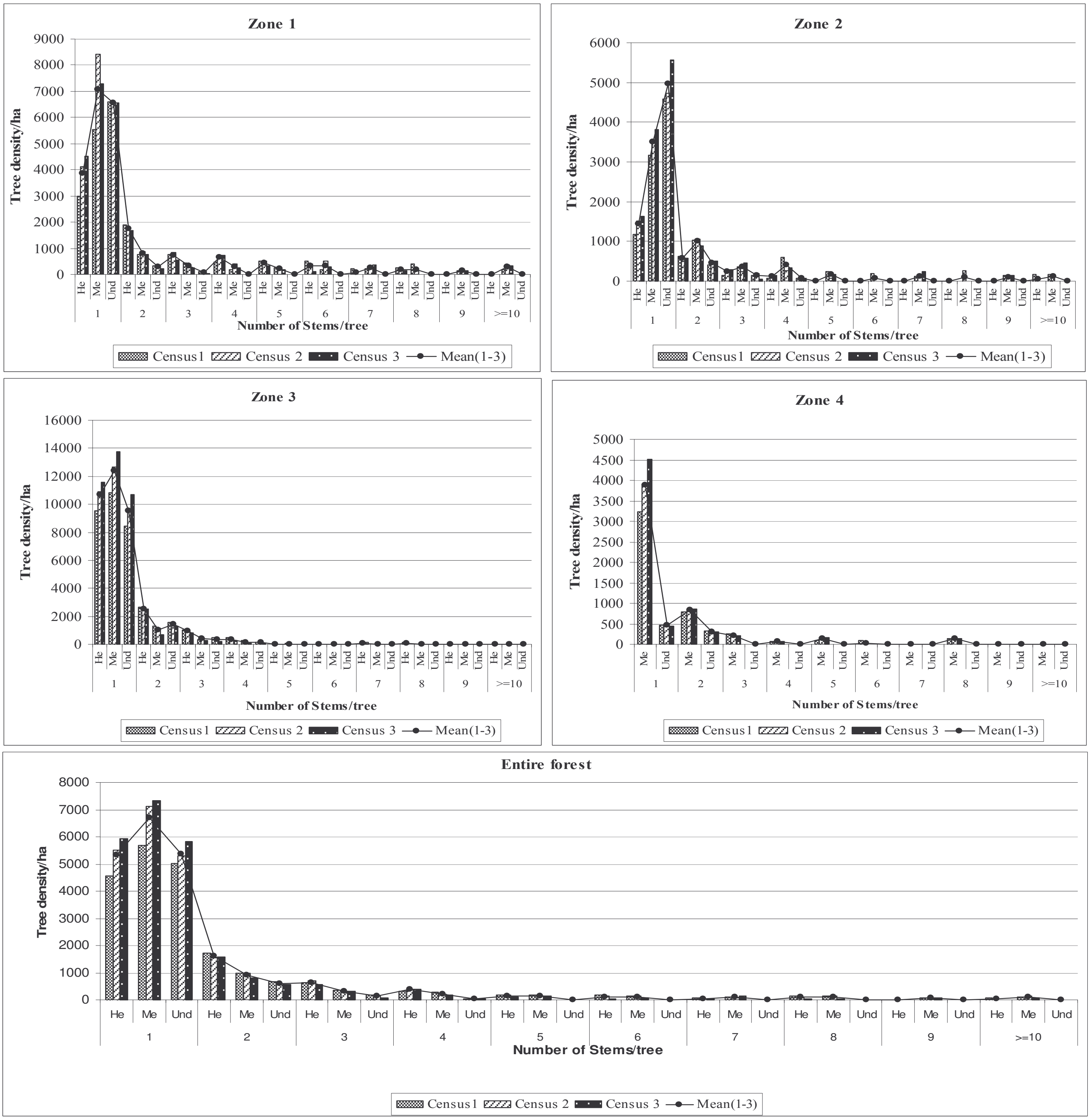


Figure 4.25: Trends in distribution of stem numbers per tree in a mangrove forest under different wood exploitation regimes in Douala-Edea, Cameroon during three census periods

Branching intensity for principal mangrove species tend to increase with disturbance and decrease with time with heavily exploitation having maximum stem per tree of 10, moderate 11 and undisturbed 4 with mean stem density per tree of 1.2 (Figure 4.26). The proportion of multi-stemmed individuals in the population was 7% and 16% for undisturbed and undisturbed forests respectively. The proportion of multi-stemmed trees tends to increase with diameter in a more determined mathematical fashion (Figure 4.27).

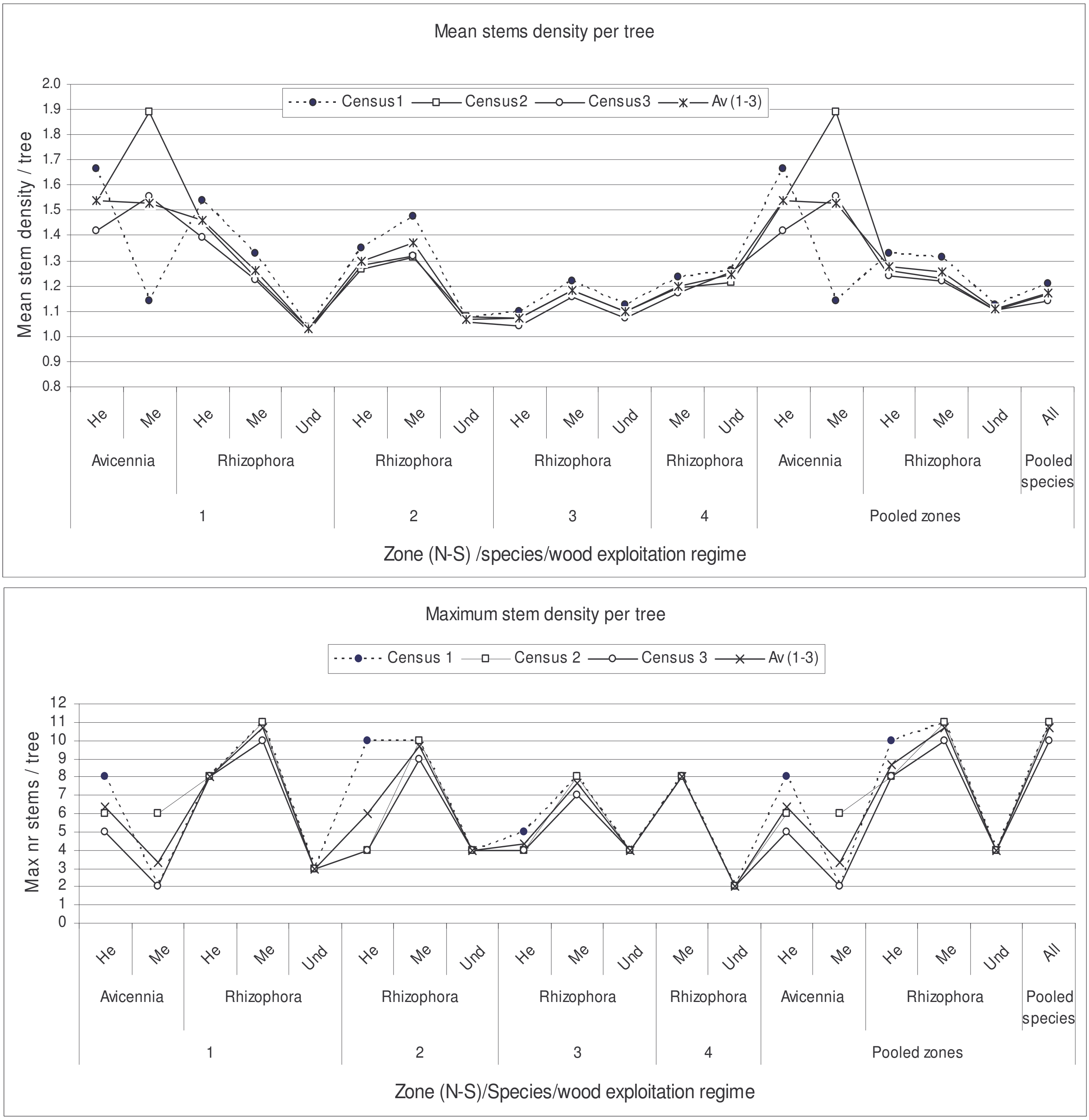


Figure 4.26.: Spatio-temporal trends in branching intensity of mangrove species of Douala-Edea Atlantic coast, Cameroon

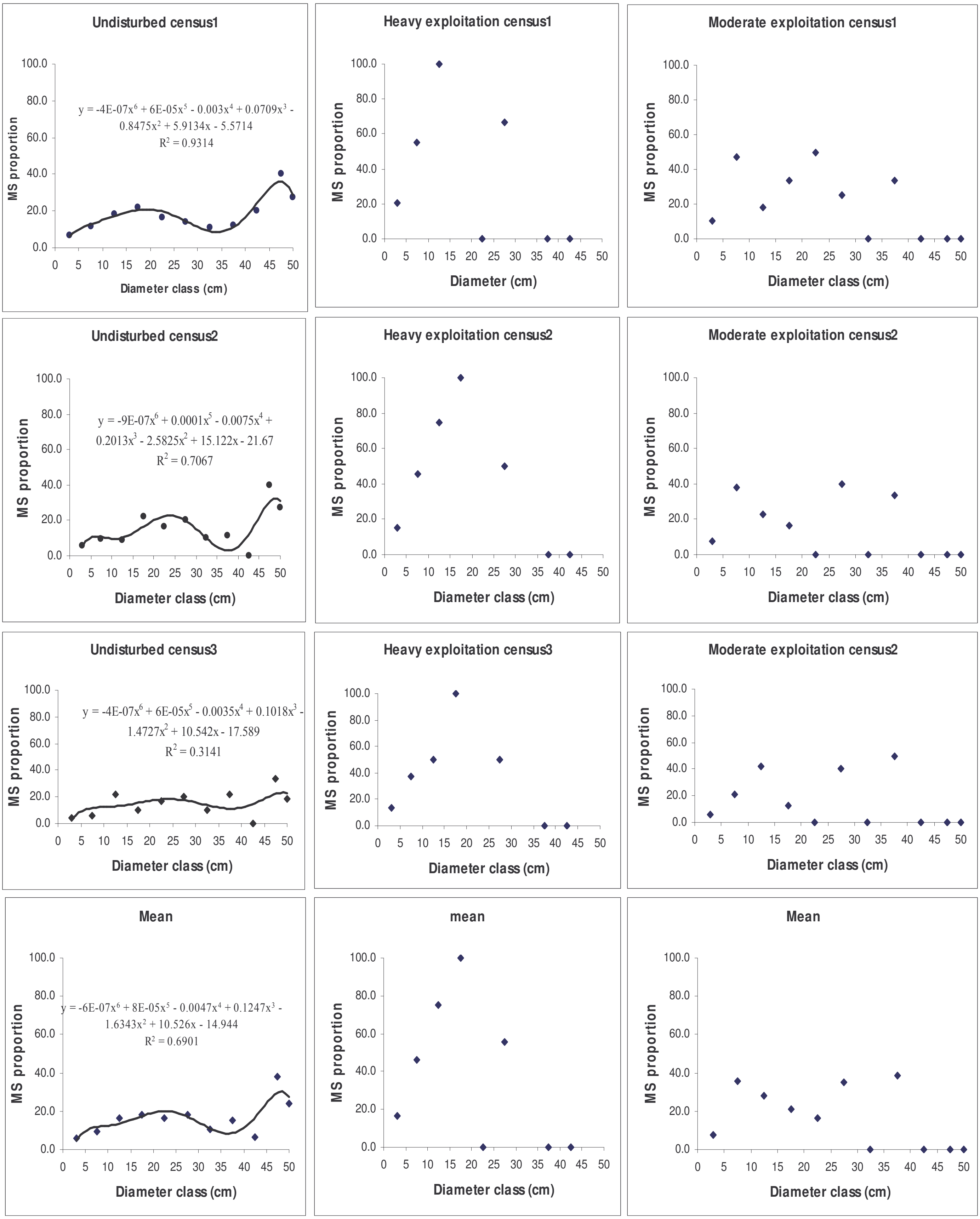


Figure 4.27: Trends in size dependent pattern of multi-stemmed tree distribution in Douala-Edea coastal Atlantic mangrove forest, Cameroon following different wood exploitation regimes

4.3.4.2. Stand parameters on tree form

All the stand parameters (stand density, basal area, volume and above ground biomass) have significant impact on tree form. There were only interactions of tree form with zone and regimes at the level of stand density. Stand parameters for undisturbed forest were estimated at: stand density: range 400 – 20100 trees/ha, mean 5416.7, SE 1930.5; 400 - 22300 stems/ha mean 5900.0, SE 2077.7(d≥1.0cm); basal area/ha: range 25.23 - 49.62m^2/ha, mean 36.85m^2/ha, SE 3.23m^2/ha; volume/ha: range 222.50 – 610.43m^3/ha, mean 402.81m^3/ha, SE 49.41m^3/ha; above ground tree biomass/ha: range 240.3 – 659 tons/ha, mean 435.03 tons/ha, SE 53.40 tons/ha (Figure 4.28). Contribution of multi-stemmed individuals was generally higher for stems than trees. Average contribution for the 3-census times for i) stand density for trees in heavily exploited regime (HE) was 12.5%, moderate exploitation (ME) 13.8%, undisturbed (UND) 6.2%; stems in HE 28.2%, ME 29.6%, UND 12.9% ii) basal area of trees in HE 31.4%, ME 19.3%, UND 18.3%; stems in HE 80.9%, ME 42.7%, UND 31.9% iii) volume/biomass for trees in HE 26.4%, ME 9.7%, UND 10.3%; stems in HE 66.8%, ME 34.4% and UND 23.8% (see Figure 4.29).

4.3.4.3. Stand growth parameters on tree form

There were significant differences among different zones on basal area, volume and above ground biomass increment. Forest disturbance seem not to have any significant impact on tree form in all the stand growth parameters considered nor any interaction effects between tree form between zones, regimes or census. Multiple comparison tests through least significant difference (LSD) analysis show that exploited regimes were superior in growth than disturbed ones. Stand growth mean values for all stems for different exploitation regimes were: i) diameter growth: heavily exploited regime 0.34cm/yr; moderate exploitation, 0.31cm/yr and undisturbed 0.28 ii) basal area growth: heavily exploited 0.38 m^2/yr/ha; moderate 0.35 m^2/yr/ha and undisturbed -0.01m^2/yr/ha iii) volume growth: heavy exploitation range: 3.41 m^3/yr/ha; moderate exploitation 2.80 m^3/yr/ha; undisturbed forests -0.87 m^3/ha/yr; and iv) above tree biomass growth: heavy exploitation 3.68 tons/ha/yr, moderate exploitation 3.68 tons/ha/yr; and undisturbed forests -0.94 tons/ha/yr (Figure 4.30).

4.3.4.4. Recruitment and mortality on tree form

Significant differences in tree form in recruitment and mortality were observed between the zones and disturbance regimes with trees generally higher. No tree form – census interactions effects on recruitment but on mortality. Generally recruitment was above mortality in most cases. Tree recruitment was generally higher than stem recruitment but stem mortality was higher than tree recruitment (Figure 4.22). Mean annual recruitment values were: i) heavy exploitation 475 trees/ha (7.6%); sec. stems 63 stems/ha (2.6%); all stems 538 stems/ha (6.8%) ii) moderate exploitation; trees 475 trees/ha (7.1%), sec stems 140 stems/ha (5.0%); all stems 615 stems/ha (7.2%); iii) undisturbed forests, trees 333 trees/ha (6.0%); sec stems 18 stems/ha (2.1%), all stems 351 stems/ha (5.8%). Annual mortality values were: i) heavy exploitation: 153 trees/ha (2.4%), sec stems 225 stems/ha (9.3%), all stems 378 stems/ha (4.8%) ii) moderate exploitation: 116 trees/ha (1.7%), sec stems 152 stems/ha (5.5%), all stems 268 stems/ha (3.1%) iii) undisturbed forests: 95 trees/ha (1.7%), sec. stems, 44 stems/ha (5.2%), all stems 139 stems/ha (2.3%).

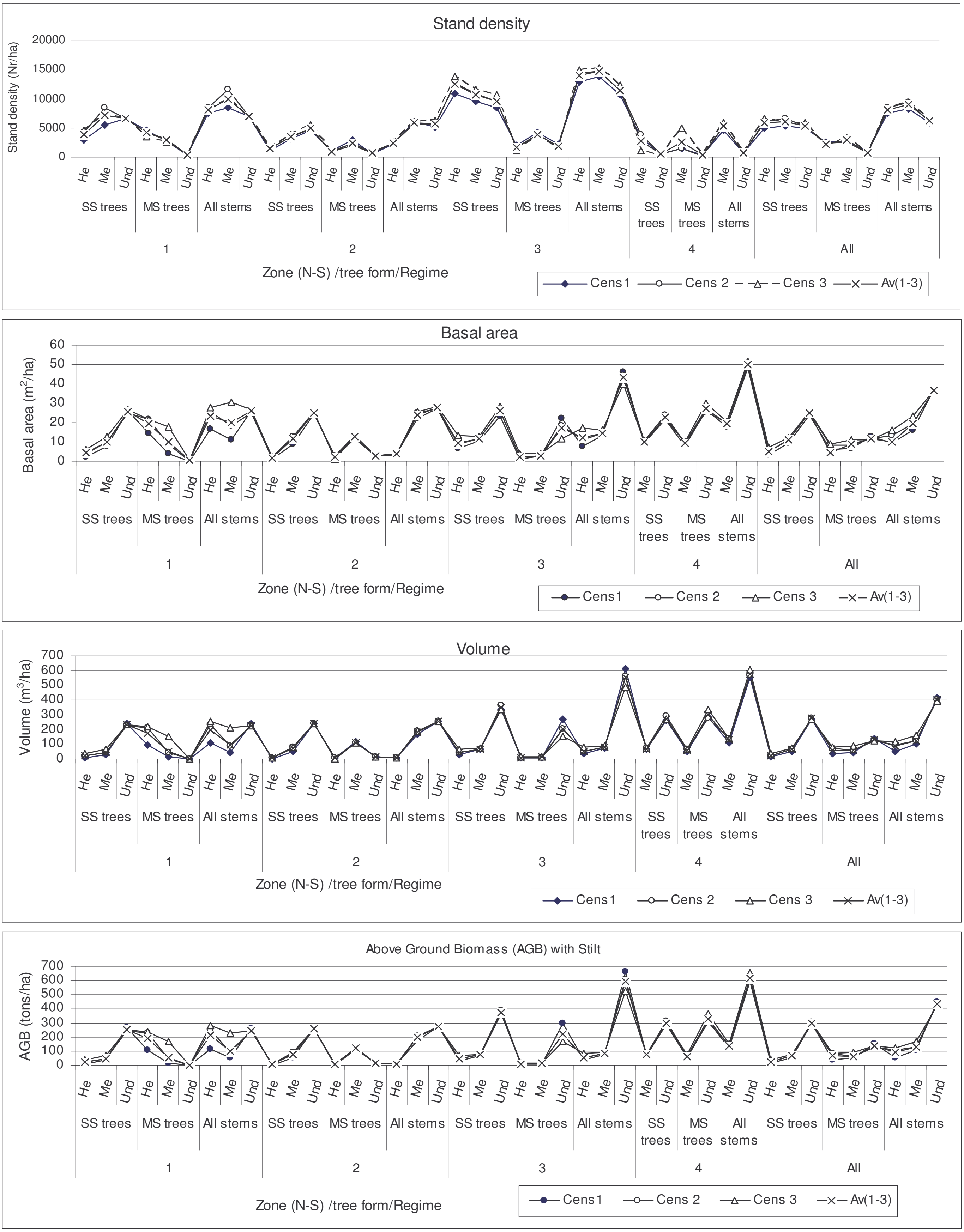


Figure 4.28: Spatio-temporal variation in stand parameters and tree forms in Douala-Edea coastal Atlantic mangrove forest, Cameroon under different wood harvest regimes

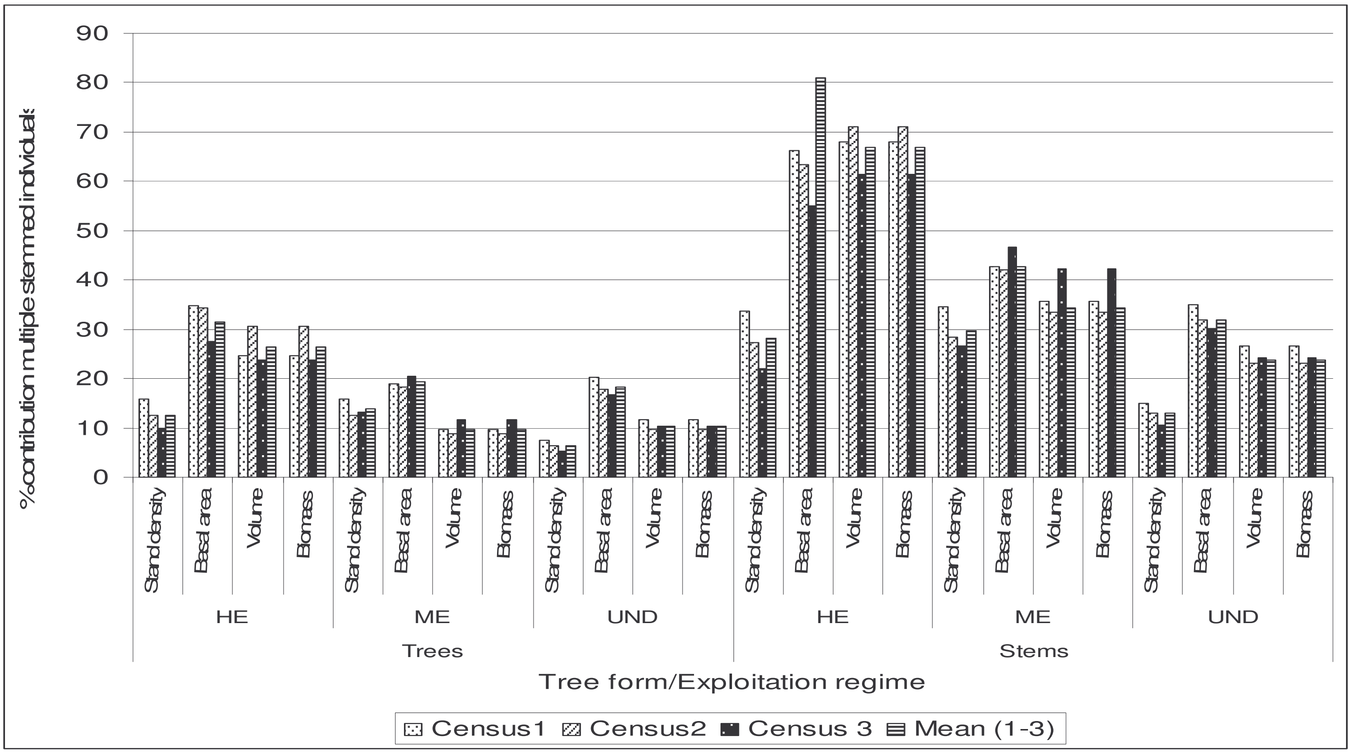


Figure 4.29: Trends in proportion of multi-stemmed individuals in different wood exploitation regimes in Douala-Edea coastal Atlantic mangrove forest, Cameroon

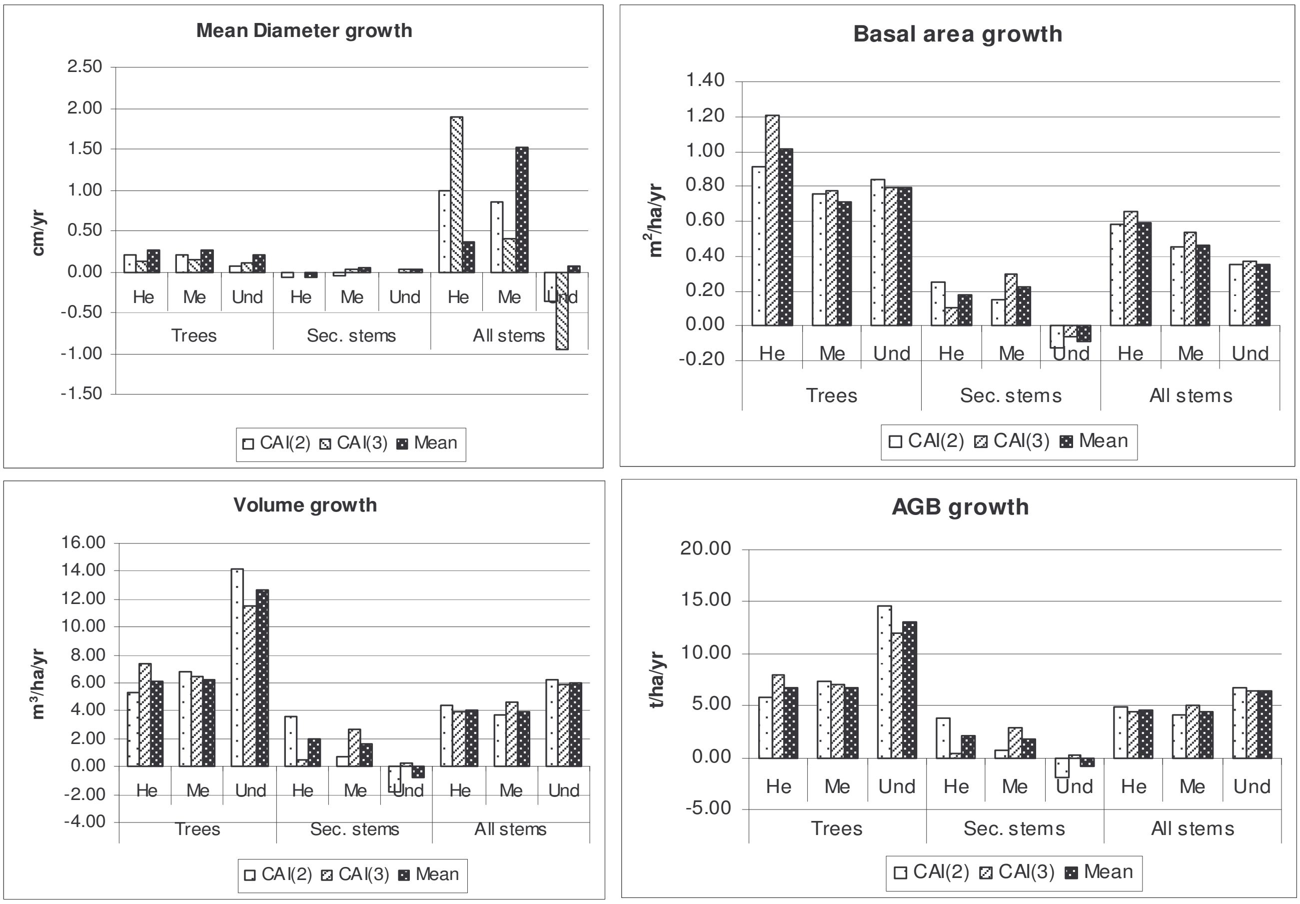


Figure 4.30. Growth and yield of primary and secondary stems in the Douala-Edea coastal Atlantic mangrove forest following different wood exploitation levels.

4.3.5. Impacts on plant invasion

Results of multivariate tests show that there were no site differences in invasive species level except Nypa palm. Forest disturbance had significant effect on invasive species level but no time or interactive effects except for ferns (Figure 4.31).

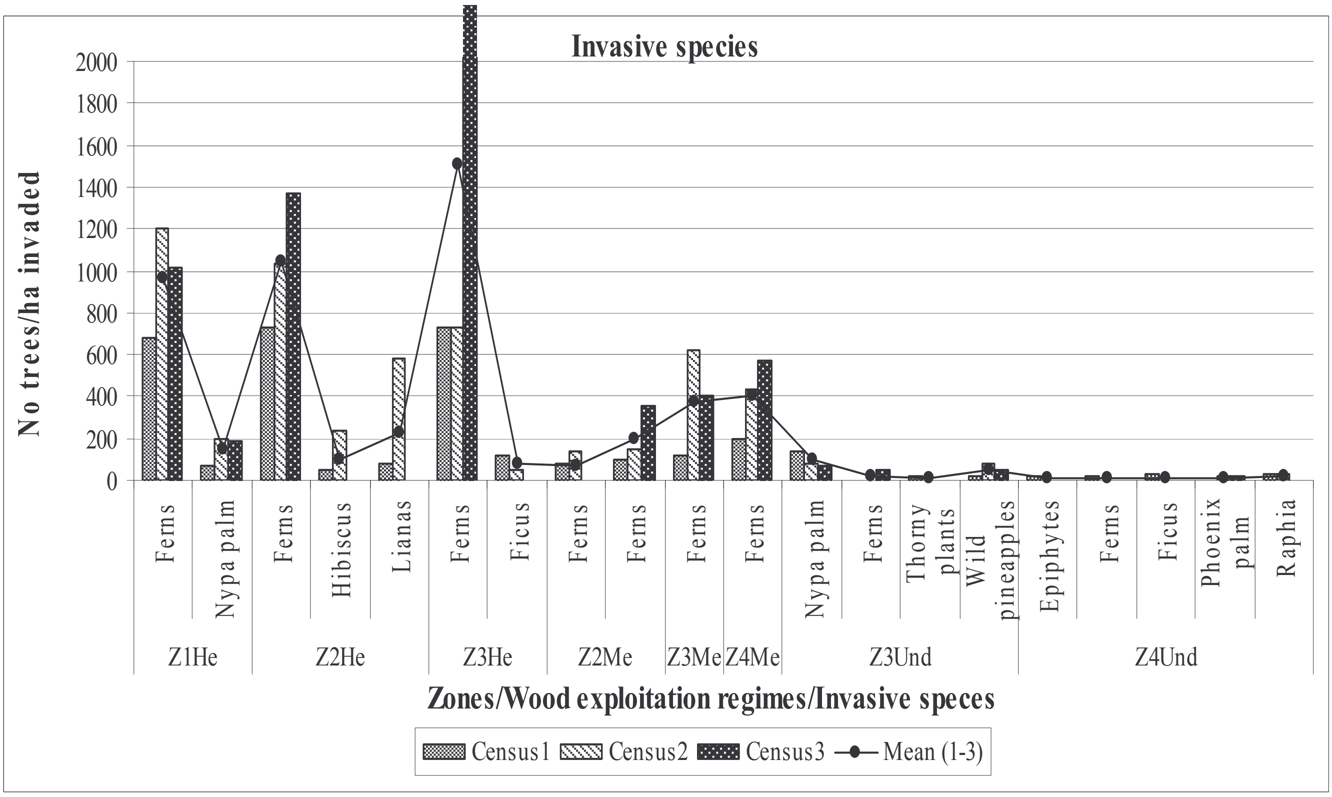


Figure 4.31. Trends in species invasion in the Cameroon coastal Atlantic mangrove forest following different wood exploitation levels.

4.4. Dynamics of *Avicennia* and *Rhizophora* in balanced mixed stands

4.4.1 Stand parameters

Except in the proportion of multi-stemmed trees that showed significant differences between the two species with *Avicennia* with between 20-100%, there were no other differences between species or their tree form in other stand parameters. However mean stand density values of *Avicennia* for all stems were 4139 stems/ha, *Rhizophora 2*850 stems/ha, mixed species 6989 stems/ha; basal area for *Avicennia* 5.18m^2/ha, *Rhizophora* 4.86m^2/ha, mixed 10.04m^2/ha; volume for *Avicennia* 44.05m^3/ha, *Rhizophora* 33.97m^3/ha, mixed 78.02m^3/ha; above ground tree biomass *Avicennia* 31.28tons/ha, *Rhizophor*a 32.0 tons/ha, mixed 63.28tons/ha (Figure 4.32).

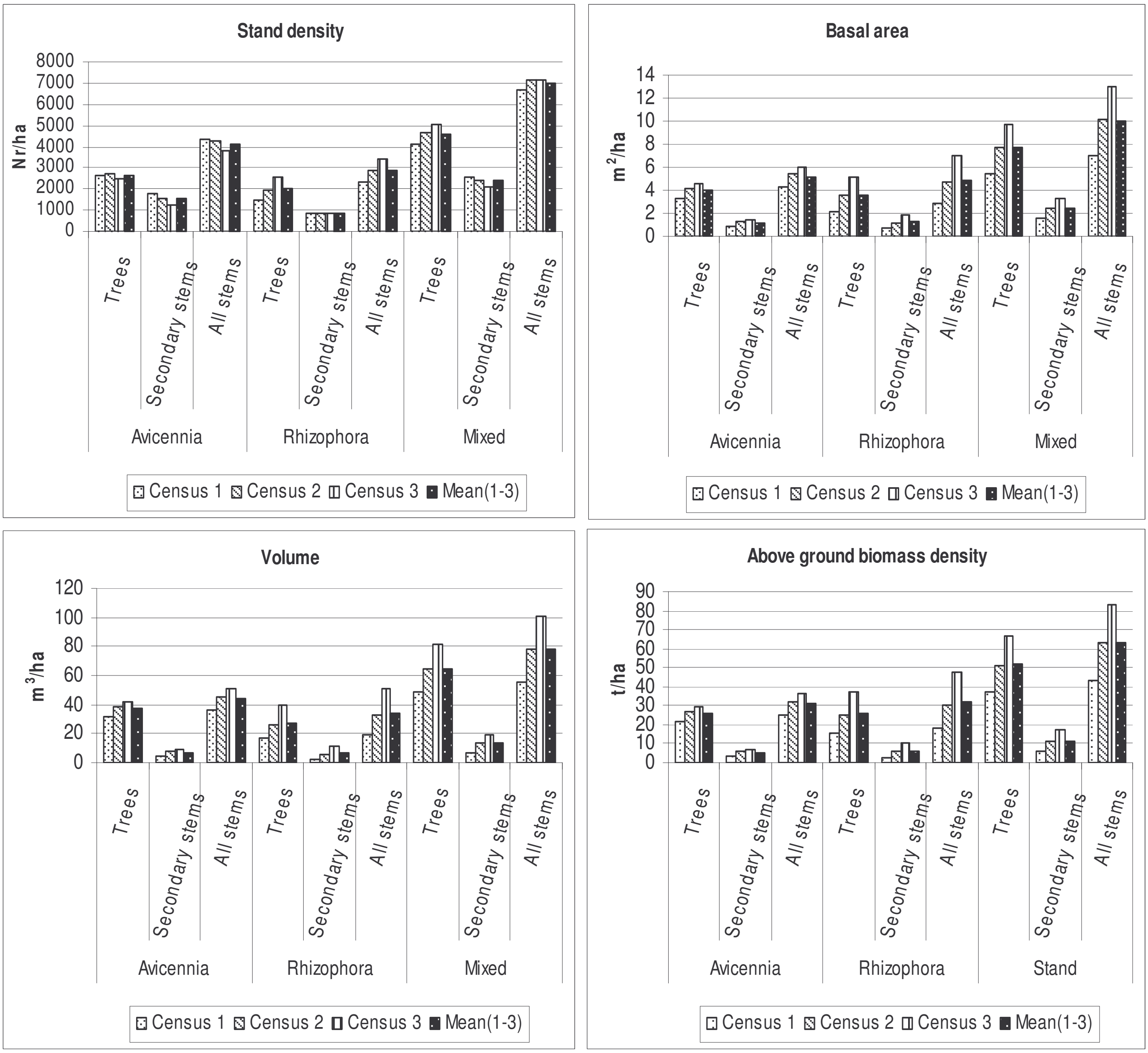
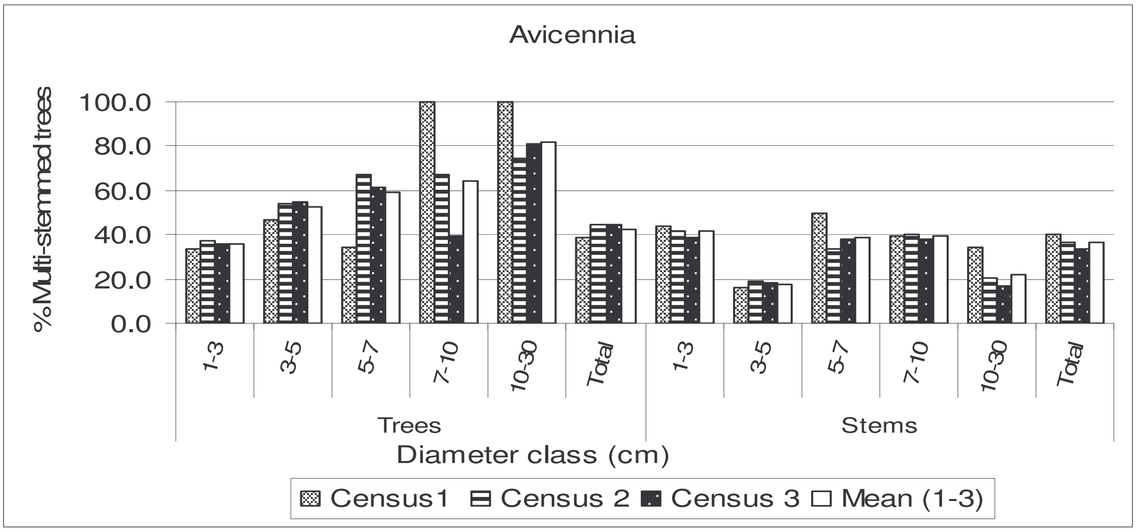
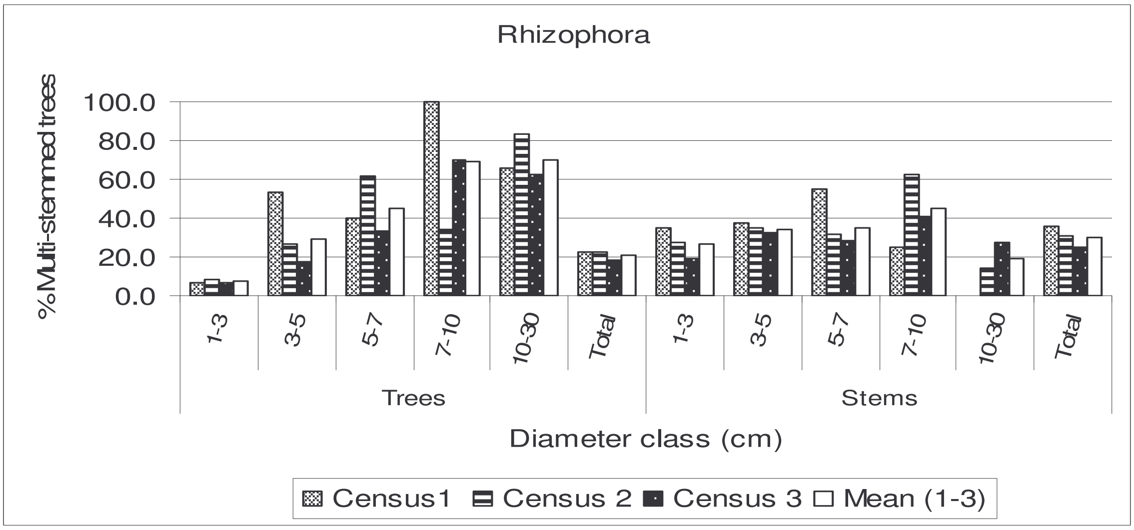


Figure 4.32: Trends in productivity of balanced mixed stands of Avicennia and Rhizophora in Douala-Edea coastal Atlantic mangrove forests, Cameroon

4.4.1 Multi-stemmed tree analysis

There were relatively more stems per tree in *Avicennia* with 20% minimiun than *Rhizophora* with minimum 0% (Figure 4.33). Consequently, multi-stemmed trees in *Avicennia* make more contribution to stand basal area, volume and above ground biomass than does *Rhizophora* (Figure 4.34).





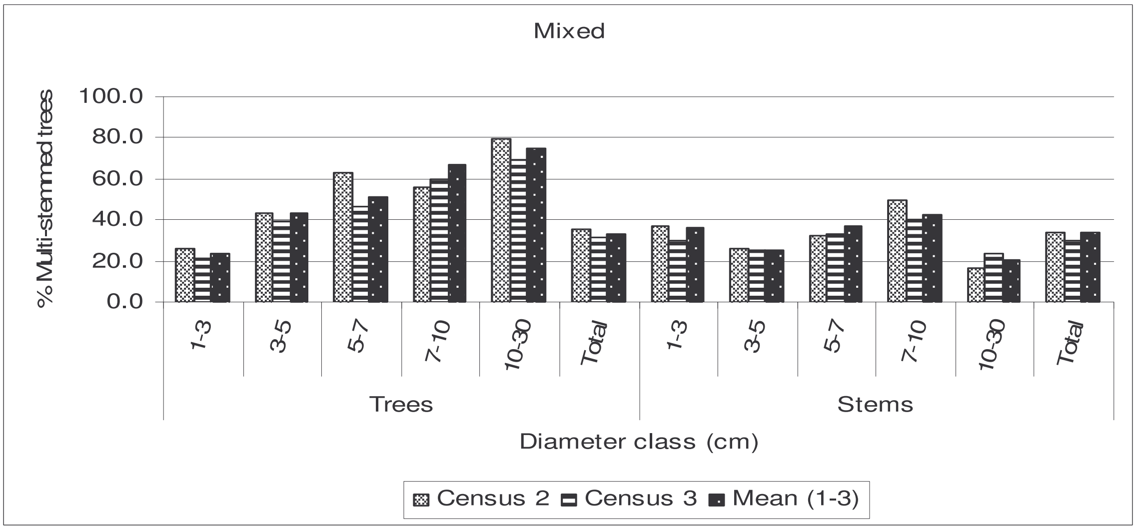


Figure 4.33: Proportional contribution of multi-stemmed trees to stand density by Avicennia and Rhizophora in Douala-Edea, Cameroon coastal Atlantic mangrove forest

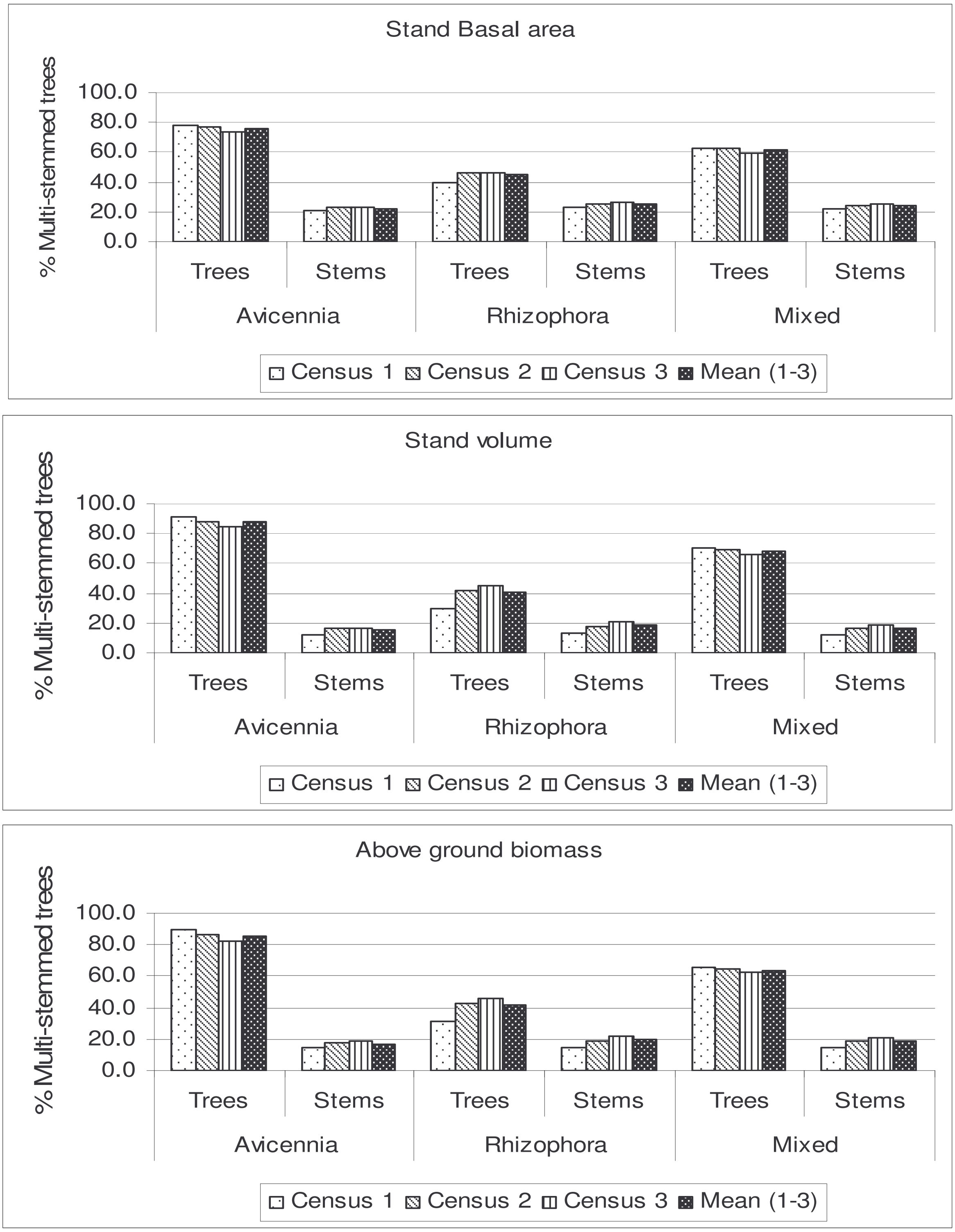


Figure 4.34: Proportional contribution of multi-stemmed trees to stand basal area, volume and biomass by *Avicennia* and *Rhizophora* in Douala-Edea coastal Atlantic Mangrove forest, Cameroon

4.4.2 Mortality and recruitment

There were significant association between tree form and species as well as between tree form and census in recruitment and mortality (Table 4.31). Recruitment was generally above mortality in both species but was higher in *Rhizophora* than *Avicennia* and vice versa for mortality. *Avicennia* recruited per year 92 trees/ha (3.5%), 183 sec. stems/ha (4.4%), all stems 275/ha (4.1%). *Rhizophora* 267 trees/ha (13.4%), 75 sec stems/ha (2.6%), all stems 342/ha (7.0%); mixed species 358 trees/ha (7.8%), 258 sec stems/ha (3.7%), all stems 616/ha (5.3%). Mortality values were: *Avicennia* 125 trees/ha (4.8%), 300 stems/ha (7.2%), all stems 425/ha (6.3%). *Rhizophora* 4 trees/ha (0.2%), 71 sec stems/ha (2.5%), all stems 75/ha (1.5%); mixed species: 129 trees/ha (2.8%), 371 sec stems/ha (5.3%), all stems 500/ha (4.3%) (Figure 4.35).

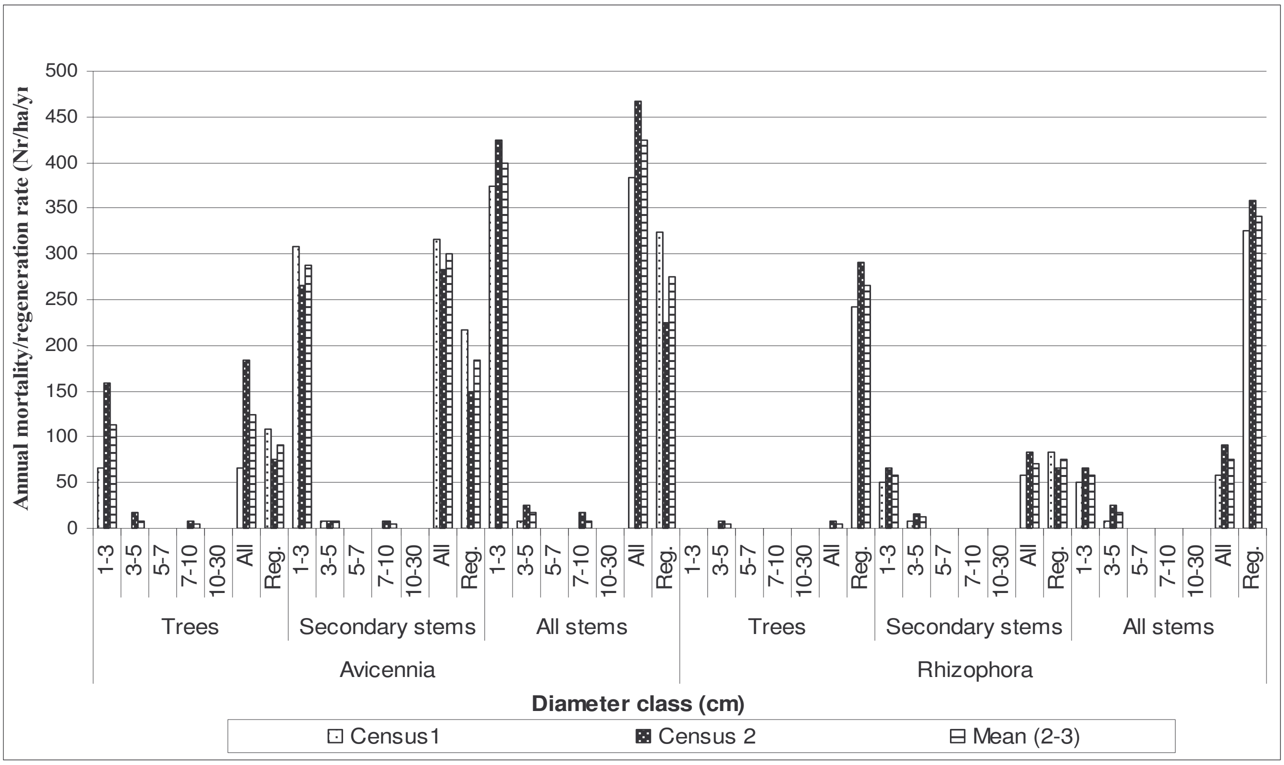


Figure 4.35: Mortality and regeneration of *Avicennia* and *Rhizophora* in balanced mixed stands in Douala-Edea Atlantic coast, Cameroon

4.5.3. Growth and yield parameters

There were significant differences in diameter growth between the species. There were no other significant differences or interaction differences in neither tree form nor census. Mean diameter growth for *Avicennia* was 0.29 cm/yr, *Rhizophora* 0.72cm/yr, mixed species 0.51 cm/yr; basal area growth for *Avicennia* 0.43m^2/ha/yr, *Rhizophora* 1.06 m^2/ha/yr, mixed

1.49m^2/ha/yr; Volume growth for *Avicennia* 3.55m^3/ha/yr, *Rhizophora* 7.81 m^3/ha/yr, mied species 11.35m^3/ha/yr; above ground biomass growth of 2.64 tons/ha/yr for *Avicennia*, 7.35 tons/ha/yr for *Rhizophora* and mixed species 9.99 tons/ha/yr (Figure 4.36).

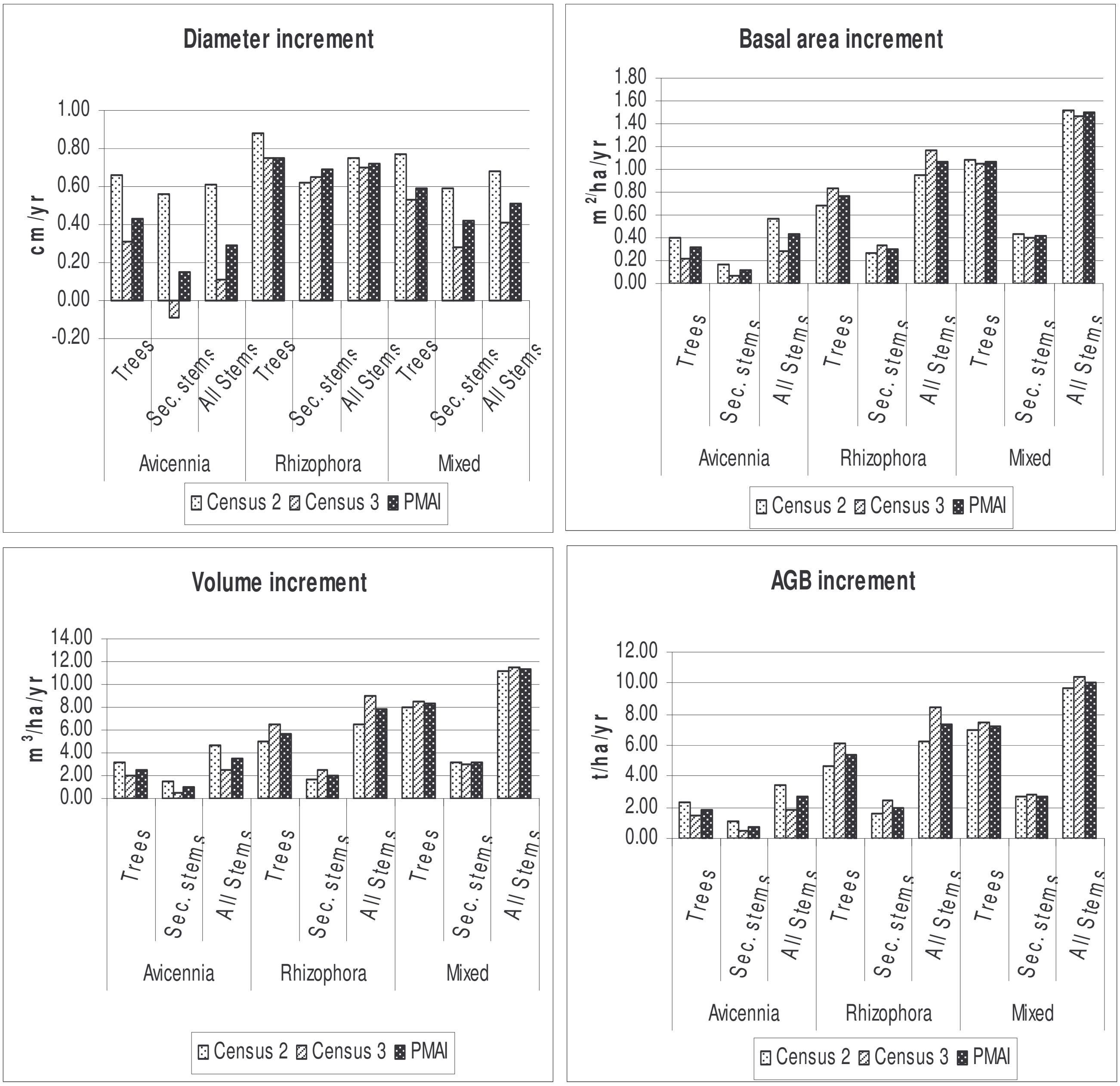


Figure 4.36: Growth and yield of balanced mixed stands of *Avicennia* and *Rhizophora* in Douala-Edea coastal Atlantic mangrove forest, Cameroon

4.5. Modeling mangrove stand dynamics following different wood exploitation regimes

The results of modelling mangrove stand dynamics following various levels of disturbance through wood extraction are presented.

4.5.1. Individual tree basal area increment models

Of a total of 3632 trees obtained from the PSP data 2408 trees were used to calibrate the model and 1224 trees to validate the predictive accuracy of the model. The characteristics of data used are presented in Table 4.12. Tree diameter ranged from 1.0 – 82.4 cm with mean of 2.84 cm.

Table 4.12: Summary statistics of main variables used for development and validation of tree basal area growth model for Douala-Edea coastal Atlantic mangrove forest, Cameroon following different wood exploitation levels.

Variables	Model development				Model validation			
	Mean	S.D	Min	Max	Mean	S.D	Min	Max
a) Size variables								
Initial tree diameter (cm) (D)	2.84	5.16	1.0	82.4	2.79	5.42	1.0	58.4
Reciprocal diameter (cm^{-1})	0.58	0.26	0.01	1.00	0.62	0.26	0.02	1.00
Arithmetric mean tree diameter (AMD) (cm)	2.84	2.19	1.79	30.08	2.79	2.44	1.64	22.18
Quadratic mean diameter (QMD) (cm)	4.9	3.81	1.96	34.54	5.08	3.59	1.78	25.25
Relative diameter (D/AMD)	1.00	1.31	0.13	20.60				
Relative diameter interation term (cm) (D^2/AMD)	1.00	1.31	0.13	1697.44	9.18	71.22	0.08	1795.65
Initial tree basal area (m^2)	0.003	0.02	0.0001	0.533	0.003	0.018	0.009	0.268
b) Competition variables								
Trees/ha	10324	7317	400	27400				
Initial stand basal area (G) (m^2/ha)	16.67	19.42	0.63	86.81	17.42	12.52	0.5	45.32
BAL[a](m^2/ha)	15.27	19.46	0.00	86.81				
Relative status (RS)[b]	0.83	0.23	0.00	1.00				
c) Site variables								
Stand top height[c] (SI) (m)	23.95	11.79	6.2	52.1				
Stand top crown ratio[d]	0.38	0.08	0.27	0.59				
d) Management variable								
Proportion of stand basal area removed (Gr)	0.52	0.38	0.00	0.97	0.37	0.39	0.00	0.98
e) Four year growth intervals								
Tree diameter growth (cm)	0.83	0.97	-1.40	7.30	0.84	0.84	-2.20	5.50
Tree basal area growth (m^2)	0.001	0.002	-0.001	0.049	0.001	0.002	-0.014	0.031
n			2408 trees			1224 trees		

[a] BAL is the sum of the basal area (m^2/ha) in trees with diameter larger than the subject tree's Dbh

[b] RS is the relative tree status expressed as BAL/G being relative position on cummulative basal area distribution (RS=0 and 1

[c] Stand top height is the average tree height of the 100/ha largest trees in diameter surrogate for site quality indicator

[c] Stand top live crown ratio is the live crown ratio of average tree height of the 100/ha largest trees in diameter

Table 4.13: Fitting statistics of basal area growth model (ln (g+1)) for Douala-Edea coastal Atlantic mangrove forest, Cameroon following different wood exploitation levels

Parameter	Unstandardized Coefficients		Stdzed Coefficients	t	Sig.	95% C.I. for B		Collinearity Statistics	
	B	Std. Error	Beta			Lower Bound	Upper Bound	Tolerance	VIF
Constant	1.170E-03	0.000		14.846	0.000	0.001	0.001		
1/D	-1.408E-03	0.000	-0.184	-13.153	0.000	-0.002	-0.001	0.935	1.069
D^2/AMD	2.232E-05	0.000	0.678	48.311	0.000	0.000	0.000	0.929	1.077
Gr	6.131E-04	0.000	0.117	6.860	0.000	0.000	0.001	0.633	1.579
G.Gr	-6.622E-05	0.000	-0.104	-6.136	0.000	0.000	0.000	0.637	1.570
Summary statistics									
R^2-adjusted		0.559							
Root MSE (SE)		0.00131							
F-ratio		764.356	$p<0.00001$						
Durbin Watson		1.40							
Std Residual	Min	-10.400							
	Max	23.630							
	Mean	0.000							
	SD	0.999							

The parameters were highly significant. The dependent variable, ln (g+1) was highly dependent on reciprocal diameter, relative interaction term D^2/AMD, interaction between basal area and exploitation level (Table 4.13).

Table 4.14: Validation of the diameter growth model for Douala-Edea coastal Atlantic mangrove forest, Cameroon

Description	Mean values	Mean difference	Mean absolute difference	Mean % bias	Paired Student t-test		
					t-value	df	p-value
Observed	0.0005						
Model	0.00054	2.97E-06	5.57E-04	-32.41	0.074	1222	0.941ns
As % of observed		0.54	103.45				
ns Not significant (P>0.05)		* Significant (P<0.05)			** Significant (P<0.01)		

The model has a reasonable predictive accuracy with a prediction bias, mean percentage difference of 0.54%, mean % bias of -32.41% with a non significant t-value (Table 4.14). The model residuals meet normal and constant variance assumptions.

4.5.2. Individual tree mortality models

The results of Wald statistics, log likelihood and Hosmer-Lemeshow's goodness-of-fit statistics for binary logistic model show that the probability of survival was dependent on reciprocal diameter, relative diameter, residual dominant stand height and wood exploitation levels. Parameter value and signs give the relative magnitude and direction of influence on tree probability of survival (Table 4.15).

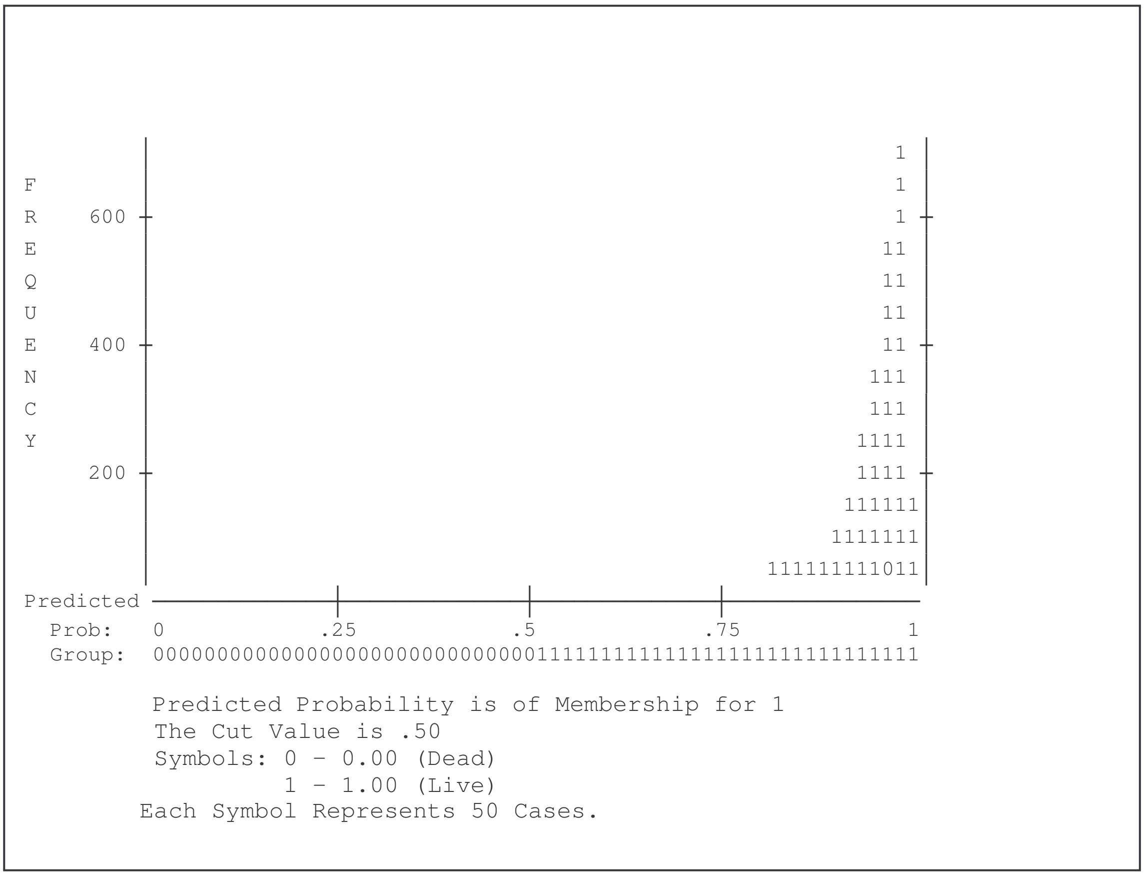
Table 4.15: Parameter estimates, their standard errors, Wald statistics, log likelihood and Hosmer-Lemeshow's goodness-of-fit statistics for binary logistic model estimating the probability of four year survival in the Douala-Edea coastal Atlantic mangrove forest, Cameroon

Parameter	B	S.E.	Wald	df	Sig.	Exp(B)	95.0% C.I.for EXP(B)	
							Lower	Upper
Constant	2.908	0.388	56.238	1	0.000	18.312		
1/D	-2.418	0.37	42.615	1	0.000	0.089	0.043	0.184
D/AMD	-0.125	0.047	7.2	1	0.007	0.882	0.805	0.967
SI	0.028	0.009	9.916	1	0.002	1.028	1.011	1.046
Gr	1.823	0.275	43.917	1	0.000	6.188	3.61	10.609
-2log likelihood				1100.836				
Hosmer-Lemeshow's goodness-of-fit statistics				5.794				
df				8				
p-value				0.670ns				

The model presents a good level of predictive accuracy against expected probability of survival (X^2 = 0.233 df = 6 p>0.05) (Table 4.16, Figure 4.37).

Table 4.16: Goodness-of-fit statistics for the survival model with validation data set for Douala-Edea coastal Atlantic mangrove forest, Cameroon

Dbh Class	Nr trees	Nr observed survival	Mean P(Z)	Nr expected survival	Chi-square
1-3	1113	1016	0.910	1012.40	0.01
3-5	149	143	0.964	143.66	0.00
5-7	12	12	0.965	11.59	0.01
7-10	10	9	0.966	9.66	0.05
10-30	26	26	0.964	25.07	0.03
30-50	15	14	0.922	13.83	0.00
50+	3	3	0.818	2.46	0.12
				Total	0.233ns
	Chi-square critical value, 6df, p=0.05				12.59
	ns: not significant (p>0.05)				



```
         |                                                          1 |
F        |                                                          1 |
R    600 +                                                          1 +
E        |                                                         11 |
Q        |                                                         11 |
U        |                                                         11 |
E    400 +                                                         11 +
N        |                                                        111 |
C        |                                                        111 |
Y        |                                                       1111 |
     200 +                                                       1111 +
         |                                                      111111|
         |                                                     1111111|
         |                                                111111111011|
Predicted ---------------+--------------+--------------+--------------
  Prob:   0             .25            .5             .75            1
  Group:  000000000000000000000000000000111111111111111111111111111111

          Predicted Probability is of Membership for 1
          The Cut Value is .50
          Symbols: 0 - 0.00 (Dead)
                   1 - 1.00 (Live)
         Each Symbol Represents 50 Cases.
```

Figure 4.37. Observed groups and predicted probabilities of survival

4.5.3. Recruitment models

4.5.3.1. Probability of recruitment

The probability of recruitment was a function of inverse of stand density, direct function of site indicator and disturbance level (Table 4.17).

Table 4.17: Parameter estimates, their standard errors, Wald statistics, log likelihood and Hosmer-Lemeshow's goodness-of-fit statistics for binary logistic model estimating the probability of four year recruitment in the Douala-Edea coastal Atlantic mangrove forest, Cameroon

Parameter	B	S.E.	Wald	df	Sig.	Exp(B)	95.0% C.I.for EXP(B)	
							Lower	Upper
1/Nr	-4266.675	1920.244	4.937	1	0.026	0.000	0.000	0.000
SI	0.143	0.072	3.934	1	0.047	1.154	1.002	1.329
Gr	5.946	2.187	7.392	1	0.007	382.048	5.257	27765.226
-2log likelihood				10.318				
Hosmer-Lemeshow's goodness-of-fit statistics				4.433				
df				8				
p-value				0.816ns				

These appear to be reasonable with practice. The model presents a good level of predictive accuracy against expected probability of recruits ($X^2 = 1.067$ df = 3 $p>0.05$) (Table 4.18, Figure 4.38).

Table 4.18: Goodness-of-fit statistics for the recruitment model with validation data set for Douala-Edea coastal Atlantic mangrove forest, Cameroon

Zone	Nr Subplots	Nr observed recruits	Mean P(Z)	Nr expected recruits	Chi-square
1	6	6	0.910	5.46	0.05
2	6	5	0.964	5.78	0.11
3	6	6	0.965	5.79	0.01
4	4	2	0.966	3.86	0.90
				Total	1.067ns
	Chi-square critical value, 3df, p=0.05				7.82
	ns: not significant (p>0.05)				

```
        32+                                                            +
          |                                                            |
          |                                                           1|
 F        |                                                           1|
 R      24+                                                           1+
 E        |                                                           1|
 Q        |                                                           1|
 U        |                                                           1|
 E      16+                                                           1+
 N        |                                                           1|
 C        |                                                           1|
 Y        |                                                           1|
         8+                                                           1+
          |                                                           1|
          |                                                         111|
          |0  00    0                         1 1              111 1011|
Predicted  ---------------+--------------+--------------+--------------
  Prob:    0            .25            .5             .75             1
  Group:   000000000000000000000000000000111111111111111111111111111111

           Predicted Probability is of Membership for 1
           The Cut Value is .50
           Symbols: 0 - 0 (absence of recruit)
                    1 - 1 (presence of recruit)
           Each Symbol Represents 2 Cases.
```

Figure 4.38. Observed groups and predicted probabilities of recruitment

4.5.3.2. Amount of recruitment

The amount recruitment (natural log of four year recruitment) was a function of stand density and disturbance. Table 4.39 gives the magnitude and direction of the parameters. The model has predictive mean % difference bias of 6.89 and t-test fit (t value = 0.797 df = 18, p>0.05). The error structure of the model meets the normal and constant variance assumptions.

Table 4.19: Fitting statistics of recruitment model for Douala-Edea coastal Atlantic mangrove forest, Cameroon following different wood exploitation levels

Parameter	Unstdzed Coefficients		Stdzed Coefficients	t	Sig.	95% Confidence Interval for B		Collinearity Statistics	
	B	Std. Error	Beta			Lower Bound	Upper Bound	Tolerance	VIF
lnNr/Gr+1	0.860	0.026	0.753	33.322	0.000	0.808	0.912	0.655	1.527
Gr	3.542	0.234	0.343	15.159	0.000	3.069	4.016	0.655	1.527
Summary statistics									
R^2-adjusted		0.987							
Root MSE (SE)		0.813							
F-ratio		1476.002	p<0.00001						
Durbin Watson		0.930							
Std Residual	Min	-2.11							
	Max	1.53							
	Mean	0.005							
	SD	0.987							
	n	39							

Table 4.20: Validation of recruitment model for Douala-Edea coastal Atlantic mangrove forest, Cameroon

Description	Mean values	Mean difference	Mean absolute	Mean % bias	Paired Student t-test		
					t-value	df	p-value
Observed	2189						
Model	2048	141	1620	-138.1	0.261	18	0.797ns
As % of observed		6.89	79.08				
ns Not significant (P>0.05)			* Significant (P<0.05)		** Significant (P<0.01)		

4.5.4. Stand volume projection models

Data used for the development of stand volume projection models following different levels of wood extraction are presented as time independent yield models with two different sets of predictor variables (Model 1-basal area, site indicator and proportion of basal area removed and Model 2-basal area and proportion of basal area removed) and short-term time dependent model (Model 3 – Basal area, proportion of basal area removed and time elapsed after disturbance) (Table 4.22).

Table 4.21: Summary statistics of main variables used for the development and validation of stand volume projection models for Douala-Edea coastal Atlantic mangrove forest, Cameroon following different levels of wood exploitation

Variables	Model development				Model validation			
	Mean	S.D	Min	Max	Mean	S.D	Min	Max
Initial stand basal area (G) (m^2/ha)	20.46	20.71	0.63	94.97	16.18	14.91	0.84	72.7
Initial stand stand volume (V) (m^3/ha)	343.53	490.67	2.14	2432.16	231.52	307.35	2.35	1383.67
Stand top height[a] (SI) (m)	24.46	20.71	6.2	52.1	20.60	10.76	4.6	37.9
Proportion of stand basal area removed (Gr)	0.48	0.43	0.00	0.969	0.44	0.39	0.00	0.98
Time (years after harvest)	2	1.6	0	4	2	1.6	0	4

[a] Stand top height is the average tree height of the 100/ha largest trees in diameter surrogate for site quality indicator

Table 4.22: Fitting statistics of stand volume projection models for Douala-Edea coastal Atlantic mangrove forest, Cameroon

Model	Dependent variable	Model summary					Parameter	Unstandardized Coefficients		Stdzed Coefs	t	Sig.	95% Confidence Interval for B		Collinearity Statistics		Durbin Watson	Residual statistics			
																		Std residuals			
		n	SE	R2-adj	Fratio	Sig		B	SE	Beta			Lower Bound	Upper Bound	Tolerance	VIF		Min	Max	Mean	SD
1	lnV	99	0.540	0.931	329.5	0.000	Constant	2.6	0.52		5.01	0.000	1.57	3.63			1.15	-3.6	3.04	0.00	0.98
							G^2	0.0002	0	0.15	4.74	0.000	0.00	0.00	0.68	1.471					
							InSI	1.024	0.144	0.35	7.12	0.000	0.74	1.31	0.301	3.318					
							SI/G	-0.239	0.021	-0.38	-11.55	0.000	-0.28	-0.20	0.669	1.495					
							Gr	-1.49	0.255	-0.32	-5.85	0.000	-2.00	-0.98	0.24	4.17					
2	V	99	85.710	0.969	1502.4	0.000	Constant	-305.17	29.07		-10.50	0.000	-362.87	-247.47			0.903	-2.2	2.5	0.00	0.99
							G	26.61	0.68	1.13	39.26	0.000	25.27	27.96	0.388	2.579					
							Gr	219.77	31.82	0.20	6.91	0.000	156.60	282.93	0.388	2.579					
3	Vt	99	82.588	0.971	1081.6	0.000	Constant	-284.15	28.93		-9.82	0.000	-341.59	-226.71			0.764	-2.4	2.74	0.00	0.99
							G	26.84	0.66	1.14	40.80	0.000	25.54	28.15	0.382	2.616					
							Gr	228.09	30.80	0.21	7.41	0.000	166.95	289.24	0.384	2.602					
							T	-14.83	5.12	-0.05	-2.90	0.005	-25.00	-4.67	0.986	1.014					

The models give a reasonable level of predictive bias (Table 4.23) and satisfactorily error structure.

Table 4.23: Validation of the stand volume projection models for Douala-Edea coastal Atlantic mangrove forest, Cameroon

Description	Mean values	Mean difference	Mean absolute difference	Mean % bias	Paired Student t-test		
					t-value	df	p-value
Observed	231.52						
Model 1	208.26	23.31	87.48	-56.21	1.488	98	0.140ns
As % of observed		10.07	37.78				
Model 2	219.71	11.81	78.18	268.80	1.153	98	0.252ns
As % of observed			5.10	33.77			
Model 3	221.53	9.99	77.62	216.93	0.973	98	0.333ns
As % of observed		4.32	33.52				
ns Not significant (P>0.05)		* Significant (P<0.05)		** Significant (P<0.01)			

4.5.5. Modelling eco-morphological phenomena

Probability of occurrence of some eco-morphological phenomena such as multi-stemmed trees and root sprout in *Rhizophora* were amenable to modelling under different wood exploitation levels.

4.5.5.1 Modelling probability of branching

The results of Wald statistics, log likelihood and Hosmer-Lemeshow's goodness-of-fit statistics for binary logistic model (Table 4.24) show that the proportion of multi-stemmed trees was dependent on tree diameter, relative tree status, interaction of basal area and disturbance and time elapsed after disturbance. The model gives a reasonable good-fit (Figure 4.39) at diameter classes above 3cm (X^2 =9.715 df=5 p>0.05) but poorly described all diameter classes caused by the first diameter class (Table 4.25).

Table 4.24: Parameter estimates, their standard errors, Wald statistics, log likelihood and Hosmer-Lemeshow's goodness-of-fit statistics for binary logistic model estimating the incidence of multi-stemmed trees in the Douala-Edea coastal Atlantic mangrove forest, Cameroon following different levels of wood exploitation

Parameter	B	S.E.	Wald	df	Sig.	Exp(B)	95.0% C.I.for EXP(B)	
							Lower	Upper
Constant	-4.084	0.227	322.951	1	0.000	0.017		
D	-0.105	0.012	76.365	1	0.000	0.9	0.879	0.921
lnD	1.816	0.106	291.689	1	0.000	6.15	4.993	7.575
RS	0.491	0.18	7.422	1	0.006	1.634	1.148	2.327
G.Gr	-0.049	0.012	17.266	1	0.000	0.952	0.931	0.975
Gr	1.445	0.125	132.712	1	0.000	4.242	3.317	5.424
T	-0.165	0.024	45.424	1	0.000	0.848	0.808	0.89
-2log likelihood					5247.286			
Hosmer-Lemeshow's goodness-of-fit statistics					13.092			
df					8			
p-value					0.109			

```
     4000 +                                                            +
          |0                                                           |
          |0                                                           |
F         |0                                                           |
R    3000 +0                                                           +
E         |0                                                           |
Q         |0                                                           |
U         |0                                                           |
E    2000 +0                                                           +
N         |0                                                           |
C         |00                                                          |
Y         |00                                                          |
     1000 +00                                                          +
          |00                                                          |
          |00                                                          |
          |000                                                         |
Predicted ---------------+--------------+--------------+---------------
  Prob:   0             .25             .5             .75            1
  Group:  000000000000000000000000000000111111111111111111111111111111

          Predicted Probability is of Membership for 1
          The Cut Value is .50
          Symbols: 0 - 0.00 (absence of multi-stemmed tree)
                   1 - 1.00 (presence of multi-stemmed tree)
          Each Symbol Represents 250 Cases.
```

Figure 4.39: Observed groups and predicted probabilities of multistemmed trees

Table 4.25: Goodness-of-fit statistics for incidence of multi-stemmed tree model with validation data set for Douala-Edea coastal Atlantic mangrove forest, Cameroon

Dbh class	Class Code	Nr trees	Nr Observed MS	Mean P(Z)	Nr Expected MS	Chi-square
1-3	1	2601	251	0.067	174.069	34.001
3-5	2	747	139	0.169	126.474	1.241
5-7	3	214	44	0.241	51.672	1.139
7-10	4	110	44	0.336	36.916	1.360
10-30	5	63	19	0.360	22.684	0.598
30-50	6	36	12	0.177	6.369	4.979
50+	7	7	0	0.057	0.398	0.398
Total (all classes)						**43.715*** **
Total (class 2-7)						**9.715ns**
Chi-square critical value, 6df, p=0.05						12.590
Chi-square critical value, 6df, p=0.001						22.460
ns: not significant (p>0.05), significant***p<0.001						

4.5.5.2 Modelling incidence of root-sprouting in Rhizophora

The results of Wald statistics, log likelihood and Hosmer-Lemeshow's goodness-of-fit statistics for binary logistic model (Table 4.26) also show that root sprouting in *Rhizophora* can be modelled. The probability of root-sprouting is controlled by the predictor variables:

relative tree status, interaction of relative status and disturbance. The model gives a reasonable good-fit at all diameter classes (Tables 4.27 and Figure 4.40).

Table 4.26: Parameter estimates, their standard errors, Wald statistics, log likelihood and Hosmer-Lemeshow's goodness-of-fit statistics for binary logistic model estimating the incidence of rootsprout in *Rhizophora* in the Douala-Edea coastal Atlantic mangrove forest, Cameroon following wood exploitation levels.

Parameter	B	S.E.	Wald	df	Sig.	Exp(B)	95.0% C.I.for EXP(B)	
							Lower	Upper
Constant	-4.312	0.499	74.761	1	0.000	0.013		
RS	-1.156	0.351	10.824	1	0.001	0.315	0.158	0.627
RS.Gr	-1.253	0.358	12.268	1	0.000	0.286	0.142	0.576
T	0.468	0.12	15.116	1	0.000	1.597	1.261	2.023
-2log likelihood					869.186			
Hosmer-Lemeshow's goodness-of-fit statistics					6.461			
df					8			
p-value					0.596			

Table 4.27: Goodness-of-fit statistics for the occurrence of root sprout model with validation data set for Douala-Edea coastal Atlantic mangrove forest, Cameroon

Dbh Class	Nr trees	Nr observed rootsprouts	Mean P(Z)	Nr expected rootsprouts	Chi-square
1-3	2440	17	0.014	35.04	9.28
3-5	474	12	0.023	10.73	0.15
5-7	98	3	0.031	3.04	0.00
7-10	33	0	0.038	1.26	1.26
10-30	54	0	0.024	1.29	1.29
30-50	29	1	0.041	1.18	0.03
50+	8	0	0.050	0.40	0.40
Total					12.414ns
Chi-square critical value, 6df, p=0.05					12.59
ns: not significant (p>0.05)					

```
     4000 +1                                                                +
          |0                                                                |
          |0                                                                |
F         |0                                                                |
R    3000 +0                                                                +
E         |0                                                                |
Q         |0                                                                |
U         |0                                                                |
E    2000 +0                                                                +
N         |0                                                                |
C         |0                                                                |
Y         |00                                                               |
     1000 +00                                                               +
          |00                                                               |
          |00                                                               |
          |000                                                              |
Predicted ---------------+---------------+---------------+------------------
  Prob:   0             .25             .5              .75             1
  Group:  0000000000000000000000000000000011111111111111111111111111111111. 250 cases by each
          Symbols: 0 - 0.00 (absence of rootsprouting) 1 - 1.00 (Presence of roorsprouting)
```

Figure 4.40. Obseved groups and predicted probabilities of rootsprouting

4.5.6. Graphical stand structural models

De Lieucourt (1889) ratios between successive diameter classes were calculated and the stand density was plotted on semi-log axis to examine the level of structural dynamics in the mangrove population (Table 4.28, Figures 4.41- 4.42).

Table 4.28: Trends in basal areas of trees and stems with estimates of q-ratios under different regimes of exploitation of Douala-Edea mangrove forest, Cameroon

Tree form	**Regime**	**BA/ha**				**Nr/ha**				**mean q-ratio**			
		(1)	**(2)**	**(3)**	**Mean**	**(1)**	**(2)**	**(3)**	**Mean**	**(1)**	**(2)**	**(3)**	**Mean**
Trees	Pooled He	3.92	5.98	8.85	6.25	5922	6972	7367	6754	3.83	3.52	3.43	3.42
Trees	Pooled Me	10.75	12.84	13.93	12.51	6367	7633	6585	6862	4.10	3.80	3.67	3.72
Trees	Pooled Und	32.14	30.97	32.01	31.71	5413	5671	6006	5697	3.67	2.92	2.47	2.39
Stems	Pooled He	4.76	7.37	10.35	7.49	7844	8528	8655	8342	4.14	4.70	4.36	4.23
Stems	Pooled Me	8.93	11.29	12.90	11.04	7958	9225	9189	8791	4.04	3.93	3.81	3.84
Stems	Pooled Und	26.06	24.81	26.88	25.92	5896	6104	6517	6172	3.53	2.89	2.43	2.73

(1), (2), (3) indicate census periods

Q-ratios show no significant difference between neither tree form, regime, census nor their interactions. However, Q-ratios were generally higher for all regimes for stems (2.43 – 4.70 mean 2.73 – 4.23) than trees (2.47 – 4.10 mean 2.39 – 3.72). Q-ratios were generally lower with decreasing disturbance and decreases with census (ie time) probably towards equilibrium (Figure 4.50).

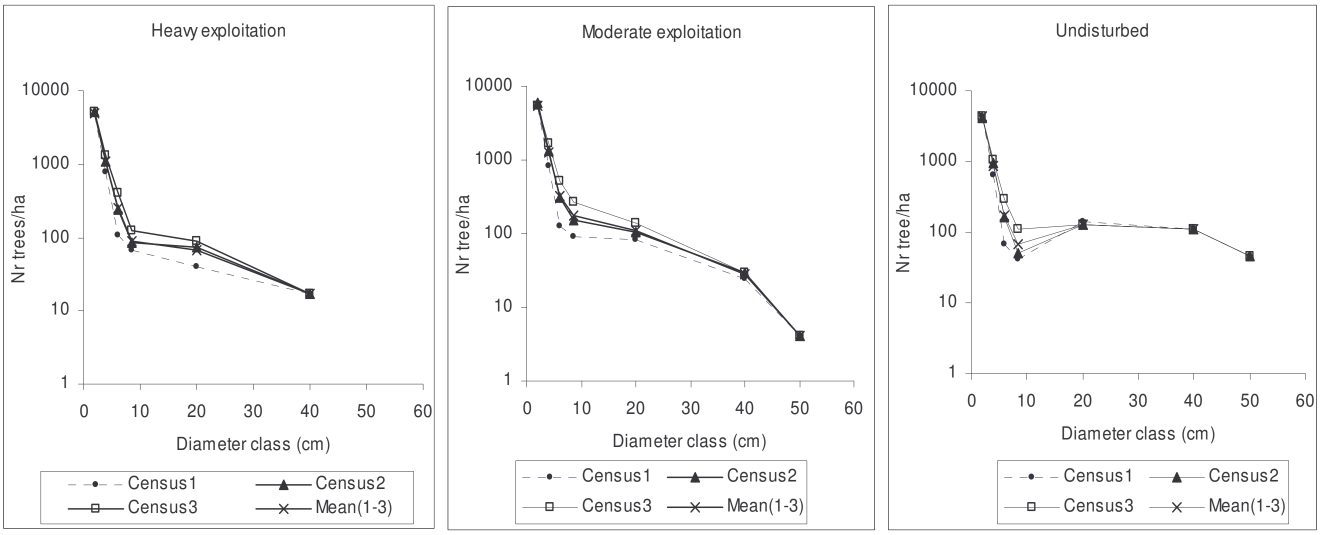


Figure 4.41: Diameter distributions from Douala-Edea, Cameroon mangroves stands under different exploitation regimes plotted on semi-logarithmic axes to show variation in curve shapes

Figure 4.42 shows various shade of rotatory sigmoid shape with various levels of disturbance from sigmoid indicating various degrees of recovery from disturbance to straight line. It could indicate mangrove forest in a continuous changing environment than upland forests. The plots from TSP data show an equilibrium forest with utmost linear to polynomial indicating increasing tendency towards inverted J-distribution of natural forest structure.

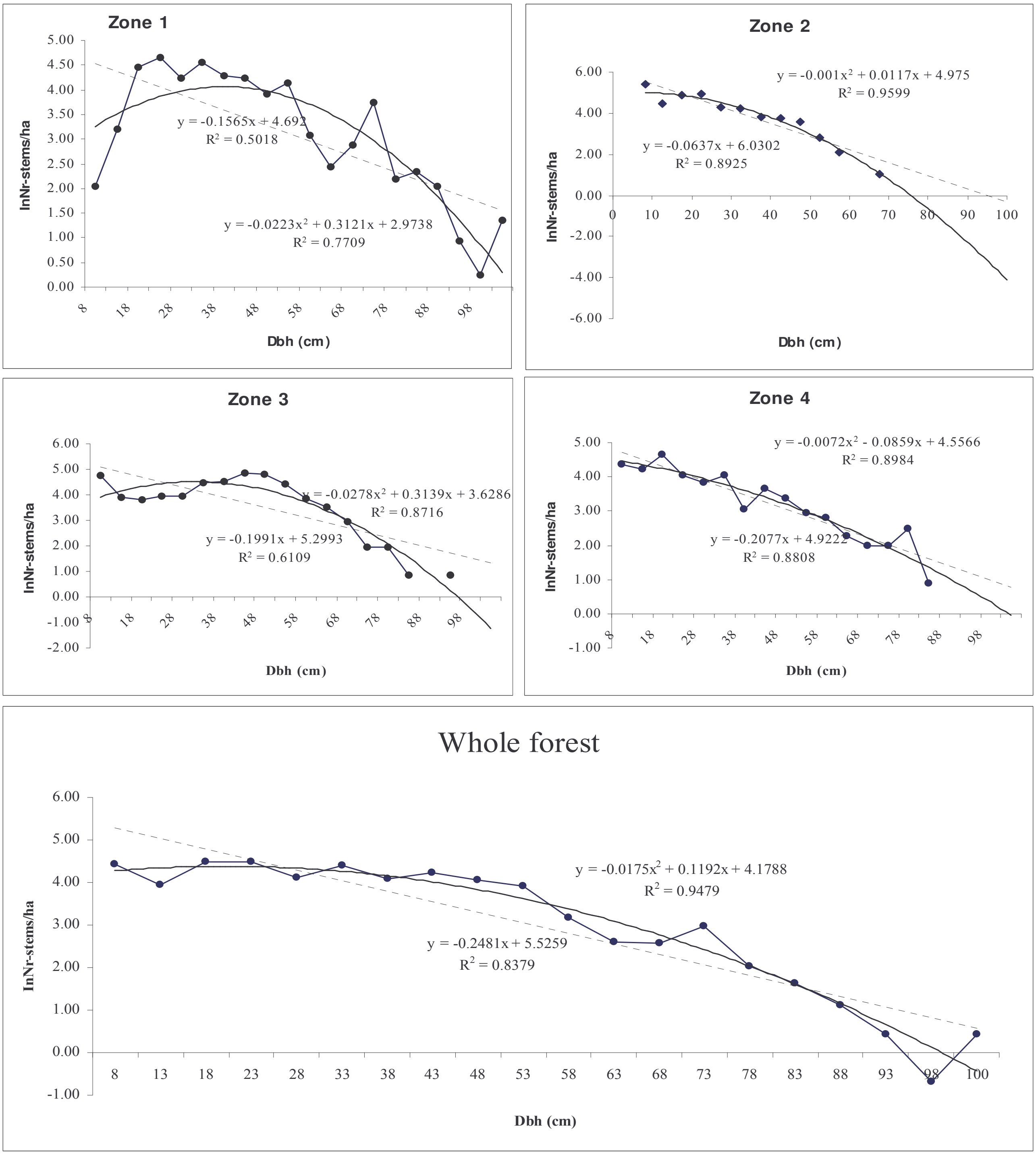


Figure 4.42. Stem diameter distribution from TSP plotted on semi-logarithmic axes to show variation of curve shapes in Douala-Edea mangrove forest, Cameroon. The straight line and curve are regression lines.

4.5.7. Matrix models

Matrix models were used to describe the change in multi-stemmed tree status and structural dynamics of tree population in the mangrove forests. Results of such analyses are presented together with goodness-of-fit tests.

4.6.7.1. Matrix models for change in multi-stemmed status in mangrove forest

Transition matrix parameters, dominant Eigen values and Eigen vectors for the transition of multi-stemmed tree status are presented in Table 4.43. The dominant Eigen values were generally one irrespective of the wood exploitation regime indicating a stable state. It could be that nature tends to maintain a stable proportion of single and multi-stemmed status in any given population irrespective of wood exploitation pressures on the ecosystem. Though there were spatial variations, the stable SS: MS proportion seems to indicate a tendency towards a greater proportion of single state trees with exploitation pressures (Table 4.43).

Table 4.29: Transition matrix parameters with dominant eigen values, eigen vectors and stable state distribution multi-stem dynamics for Douala-Edea mangrove forest, Cameroon under various wood exploitation regimes.

Zone	Wood Exploitation Regime	Transition Matrix A				Dominant Eigen value	Eigen vector		Stable proportion	
		Row1		Row2			Row1	Row2	Row1	Row2
		A_{11}	A_{12}	A_{21}	A_{22}					
1	He	0.928	0.102	0.072	0.898	1.0000	0.817	0.577	0.586	0.414
	Me	0.987	0.018	0.013	0.982	1.0000	0.811	0.586	0.581	0.419
	Und	0.998	0.002	0.002	0.998	1.0000	-0.707	-0.707	0.500	0.500
2	He	0.969	0.053	0.031	0.947	1.0000	0.863	0.505	0.631	0.369
	Me	0.984	0.061	0.016	0.939	1.0000	0.967	0.254	0.792	0.208
	Und	0.977	0.017	0.023	0.983	1.0014	-0.594	-0.804	0.425	0.575
3	He	0.993	0.016	0.007	0.984	1.0000	-0.707	-0.707	0.500	0.500
	Me	0.987	0.025	0.013	0.975	1.0000	0.887	0.461	0.658	0.342
	Und	0.997	0.018	0.003	0.982	1.0000	0.986	0.164	0.857	0.143
4	Me	0.991	0.004	0.009	0.996	1.0000	-0.406	-0.914	0.308	0.692
	Und	0.974	0.079	0.026	0.921	1.0000	0.950	0.313	0.752	0.248
Whole forest	He	0.974	0.041	0.026	0.959	1.0000	0.845	0.536	0.612	0.388
	Me	0.987	0.026	0.013	0.974	1.0014	0.903	0.429	0.678	0.322
	Und	0.992	0.015	0.008	0.985	1.0000	0.882	0.471	0.652	0.348

The model showed various levels of predictive accuracies. Generally the matrix model made accurate predictions for overall total tree population followed by single stemmed trees and multi-stemmed trees across disturbance regimes (Figures 4.43 & 4.44).

Predictions for diameter classes were generally over estimated irrespective of the regimes for lower classes (1-3 cm, 3-5 cm) that caused in various cases, significant chi-square for overall distribution. The accuracy of the model in predicting diameter distribution greatly improved with decreasing disturbance status for both single stemmed, multi-stemmed and total tree population.

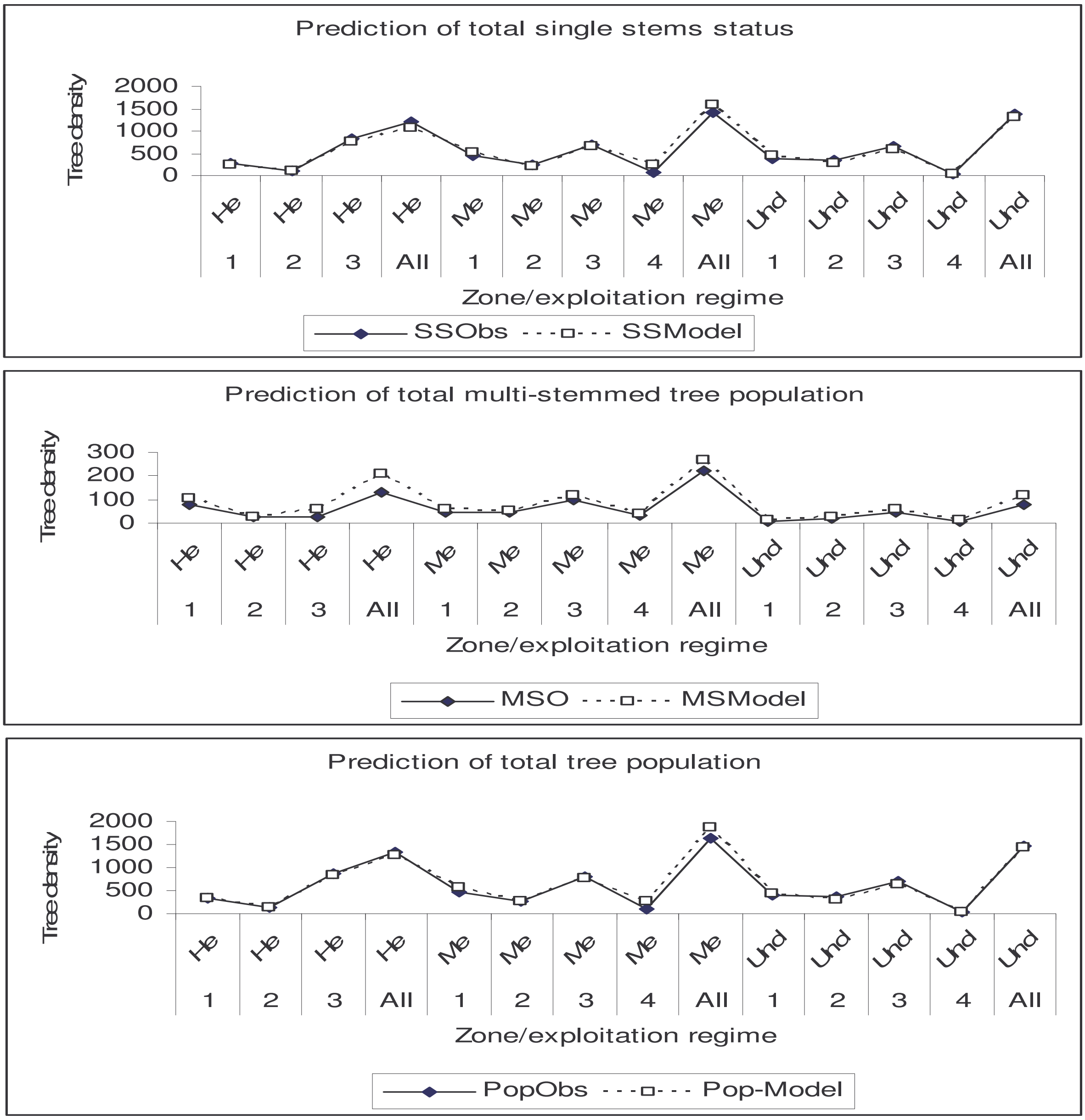


Figure 4.43: Prediction accuracy of components of total tree population by the multi-stemmed tree matrix model for different wood exploitation regimes in Cameroon coastal Atlantic mangrove forest (Tree density is on per transect (0.18 ha) basis)

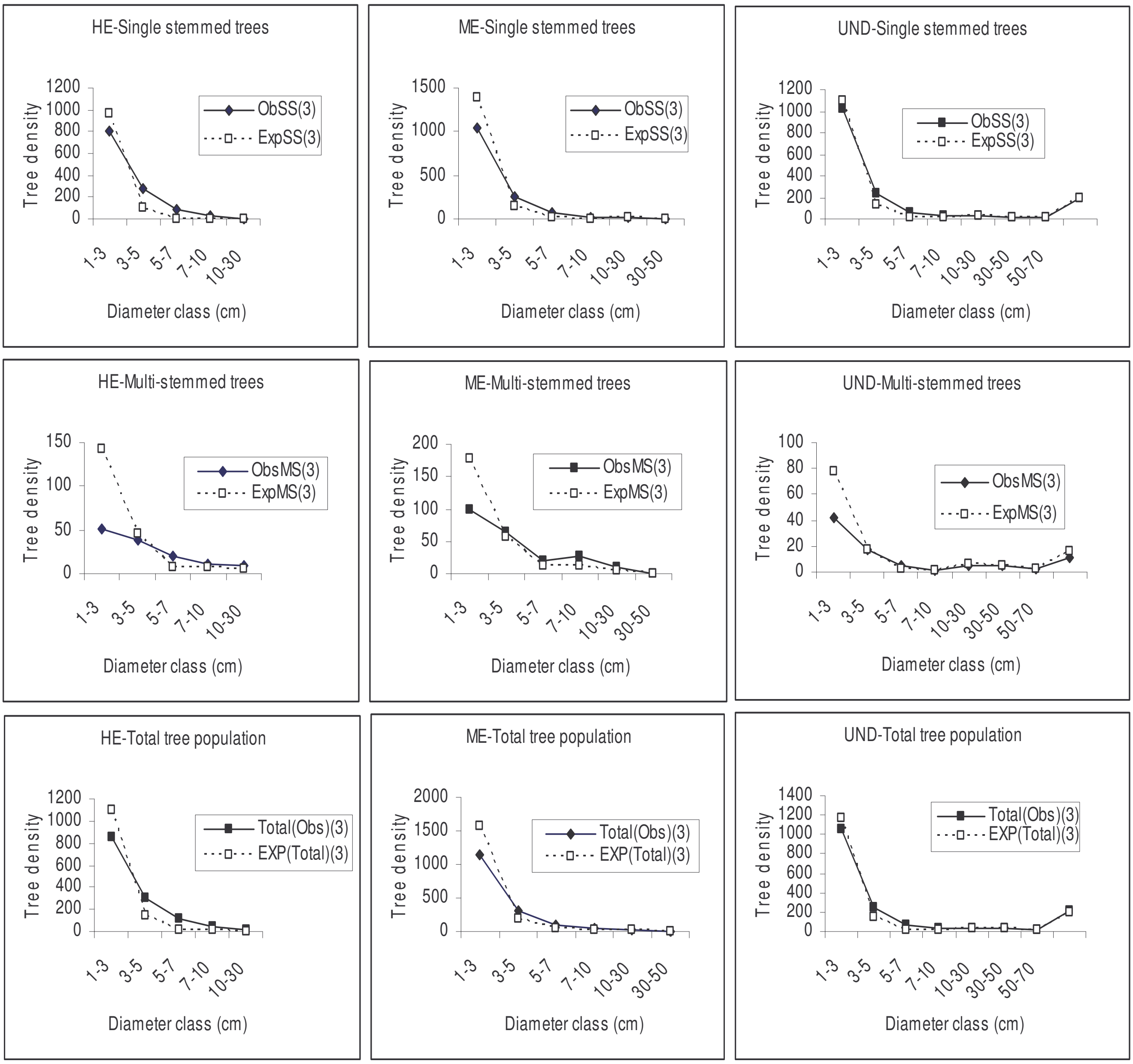


Figure 4.44: Predictive accuracy of diameter distribution by the multi-stemmed tree matrix model for different wood exploitation regimes in Douala-Edea coastal Atlantic mangrove forest, Cameroon (tree density values are on per transect (0.18ha) basis)

4.6.7.2. Matrix models for structural dynamics of mangrove tree population

Calculation of transition matrix parameters followed a life table analysis of population status from census 1 to census 2 through the analysis of proportion of trees living or remaining as well as recruitment within the population. They ranged from 5x5 to 7x7 matrices according to the available diameter classes. The tree population structure is highly variable. Except for certain undisturbed forests, most regimes and pooled conditions have dominant Eigen values (λ) greater than unity. This indicates an actively growing population. There were significant differences between dominant Eigen values across regimes and sites (Table 4.30). Eigen values were significantly higher for disturbed than disturbed regimes. With the current recruitment rate, stable stage distribution for all pooled regimes and zones will be 100:13:3:1:0:0 for size classes 1,2,3,4,5,6 and 7 respectively. This forest structure associated with the greatest latent root maximises the available yield from the forest. The stable stage distribution was highly variable between regimes and zones, in some cases with some classes having zero population. This shows that adequate regeneration is needed to sustain production and growth of the affected forest to forestall possible extinction while in other cases some harvests will be encouraged to stabilise the forest. The model enjoyed various levels of predictions for various diameter classes for third census population structure (Figures 4.45 – 4.49) though over-estimation of the lower diameter classes (1-3cm and 3-5 cm) occasioned significant chi-square values. The model generally over estimates the total tree population in a number of sites (Figure 4.45). Stems population projections (diameter distribution) for the years 2007 – 2013 for pooled regime types and sites are given by the model as shown in the Figure 4.50. The models generally predict increasing tree population.

Table 4.30: Statistical inferences on Eigen values for Douala-Edea, Cameroon mangroves under different wood exploitation pressures

Descriptives

Regime	N	Mean	Std. Deviation	Std. Error	95% CI for Mean Lower Bound	95% CI for Mean Upper Bound	Min	Max
HE	4	1.57293	0.35615	0.17807	1.00621	2.13964	1.052	1.825
ME	5	1.29454	0.21511	9.62E-02	1.02745	1.56163	1.038	1.585
UND	5	1.0195	0.15071	6.74E-02	0.83237	1.20663	0.800	1.221
Total	14	1.27585	0.32103	8.58E-02	1.09049	1.46121	0.800	1.825

ANOVA

Source of variation	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	0.683	2	0.342	5.725	0.02
Within Groups	0.656	11	5.97E-02		
Total	1.34	13			

Multiple Comparisons: LSD

(I) Regime	(J) Regime	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
HE	ME	0.27838	0.16388	0.117	-8.23E-02	0.63907
	UND	0.55342*	0.16388	0.006	0.19274	0.91411
ME	HE	-0.27838	0.16388	0.117	-0.63907	8.23E-02
	UND	0.27504	0.1545	0.103	-6.50E-02	0.6151
UND	HE	-0.55342*	0.16388	0.006	-0.91411	-0.19274
	ME	-0.27504	0.1545	0.103	-0.6151	6.50E-02

* The mean difference is significant at the .05 level.

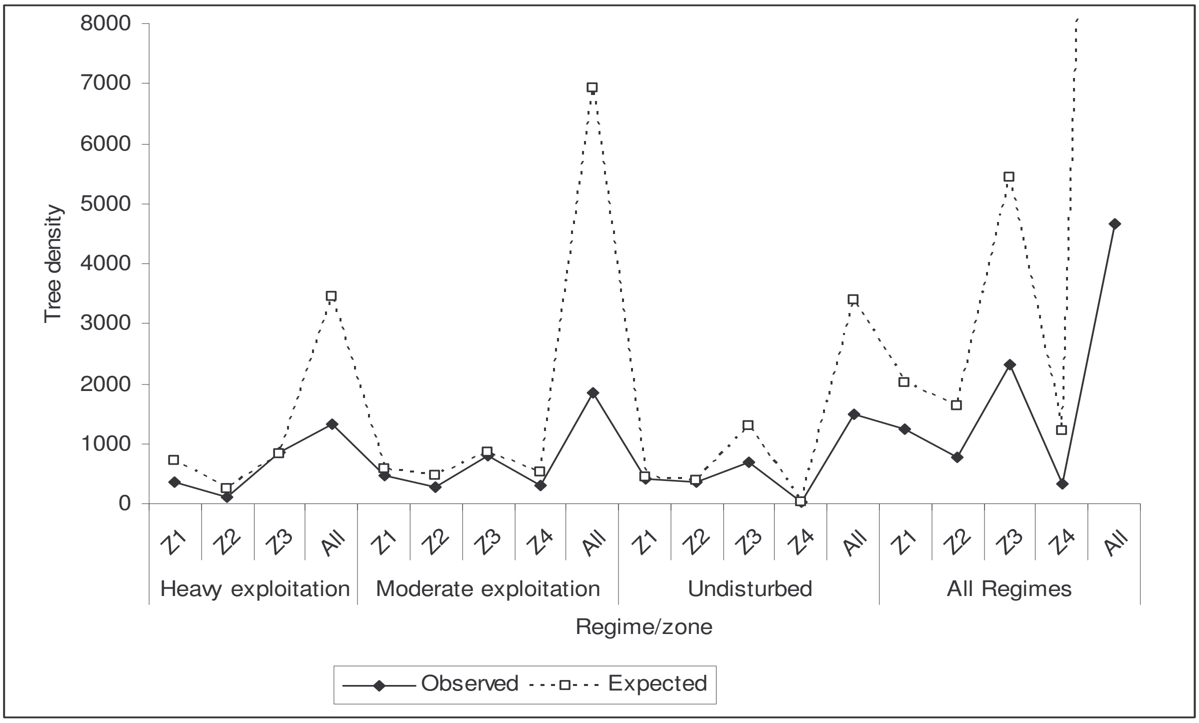


Figure 4.45: Predictive accuracy of total tree population by the matrix model in Douala-Edea coastal Atlantic mangrove forest, Cameroon under different wood exploitation regimes

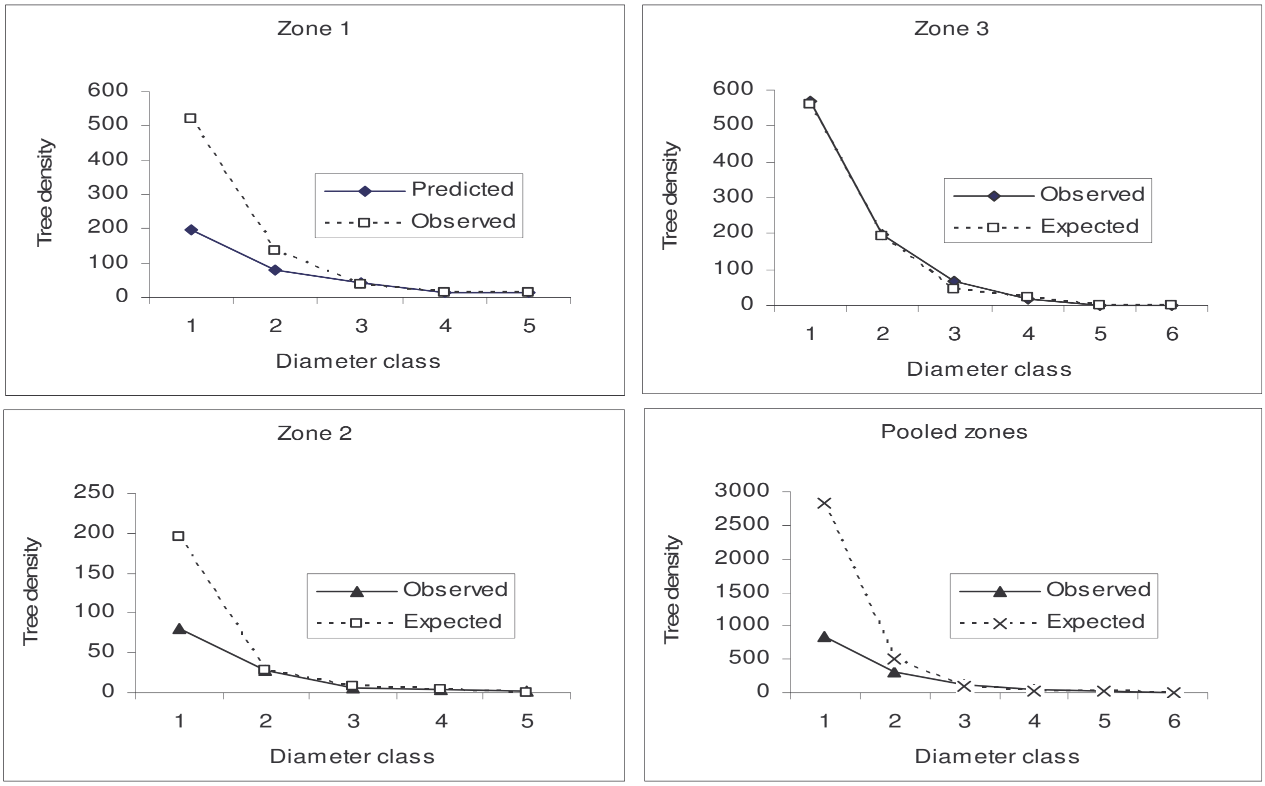


Figure 4.46: Observed and expected distribution for census 3 for heavily exploited regime

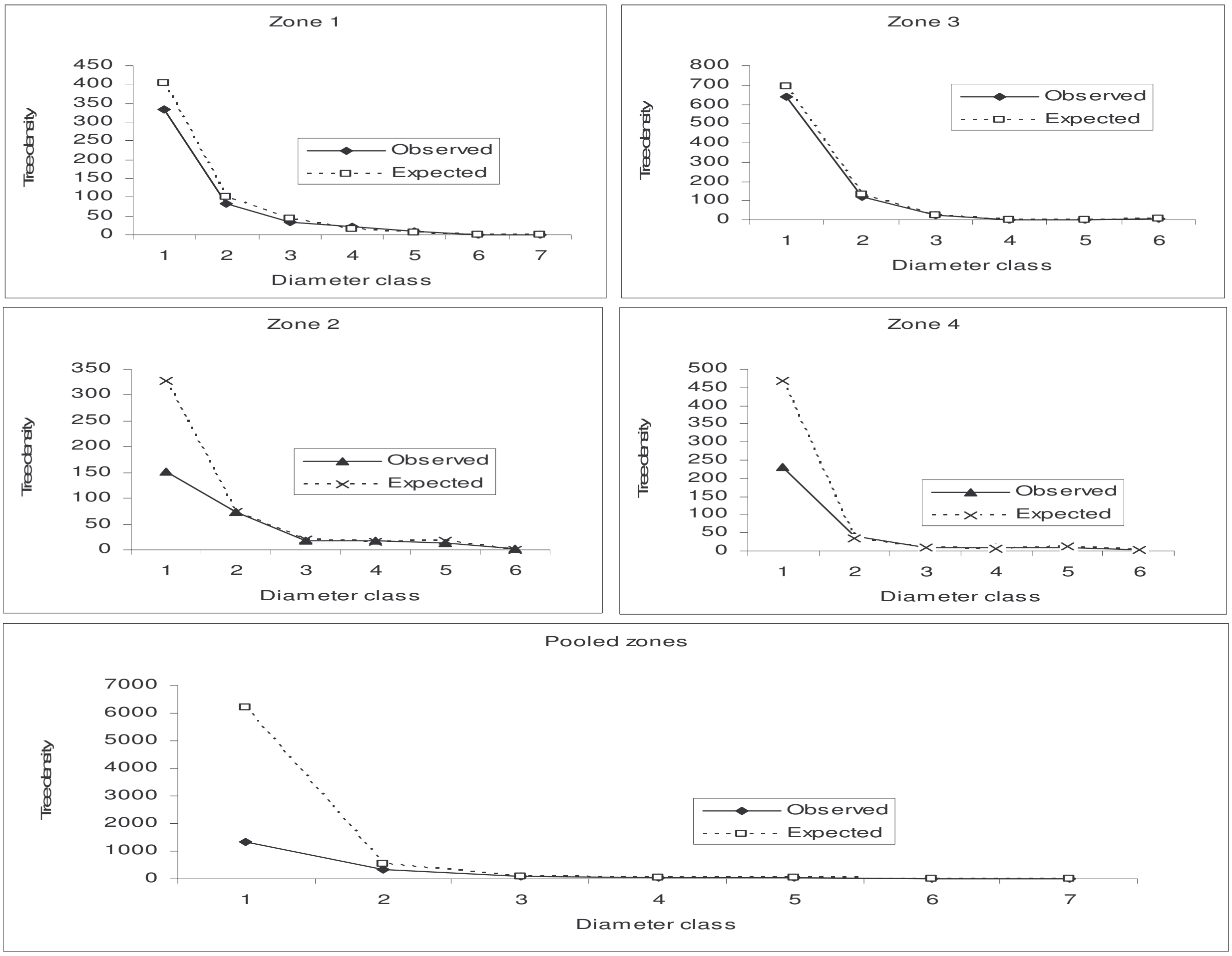


Figure 4.47: Observed and expected distribution for census 3 for moderately exploited regime

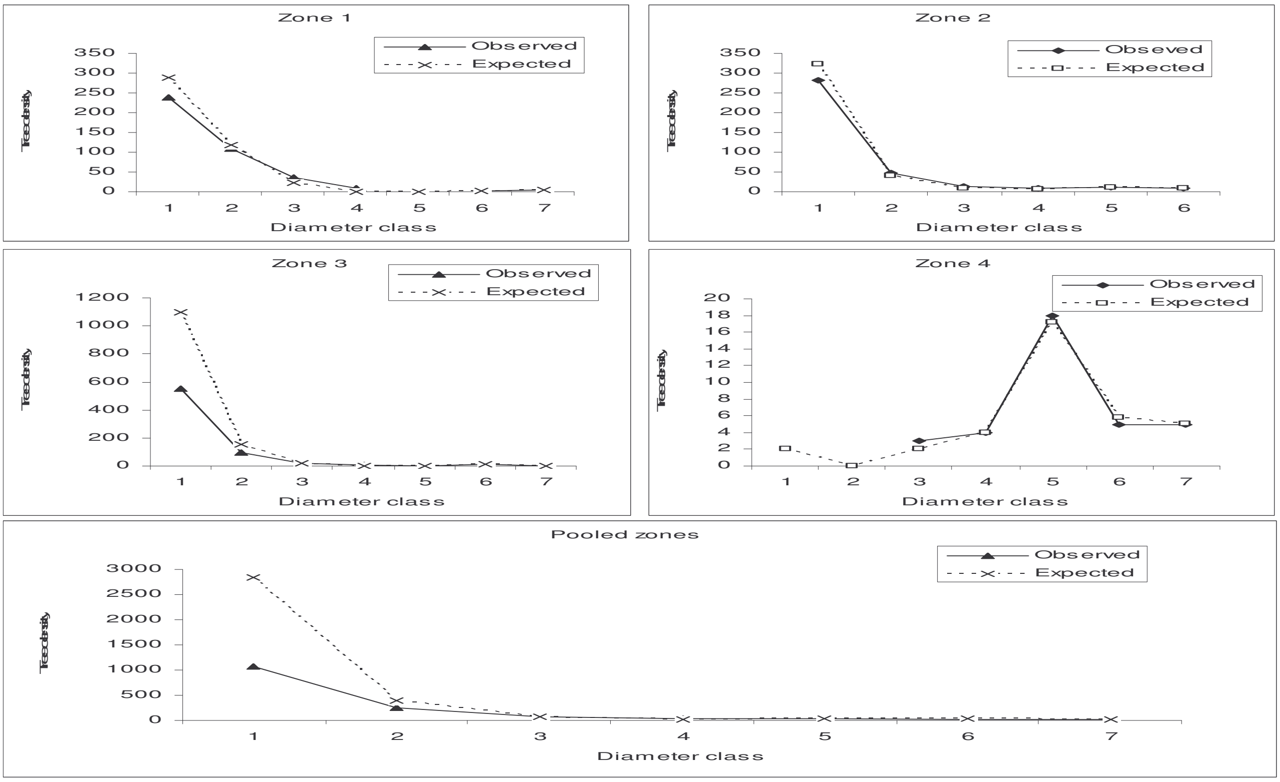


Figure 4.48: Observed and expected distribution for census 3 for undisturbed regime

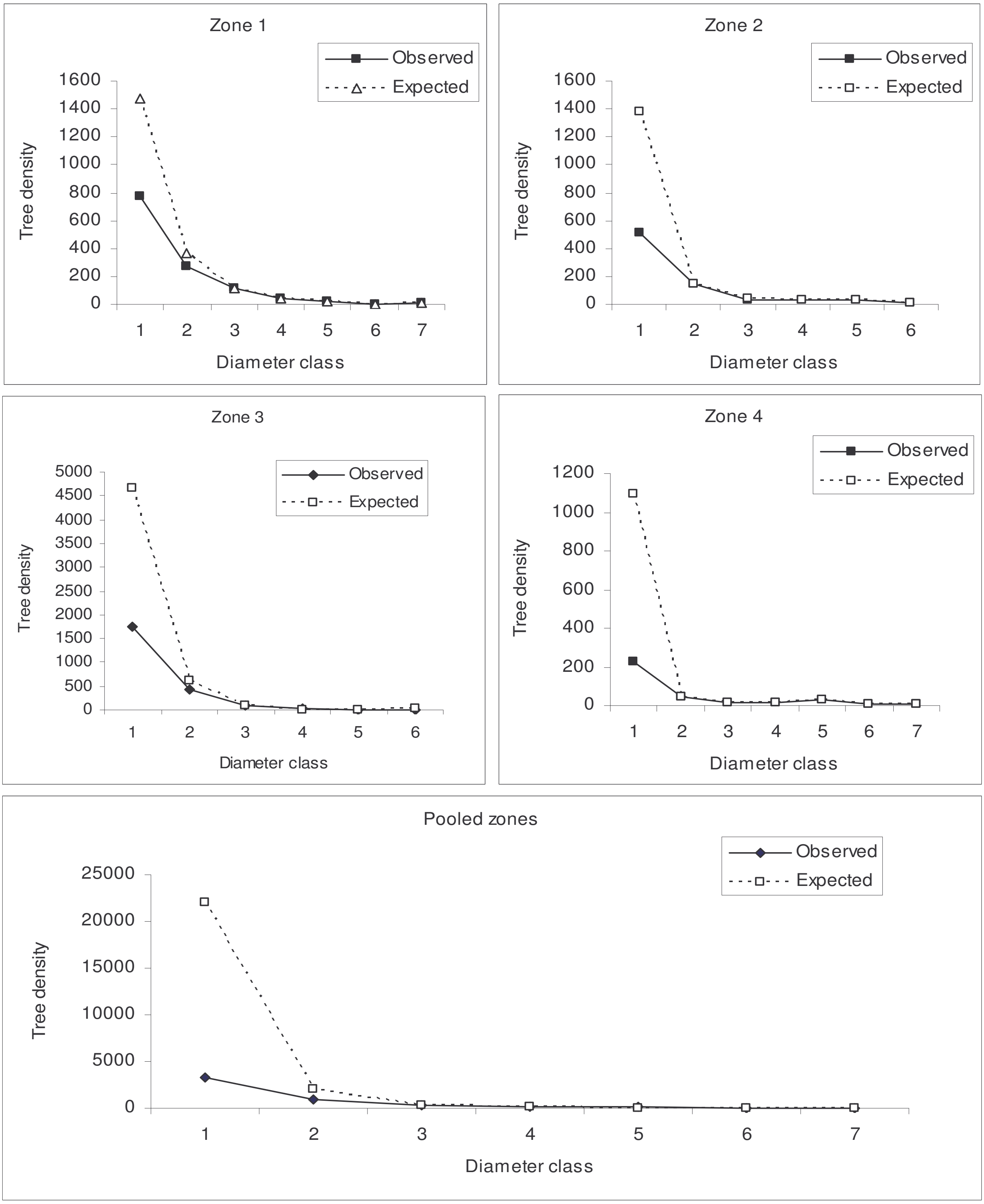


Figure 4.49: Observed and expected distribution for census 3 for pooled regimes

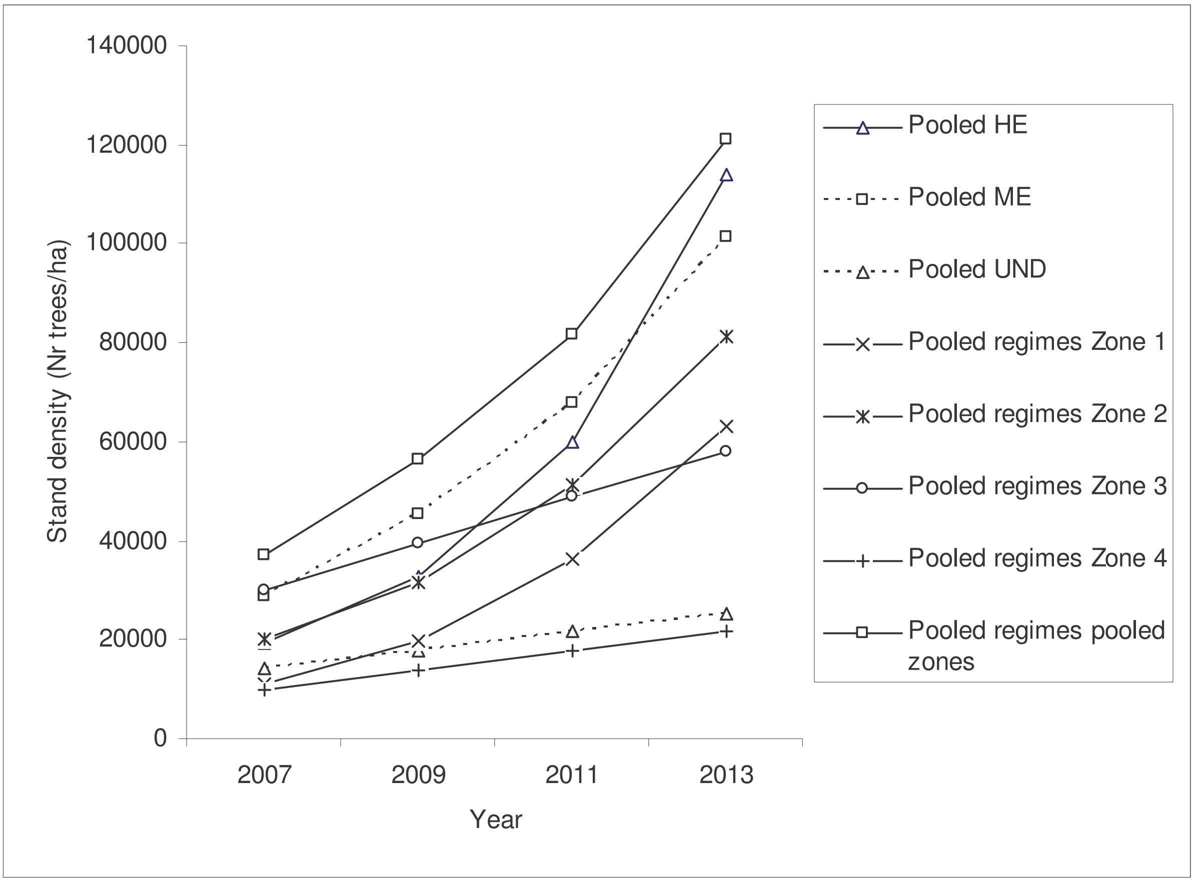


Figure 4.50: Total tree population projection between 2007-2013 for Douala-Edea coastal Atlantic mangrove forest, Cameroon following different regimes of exploitation

4.6. Comparison of different modelling methods used

The predictive accuracies of different models have been examined separately in Section 4.6. For convenience, the body of models used here is divided into regression or non matrix models (basal area growth models, survival models and regeneration models) and matrix models (for projection of multi-stemmed tree status and forest structural dynamics). The degree of harmony of the different model types are tested in a stand table projection approach where all initial conditions are described during census 1 and predictions are made for census 3 and then compared through error analysis and goodness-of-fit tests especially Chi square test. Figure 4.51 summarises the result of predictive harmony of the regression and matrix models. In most occasions the matrix development through multi-stemmed dynamic approach was better than through the diameter distribution approach. Generally the models predict diameter class distribution with varying accuracies with overestimation of lower diameter classes especially 1-3 cm class that caused significant Chi-square results. Like with matrix models, the predictive accuracy of the regression models improved with decreasing forest disturbance with the undisturbed state being the best. The models performed very well in diameter classes above 10cm. It should also be noted that lower predictive accuracies may be due to association of values of many variables at mid class interval.

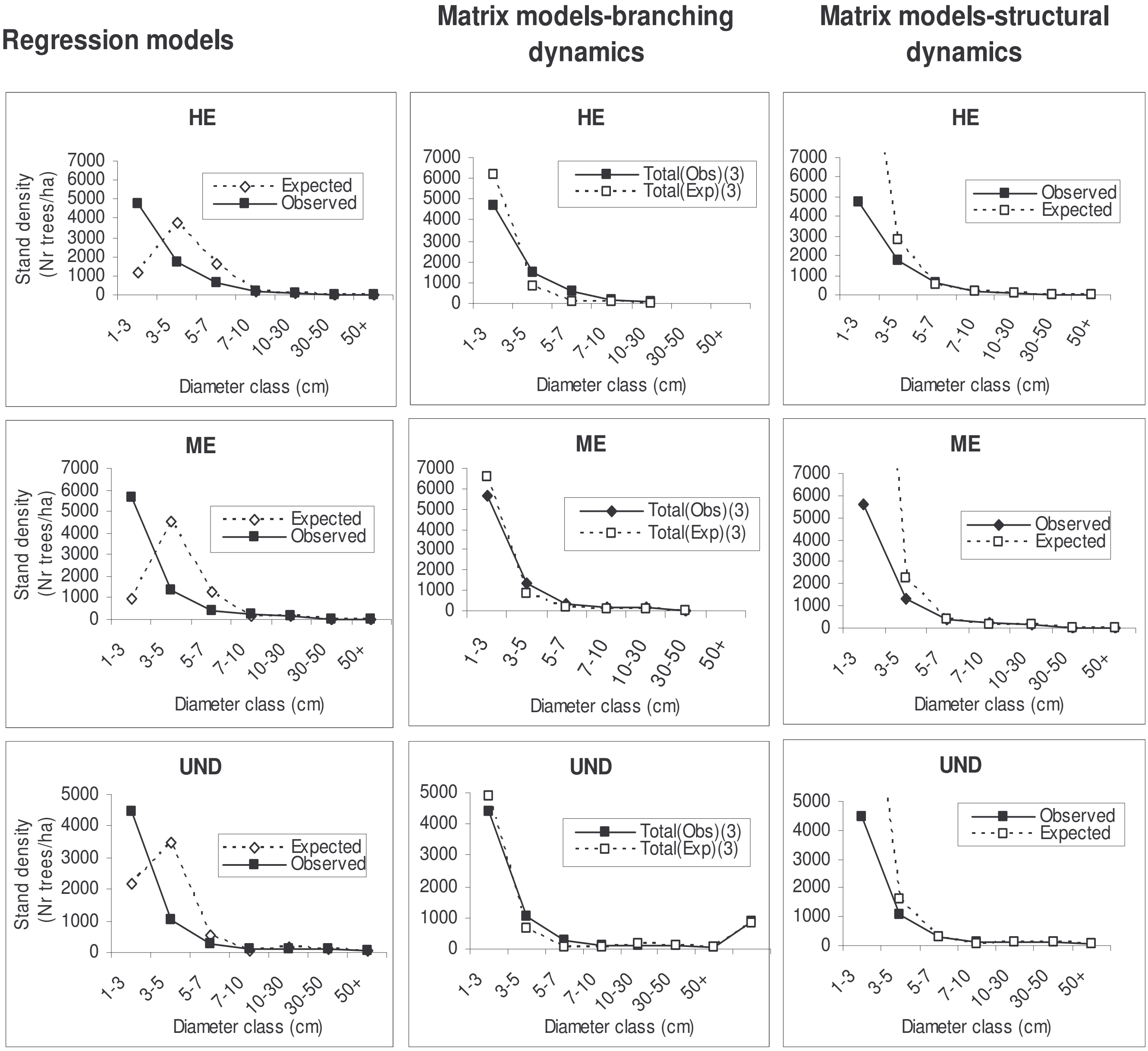


Figure 4.51: Consistency of regression and matrix growth models in stand table projection for Douala-Edea coastal Atlantic mangrove forest, Cameroon under different wood exploitation regimes

5. DISCUSSION

A vast literature and information exist on the dynamics of upland forest ecosystem as affected by different human interventions but comparatively less on mangrove ecosystems. Few researchers have also attempted to model forest ecosystems under disturbed conditions, let alone mangrove ecosystems. This limits greatly the comparability of results from this study. Again especially as this study was conducted for a shorter growth period of four years. The following discussions will be carried out by comparing the results obtained with available information from upland and mangrove forest ecosystems under the headings: i) towards a unified forest mensuration system, ii) stock assessments, allometric studies and structure of mangroves ecosystems, iii) impact of forest disturbance, iv) productivity, growth and yield of mangrove species v) modelling mangrove forests following disturbance.

5.1. Towards a unified mangrove forest mensuration system

Due to diverse tree forms, branching and eco-morphological features, the present mensuration system based on traditional forestry research often limited to single tree or where stems are isolated as individuals yet belonging to individual trees may not respond to advancing search for ecological understanding of forests and socioeconomic demands that must be met by more objective assessment of forest resources. MacDicken *et al.* (1991) have noted that forestry research has relied on standard approaches such as height and diameter measurements for over 100 years with many textbooks describing these methods in great detail, yet they are not appropriate for multipurpose trees and shrubs with multiple stem habits. They therefore need to be modified or replaced by more suitable techniques. This arises because of difficulties in isolation of plant individuals unlike animals. Most researchers simply ‘escape’ from the multi-stemmed structure by usually treating secondary stems as individual trees e.g Clough *et al.* (1997) treated each stem as discrete tree that shares a proportion of the butt and other elements common to all stems when developing biomass relationships in multi-stemmed mangrove trees. Given that most of forest resources are from multi-stemmed tree forms including forests of drier zones, with the increasing need for more ecological understanding of forest structure and processes coupled with multiple use value of forests and demand of a range of forest products other than timber and more especially the need to assess and monitor the population structure and dynamics over time, there is need to modify these systems of measurement. This study has further buttressed this need where stand characteristics and dynamics were found to differ with tree form that may require separate and combined analyses. Some initiatives have recognised the need and taken the lead to modify current mensuration practice to take account of tree forms. For example Multipurpose Tree Species Network Research has recommended tree diameter measurements in addition to the traditional forestry measurement at 1.3m, diameter at breast height (dbh) to 30 cm diameter at knee height (dkh) d_{30} to accommodate both single and multiple stem trees (MacDicken *et al.*, 1991). Another inventory problem is the diameter limit used, most forestry measurements are limited to a minimum diameter of 10cm, these result in loss of most ecosystem vital information on trees and other life forms (seedlings, shrubs, etc) below this limit that comprise some 80% of individuals though may not contain up to 20% total biomass especially regeneration for adequate understanding of forest dynamics. However, many PSP systems especially efforts by Smithsonian Network of Forest Dynamics Plots have improved on this by measuring trees down to 1 cm (Condit, 1998; Su *et al.*, 2007). This results in huge data bases, the availability of computing facilities not withstanding, there is a need for a codification systems (as presented in this study) that will allow easy field measurement of parameters, simple and cost effective, accessible to non technical audience and amenable to fast but accurate analyses at all phases using affordable software especially spreadsheets. This is further premised by the urgent need to involve all stakeholders in the natural resource assessment in a participatory approach for sustainable ecosystem management.

5.2. Stock assessments, allometric studies and structure of mangrove forests

Many studies have been carried out on biomass of upland forests and plantations in Africa (Brown, 1997) but relatively very little on mangroves compared to other continents (Komiyama *et al.,* 2008). Many site specific biomass allometric equations have been developed across several sites in America (e.g. Smith and Whelan (2006), Australia (Komiyama, 2005) and SE Asia (Ong *et al.*, 2004) but little on any African mangrove sites (except e.g. Slim *et al.*, 1996; Steinke *et al.*, 1995). This study is an attempt to open up insights into allometric study of African mangroves. The volume equations developed were similar in form having the log pattern to those developed by Cole *et al.* (1999) for the mangroves of the islands of Micronesia in the Pacific coasts. The biomass figures 435.0 ton/ha obtained here in Douala-Edea *R. racemosa* dominated primary mangrove forest (3º14'-3º53'N, 9 º35'- 10º05'E) compares well and may rank Central African mangroves as amongst the highest mangrove biomass in the world following Komiyama (2008) biomass ranking of mangroves across the world as first: Malaya (Matang) 4º48'N, 100 º35'E primary mangrove forest of *Rizophora apiculata* dominated forest reported by Putz and Chan (1986) with 460.0 tons/ha. Second: Indonesia (Halmahera) 1º10'N, 127 º57'E primary mangrove forest of *Bruguiera gymnorrhiza* forest by Komiyama *et al.* (1988) with 436.4 tons/ha. Third:

Indonesia (Halmahera) 1º10’N, 127 º57’E primary mangrove forest of *B. gymnorrhiza* forest by Komiyama *et al.* (1988) with 406.6 tons/ha. This is expected given the latitudinal position and dense hydrological network of the world’s second largest Congo Basin forest which the study area is a part. The mangrove forests present a log-normal structural type and with De Liocourt q-ratios of between 0.3 to 5.0 with mean 1.5 though varying between disturbance regimes and sites. In his stand table projection model for dipterocarp forests in Malaysia, Korsgaard (1989) cited by Vanclay (1994) found that quotients ranged from 1.3 to 1.6, and remained relatively constant over time and across stands. Leak (1996) got a mean q-ratio of 1.39 from uneven-aged northern hardwoods in New Hampshire. Amongst some limited mangrove forest studies in African, Kairo *et al.* (2002) studied the structure and regeneration patterns of Mida Creek mangrove vegetation along belt transects at 2 forest sites of Mida Creek (3°20'S, 40°00'E): Uyombo and Kirepwe. Tree density varied from 1197 trees ha–1 at Kirepwe to 1585 trees ha–1 at Uyombo and mean tree height was higher at the former site compared to the latter. The size class structure at both 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 (Morisita’s Index $I_{\delta} << 1$) for trees, but a tendency to random distribution ($I_{\delta} = 1$) for juveniles. Another prominent feature of mangrove forest is the high branching habit of woody species. Su *et al.* (2007) found 25% of branched individuals and number of branches (stems) per tree averaged 0.5 in sub-tropical typhoon prone forests in Taiwan. The contribution in basal area and volume was higher for bigger canopy trees. Ishii *et al.* (2003), Su *et al.* (2007) attributed this to species strategies to maintain dominance and survivorship. In this study the proportion of branched indiduals in undisturbed forest was lower (7%) but the number of stems per tree was higher (1.2). This may be due to greater effects of typhoon and higher lifeform and species diversity compared to the mangroves though also an unstable environment.

5.3. Impact of disturbance on forest dynamics

Many studies have been carried out especially in upland forests on human impacts on forest disturbance. Examples of such studies are presented though may not be very comparable with this study because of the short study period of 4 years than obtained in these studies ranging from 4-years to 15 years, however, the mono-cultural character of mangrove stands may still permit this short term study. Generally like in this study, most studies have shown logging to have minimal impact on forest dynamics at least on the short-run (Vanclay 1990; Palmer, 2003). Enright (1978) reported that growth rates of individual trees in the residual stand dropped markedly with extensive damage to residual stand after logging where over 54% of stands composing nearly all of *Araucaria cunninghamii* was dominant species. Vanclay (1990) analysed data from 212 PSP from selection logging system in Australian rainforest and got no evidence of any decline in rainforest productivity after three cycles of selection logging. Hamilton (1986) also found that time since and type of thinning had no impact on mortality rates following thinning in forests in Idaho (USA). Silva *et al.* (1995) studied the dynamics of Brazilian Amazon 13 years after logging and found that logging changed the canopy structure and altered the composition of the stand, reducing the number of shade tolerant species and stimulating light demanding species. There was a net increase in stem number and stand basal area during the 11 year observation period, and this trend also held for most of the individual species. The stand basal area 13 years after logging was about 75% of that in a comparable unlogged forest. Logging stimulated growth, but this effect was short-lived, lasting only about 3 years, and current growth rates were similar to those in the unlogged forest. Between the first and second re-measurements, average diameter increment decreased from 0.4 to 0.2 cm yr-1, mortality remained relatively constant at 2.5% per year, while recruitment (at 5 cm dbh) decreased from 5% to 2%. This contrasts with this study which witnessed increased recruitment with disturbance especially the moderately disturbed types. Total volume production declined from approx. 6 to 4 m^3/ha/yr, while commercial production remained about 0.8 m^3/ha/yr. New commercial species increased the commercial volume in 1992 from 18 to 54 m^3/ha, and the increment to 1.8 m^3/ha/yr. There was also negative growth in some cases in this study especially in undisturbed regimes. Kariuki *et al.* (2006) have noted that negative and zero diameter increments are common growth phenomena in the rainforest trees where these mangroves form a part in the Central African Congo Basin rainforests. Negative growth in some trees according to Kariuki *et al.* (2006), may be attributed to measurement errors, senescence or unfavourable growing conditions such as drought. Though results from this study are preliminary due to short study period, the high values indicate high resilient and recovery rate of mangrove forest following disturbance compared to upland forests examples cited. These may corroborate Zuleiku *et al*. 2003 ascertion that mangroves in general have a great capacity to recover from major natural disturbances. However, recovery will depend on: forest type, nature, persistence and recurrence of disturbance and availability of propagules (Pool *et al*., 1977; Hamilton and Snedaker, 1984; Field, 1997; Lowenfeld and Klekowski, 1992).

5.4. Productivity, growth and yield of mangrove species

Devoe and Cole (1998) studied matured unmanaged mangrove stands of unknown age, highly exploited in the Federated States of Micronesia (9 º33’N) using PSP installed in 1983 remeasured some 10 years later (1990 – 1992). They recorded growth rates for *Rhizophora apiculata* at 0.25cm/yr, *R. mucronata*, 0.37 cm/yr, MAI volume was 4.5m^3/ha/yr, and there was high variability in growth rates among tree and plots. *R. apiculata* with maximum diameter of 60cm had a diameter growth range of 0.24 – 0.77 cm/yr in Malaysia, *R. mucronata* (max diameter of 40m) 0.19 – 0.73 cm/yr. Duke and Allen (2006) citing others put growth rates of *Rhizophora* species (*R. mangle, R. racemosa and R. harrisonnii*) in Atlantic – East Pacific red mangroves as 0.14 – 0.19 cm/yr for diameter less than 10cm and 0.08 – 0.17 cm for diameter above 10cm, estimated MAI volume was 6m^3/ha/yr some stands 11-14m^3/ha/yr. Values recorded here were slightly higher due to slightly lower latitude than the cited studies. In a mangrove restoration monitoring experiment established by Usongo (2007) in the study area from externally raised 569 seedlings each of *Avicennia germinans* and *Rhizophora racemosa* planted in the three regimes of wood exploitation from heavily, moderate to undisturbed forests, the results after 133 days after planting showed that heavily degraded mangrove habitats enhanced growth and survival of *R.racemosa* while minimally disturbed mangrove zones with small canopy gaps were conducive environments for *A. germinans* seedlings growth. Seedling mortality of both species was highest under closed canopies.

5.5. Modelling mangrove forests following disturbance

Few models have been developed for upland forests following disturbance let alone mangrove forests. Kariui *et al.* (2006) have modelled growth, recruitments and mortality to describe and simulate dynamics of subtropical rainforests following different levels of disturbance. Simulations with estimated parameters indicate that moderate harvesting (47% overstorey basal area (BA) removal) in a checkerboard of logged and unlogged patches (group selection) on a 120-year cycle could enable sustainable timber production without compromising the ecological integrity in these rainforests. This is due to reduced logging damage in group selection, which also released retained stems and facilitated recruitment of both shade tolerant and intolerant trees. Single-tree selection (35% BA removal) created small canopy gaps that resulted in low recruitment, a slight increase in the growth of retained stems and recovery time of 150 years. Intensive single-tree selection (50% BA removal) resulted in high logging damage that increased recovery time to 180 years. Intensive logging (65-80% BA removal) decreased the stem density and created larger canopy gaps allowing for high growth rates and recruitment of both shade tolerant and intolerant trees. However, few retained stems and high mortality of recruits, increased the recovery time to 180-220 years. Pre-harvest climber cutting coupled with poisoning of non timber species followed by logging could allow harvesting on a 300-year cycle. Shorter logging cycles may lead to changes in species composition as well as in the forest structure. Mendoza and Gumpal (1987) developed a growth projection linear model for a selectively cut over dipterocarp forest in Northern Luzon in The Philippines involving the logarithm of stand yield as a function of the logarithm of the initial basal area and time and the ratio of site quality and time. A set of abstracted time series data from sample plots based on actual logging settings was used. Time was expressed in terms of number of years elapsed after logging operations. A site indicator for the selectively cut-over diperocarp forest was developed using the average total height of the dominant and codominant dipterocarp trees which were left after logging. For modelling mangroves, Chen and Twilley (1998) have developed mangrove species into individual-based model that simulates the longterm dynamics of mangrove forest development in a 0.05 ha forest based on modifications of JABOWA and FORET models (Botkin, 1993; Shugart, 1984). The model used a gap size of 500m^2, typical from lighting gaps at study site. Succession for 500 years showed that long-term forest dynamics were sensitive to species- specific maximum sapling recruitment rates. In absence of large –scale disturbance, initial dominance by *Langucularia racemosa* was predicted to be replaced eventually by *Avicennia germinans* even when maximum sapling recruitment rate of *A. germinans* was set to half of *L. racemosa* and *R. mangle*. Response curves for each species along gradients of soil nutrient resource and salinity illustrated their relative competitive balance over time (up to 300 years). Though many matrix models have been developed for other uplands uneven-aged stands (e.g Osho, 1991; Liang *et al*., 2005), we are yet to find for mangrove forest dynamics especially describing changes in multi-stemmed status. This is also true of the many diameter increment and mortality models that have been developed for upland forests (e.g Vanclay, 1991, 1992; Zhao *et al.*, 2004) but little for mangroves apart from summary description of demographic parameters (e.g. Putz and Chan, 1986). However, these equations follow similar forms.

6. MANAGEMENT APPLICATIONS

Mangrove forest ecosystems support important wetland communities of plants and animals. They are characterised by unique species of trees and shrubs that fringe the inter-tidal zone along sheltered coastal, estuarine and riverine areas in tropical and subtropical latitudes of the world. Coastal habitats across the world are under heavy population and development pressures. Mangroves have been particularly vulnerable to exploitation because they contain valuable wood and fisheries resources, and occupy coastal land that is easily converted to other uses. The scale of human impact on mangroves has increased dramatically over the past three decades or so, with many countries including those of West and Central Africa showing losses within the past three decades (Macintosh and Ashton, 2002; UNEP, 2007). The problem is further compounded by the very high concentration of population along the coastal areas where there are mangroves. In recognition of the environmental, social and economic impacts associated with the decline and degradation of mangrove forest ecosystems, sustainable use strategies are now being addressed through various legislative, management, conservation and rehabilitation efforts aimed at mitigating the negative impacts of previous (and planned) coastal development. Unfortunately, these efforts have been hindered by lack of appropriate resource assessment tools and relevant information especially on the dynamics nature of the mangrove resource as affected by disturbance caused especially by human driven factors for any meaningful sustainable management applications. The following sections show how information obtained from this study and models developed can be used flexibly in various disturbance regimes to enhance sustainable management of mangrove forests. Generally the use of models can guide planning and management decisions related to when, where and how much to harvest taking into account the identified model bias. The following sections will consider: Codification system to improve current systems of assessment and monitoring mangrove forest resources; setting rotations; planning harvests; yield projections/predictions; assessing impacts of wood extraction or deforestation; planning silvicultural or mangrove restoration operations; and policy, legal and institutional frameworks for implementation.

6.1. Codification system for effective assessment and monitoring of mangrove forest resources

As Bih (2007) noted by citing the old saying that “if you can’t measure it, you can’t manage it”, forest assessments as defined by FAO (2000) provide the information about forest resources with the view to establishing within a defined framework of expectations, the current status and probable future direction of interactions between human beings and forests, using certain criteria and indicators. The need for valuation of wetland resources including mangroves important for policy-making, planning and resource management has been stressed (Barbier, 1996). Any resource assessment and monitoring framework should have a simple data collection and processing framework accessible to various stakeholders in a participatory/integrated process to provide needed information for joint action to enhance sustainable resource use. Given the multi-stemmed and diverse eco-morphological structures of mangrove forests, a codification system is proposed based on isolating trees and stems (branches) with their demographic characteristics. This provides a means by which such baseline field data can be captured easily, processed with the use of spread sheet for resource dynamics parameters necessary for proper understanding of the mangrove ecosystem. These codes make record of every tree as individual, with identification of secondary stems using a dynamic data entering system that allows tree to gain or loss multi-stem status yet facilitating rapid evaluation and processing of their dynamic parameters especially mortality, growth and recruitment by various use and manipulation of PIVOT TABLE submenu under the DATA Menu in Excel. Capital (upper case) letters are used for tree reference information while small (lower case) letter are used for secondary stems (branches).

6.2. Setting rotations

Rotation in forestry (usually applied to even-aged forests) is the planned numbers of years between planting and felling, put simply, it is the period of time a crop is allowed to grow (Evans 1982). In even aged forest stands, it is referred to as cutting cycle. Rotation or cutting cycle length is an important tool for controlling tree size – the longer the rotation, the larger a tree can grow. But rotation according to Evans (1982) markedly influences yield, profitability and regeneration methods. So any one of these factors can be the main determinant of length. Stand table (tabular summary showing number of trees in each of several size classes usually of equal width) has long been used to summarise inventory data and provided the basis for several popular growth models for mixed forests. The ‘time of passage’, time for a tree to grow through a diameter class estimated by dividing the class width by average increment within each class has been the classical approach used in the determination of cutting cycles in uneven-aged forest stands. The length of the cutting cycle can then be estimated from the time of passage and the cutting limits (Vanclay, 1994). Based on time of passage method and mean periodic four year increments, rotation lengths (years) have been determined for 3 mangrove product classes: Fuelwood (<10cm), with minimum rotation period of 10-15years, poles (10-30 cm, mid class 20cm) minimum of 25 years, saw timber size (30 – 50 cm, mid class 40cm) minimum of 41 years and veterans (above 50cm with class limit 50cm) with a minimum period of 60 years (Table 6.1). The rotation limits can be used for both disturbed and undisturbed forest as there were no significant differences between wood exploitation regimes (F ratio = 2.397) p= 0.108) in rotation length.

Table 6.1: Rotation periods for different wood product classes in the mangrove forest of Douala-Edea, Cameroon under different wood exploitation regimes

Zone	**Wood exploitaion regime**	**Product Class (cm)**	**Nr-trees**	**Mean DMAI**	**SD**	**Mean rotation (yrs)**
1	Heavy	5	254	0.333	0.312	15.0
		10	14	0.748	0.488	13.4
		20	5	0.785	0.548	25.5
	Moderate	5	367	0.313	0.314	16.0
		10	10	1.025	0.524	9.8
		30	1	0.200		150.0
		50	1	0.475		105.3
	Undisturbed	5	399	0.268	0.229	18.7
		30	3	0.433	0.218	69.2
		50	5	0.837	0.496	59.7
2	Heavy	5	84	0.138	0.105	36.3
		10	10	0.233	0.096	43.0
		20	1	0.175		114.3
	Moderate	5	206	0.109	0.168	45.9
		10	27	0.156	0.193	64.3
		20	11	0.200	0.120	100.0
		30	1	0.175		171.4
	Undisturbed	5	257	0.092	0.112	54.1
		10	16	0.192	0.192	52.2
		20	11	0.228	0.120	87.9
		30	8	0.147	0.303	204.3
3	Heavy	5	695	0.301	0.249	16.6
		10	2	0.563	0.866	17.8
		30	1	0.725		41.4
	Moderate	5	666	0.112	0.115	44.5
		10	7	0.204	0.125	49.1
		20	1	0.375		53.3
		30	3	0.150	0.025	200.0
	Undisturbed	5	544	0.148	0.134	33.9
		10	3	0.225	0.109	44.4
		20	3	0.042	0.232	480.0
		30	12	0.218	0.125	137.9
		50	1	0.325		153.8
4	Moderate	5	201	0.133	0.115	37.7
		10	14	0.248	0.180	40.3
		20	9	0.253	0.182	79.1
		30	3	0.633	0.267	47.4
	Undisturbed	5	3	0.125		40.0
		10	7	0.079	0.046	126.3
		20	19	0.174	0.152	115.2
		30	4	0.231	0.105	129.7
		50	5	0.205	0.127	243.9
Forest	Heavy	5	1033	0.166	0.202	30.2
		10	26	0.459	0.425	21.8
		20	6	0.639	0.516	31.3
		30	1	0.150	0.025	200.0
	Moderate	5	1440	0.252	0.256	19.8
		10	58	0.347	0.436	28.8
		20	21	0.224	0.149	89.4
		30	8	0.500	0.297	60.0
		50	1	0.475		105.3
	Undisturbed	5	1203	0.171	0.178	29.2
		10	26	0.168	0.164	59.6
		20	33	0.178	0.154	112.3
		30	27	0.223	0.213	134.5
		50	11	0.470	0.436	106.4
	All regimes	5	3676	0.203	0.223	24.7
		10	110	0.339	0.399	29.5
		20	60	0.248	0.262	80.5
		30	36	0.265	0.243	113.0
		50	12	0.470	0.414	106.3

Rotation lengths are slightly comparable but lower than those obtained by Devoe and Cole (1997) for *Rhizophora* mangrove forests of the Fedrated states of Micronesia as follows: R.

apiculata, fuelwood, 10cm (9 – 55 yrs), pole timber, 25cm (20-106 yrs), saw timber, 35 cm (32 – 131) years, then R. *mucronata*: Fuelwood, 10cm dbh (25 – 31 yrs), pole timber, 25 cm (63 – 71 yrs), saw timber, 35 cm (101 – 110 yrs). This is due to lower mean growth rates (0.25 - 0.37 cm/yr) than obtained in this study (Table 6.1).

6.3. Planning harvests

The concept of sustained forest yield management is based on the continued production of the goods and services for which a forest stand is being managed. Over exploitation would result in an untimely termination of the supply of the desired goods and services. On the other hand, underutilisation would lead to early reduction of growth in the forest stand. Adequate information on the basal area growth and forest stand dynamics in a forest area would be very useful for any harvest decision aimed at preserving ecosystem function and processes especially in the determination of the quality of harvest such that production could be sustained over the years. Eigenvalue concept can also guide in this direction. For instance, a regeneration improvement to sustain the forest should be embarked upon, when the magnitude of the eignvalue is less than unity. Where $\lambda > 1$ implies a harvest should be done. Such sustained harvests according to Usher (1966) can be estimated from:

$H = 100(\lambda - 1)/\lambda$ ………………………………………………………………….6.1

Where H = percentage of trees in the stand to be harvested

λ = eigenvalue associated with the population projection matrix

Such harvests can either be concentrated to some classes or spread evenly depending on the objectives of such harvests. Consequently, forest stands whose dominant eigenvalues are less than one ($\lambda<1$), harvests should be discouraged in favour of regeneration. Based on volume growth, annual wood harvests for this mangrove forest should be between 10-15m^3/ha. However, due to high resilient rate, this can be weighted with recruitment rate usually above 5% in moderately exploited stands. Once the decision to harvest has been taken, the intensity of harvest and yield control through determination of harvest quotas and the setting up of a compliance mechanism for wood cutters can be guided by the various allometric models or use of tables produced from them.

6.4. Yield projections/predictions

Reliable yield forecast is important for any sustainable management of forest resources and planning. Stand table has long been used to summarise inventory data and project future composition and yield of uneven-aged forests from present stand table by adjusting each entry in the table with the estimated diameter increment (and mortality) (Vanclay, 1994, Husch *et* *al*, 2003). The diameter increment model, recruitment model and mortality model developed here can be used but taking into consideration their bias to update stand table of mangroves. Generally these models including matrix models are tenable for short term projections and at diameter classes above 7cm which luckily is a tolerable product utility size limit. The matrix model can be used in conjunction with the tree/stand volume equations with biomass expansion factors or their tables to project stem frequencies by diameter classes from which expected basal area, volume or biomass can be determined from the equations or simply read from the tables prepared from them.

6.5. Assessing and monitoring impacts of wood extraction or deforestation

There is rising interest and efforts made by different countries in the assessment and monitoring of their forest resources in order to forestall further degradation and plan sustainable management of resources. In this light, precise information on the intensity and spread of degradation is necessary to plan restoration programmes. The models developed here especially the diameter determined allometric models in conjunction with various GIS techniques can be used to assess the status of the forest. For example quantity and distribution of wooded vegetation in volume or biomass terms can be determined from the diameter determined tree volume/biomass equations, stump diameters can easily be measured on the ground or trees can be assessed from aerial photographs or a combination of techniques then converted to heights, volume or biomass.

6.6. Planning silvicultural or mangrove restoration operations

In the search to restore degraded mangrove forests, mechanisms have been established at various levels ranging from individual, community, civil society organisations as well as the private sector operators embarking on various mangrove restoration programmes. As Smith and Whelan (2006) have noted, a resource manager in such restoration schemes needs simple but accurate tools to measure restoration. The growth models including the diameter determined allometric models can be used to gauge the restoration success of such schemes by rapid biomass assessment and change overtime, taking advantage of the minimum diameter of 1cm used to develop such models. Smith and Whelan (2006) have demonstrated how the allometric relation they developed for three mangrove species could be used in the Greater Everglades Ecosystem Restoration Programme in South Florida.

6.7. Carbon stock assessments

The current global issues of abating climate change impacts through the reduction of carbon dioxide emissions from various evolving schemes especially within the framework of the Clean Development Mechanisms (CDM) and Reduced Emission from Deforestation and

Degradation (REDD) necessitate reliable forest carbon stock assessments at various levels. The tree diameter dependent and stand biomass conversion factor equations with tables drawn from them may be very useful in carrying out such assessments especially at local scale. Tree and stand volume estimates can then be easily converted to biomass and carbon stock (usually 50% biomass) values to meet the needs of evolving carbon markets (Tavoni *et al*., 2007).

6.8. Research

Research remains an important information gathering tool that can improve assessment and monitoring of mangrove forest resource use. The models developed can be used to measure the response of mangrove ecosystems to different treatments to develop or test hypotheses where measurements need to be taken on diameter or height or their derivatives like volume or biomass. They could be used or improved upon for the general understanding of the ecosytems structure and processes especially the branching and sprouting phenomena for deeper understanding of ecosystem structure, function and processes for enhanced predictability.

6.9. Policy, legal and institutional frameworks for implementation

As Macintosh and Ashton (2002) have aptly noted, examples of mangrove forest conservation are rather isolated, usually small areas not representative of how mangrove forests are managed overall. Although, they illustrate the problems and issues well and suggest working remedies to solve them, there is need for an integrated approach to mangrove management built on a solid information exchange, capacity building foundation within a coherent policy environment and concerted action framework. This is increasingly being regarded as the best way to achieve conservation and sustainable use of the coastal resources which mangrove ecosystems support. Already pressure group of civil society organisations like African Mangrove Network (AMN) with their national ramifications for example Cameroon Mangrove Network (CMN) are already contributing in shaping national and regional policy actions in mangrove conservation (CMN/RCM 2007, RAM/AMN 2008, www.mangrove-africa.net). Such associations and aggregations are necessary, they need to be informed of the available management information and subsequently built their capacities to use models or innovative technologies to promote sustainable utilisation of the mangrove ecosystems and its resources.

7. CONCLUSION AND RECOMMENDATIONS

7.1. Conclusion

Attempts have been made to develop models for the assessments and monitoring of mangrove dynamics in Cameroon Atlantic coast. The following conclusions can be drawn from this study:

- *Mangrove forest assessments*. Like other biological systems allometric relations can fully characterise mangrove forests and can be employed to make reliable estimates of tree and forest volume and biomass from easily measurable characteristics like tree diameter useful for forest use regulation. Due to the mono-cultural characteristics and very difficult accessibility of mangrove forest, simple random sampling may well economically substitute for complex sampling schemes.
- *Disturbance and dynamics of mangrove forests*. Due to multi-stem and eco-morphological structures of mangrove forests, an appropriate tree/stem coding system accessible to all users and stakeholders such as the one described here is necessary in order to make precise estimates of stocks and dynamics of this forest with consideration of single, multiple and aggregate stems. Results show that they exhibit different resource stock and flow (dynamics) characteristics. Though the time period of four years was relatively short for any meaningful study of the dynamics of this system, results already show that tolerant forest disturbance levels generally encourage growth and recruitment processes, extremes favour mortality and degradation. Comparatively higher values of forest dynamic parameters with examples from upland forests indicate higher resilient or reovery rate of mangrove forests than upland forests.
- *Cultures of Rhizophora and Avicennia.* Being two flagship genera in West and Central African mangrove landscape, it has been shown that they can equally perform well in balanced mixed stands of this species pending other silvicultural tests.
- *Modelling the dynamics of mangrove forest following regimes.* Linear and binary logistic models can be used successfully to model mangrove forest dynamics processes especially growth, recruitment, mortality including some eco-morphological features such as incidence of multiple trees and root sprouting under different disturbance regimes. Predictions improve with increasing diameter class. An appropriate disturbance scale is necessary, quantitatively defined in this study as proportion of basal area removed with adjacent undisturbed forest as the basis. Matrix model construction based on multiple - stem dynamics are generally more simple and precise than matrix construction based on diameter distribution.

7.2. Recommendations

Results from this study are very preliminary owing to limited time period of four years. However, they indicate encouraging insights into exploring the dynamics of mangrove system and impact of different disturbance systems. The following recommendations can be made.

- *Testing the codification system.* The codification system proposed be tested in order to improve the quality of information on mangrove forest assessments and monitoring effects.
- *Allometric study of African mangroves*. Given the role of allometry in the management and biomass relations of mangrove forests, there is need to intensify research in this area. Though there have been extensive allometric study of mangroves of other regions, little information exists on African mangroves. In spite of the existence of such allometric information for mangroves of other regions, they appear very limited due to very limited tree diameter coverage which is often a little beyond 50cm dbh yet trees beyond this category carry a greater proportion of mangrove biomass.
- *Impacts of forest disturbance systems on mangrove forest dynamics*. There is need to observe this over longer time spans.
- *Modelling forest dynamics following disturbance*. Efforts and resources be stepped up to improve modelling of mangrove forest processes especially under different disturbance treatments with simulation studies on the models with the view to identifying critical states for the maintenance of this fragile but yet resilient systems.

8. SUMMARY

Mangrove forests existing at the interface between the sea and land in inter-tidal zones in tropical and subtropical areas playing quite significant ecological, socioeconomic and climate amelioration functions across the globe have been badly degraded over the years due mainly to human factors. Efforts to manage these forests have been widely demonstrated and documented. While mainly undisturbed states of these forests have been studied, relevant information especially on stock and ecosystem responses to human driven factors is often lacking for management applications. Furthermore, systems of forest assessments and monitoring often applied to upland forests appear inappropriate to these systems with varied multi-stemmed and diverse eco-morphological structure of tree forms. The main objective of the study was to develop appropriate models to facilitate the assessment, monitoring and sustainable management of mangrove forest resources following different wood exploitation pressures in the coastal Atlantic forests of Cameroon, Central Africa. It is a contribution to the understanding of the recovery dynamics and resilience of mangrove systems to various disturbance systems. Results provided are based on data on temporary sample plots and four year observations with two remeasurements intervals on permanent sample plots established in heavily exploited, moderately exploited and undisturbed mangrove forests in the Douala-Edea Wildlife Reserve mangroves in Cameroon Atlantic coast.

8.1. Allometric equations to facilitate assessment and monitoring of mangrove forest resources

Tree diameter dependent allometric relationships were developed to guide sustainable exploitation of mangrove forest including height partitioning relationships, stand curves, tree and stand volume equations with their statistical and graphical fit tests. Tree diameter dependent biomass expansion/conversion factor equations or constants have also been developed based on ratios of tree volumes to total biomass obtained from relevant published generic biomass equations. Tables are prepared from the best models.

8.2. Stock assessments

The cost of establishing or measuring PSP with min diameter 1.0cm was 3 times that for TSP with min diameter 6.4cm. These *Rhizophora* dominated (*Rhizophora* –rel freq 89.9%, *Avicennia germinans* (rel. freq. 0.25 %) estuarine mangroves attain maximum height of 59m and diameter of 131.7 cm with mean stand density, basal area and volume of 651 trees/ha, 784 stems/ha (d≥6.4cm), 88.43 m^2/ha and 1879m^3/ha respectively in well stocked stands. Stand density, basal area, volume and total tree above ground biomass in undisturbed stands varied from 400 – 20100 trees/ha (mean 5416.7, SE 1930.5), 400 - 22300 stems/ha (mean

5900.0, SE 2077.7) (d≥1.0cm); 25.23 - 49.62m^2/ha (mean 36.85, SE 3.23); 223 - 611 m^3/ha (mean 402.8 and SE 49.4); and 240.3 - 659.3 tons/ha (mean 435.03 SE 53.4) respectively. Standing biomass values are amongst the highest in the world mangroves. Diameter distribution tends to approximate the log-normal type with Weibull shape and scale parameters ranging from 1.43 to 2.62 between sites 1.66 pooled sites and 25.06 to 39.57 between sites and pooled sites 36.07 respectively. De Liocourt q-ratios were variable with minimum values range from 0.3 –5.0 and mean 1.5 CV 40.8% for pooled sites. Due to the mono-specific nature of forest, simple random sampling could economically substitute for other stratified sampling schemes given a comparatively favourable sampling efficiency with stratified random sampling just over 1.1 times efficient.

8.3. Impact of wood exploitation on mangrove forest structure and dynamics

There were significant site differences in all of the stand parameters (nr-trees, nr-multi-stemmed trees, stand basal area), except incidence of problem trees. There were significant disturbance effects in all stand parameters. Census time had no significant effect on any of the parameters; the only interaction effects noted was between disturbance regimes and zones in incidence of multi-stemmed trees. Spatial patterns of tree developmental stages and mortality were varied with clump structures dominating. Except for mortality and multi-stemmed trees, there were no significant site, disturbance, census time or interaction differences in spatial patterns in all the tree developmental stages. There were only significant site differences in recruitment and regime differences in basal area increment. Mean recruitment over the period was generally above mortality. Exploitation seems to promote mortality with highest in heavy exploitation, medium in moderate exploitation, and lowest in undisturbed forest. As expected, mortality was generally higher in lower diameter classes especially the lowest class 1-3cm. Exploitation generally favour recruitment at tolerant levels with highest in moderate exploitation then heavy exploitation and then undisturbed forest. There was almost normal distribution in diameter growth categories with most trees being of the average growth category (0.11-0.50cm/yr) less at the lowest extreme (negative or nil performance (-ve - 0.00)) and at highest extreme that consists of excellent performance (over 1.00 cm/yr).

8.4. Impact of disturbance on tree forms (branching patterns)

Stand tree density decreases with increasing stem density per tree in an L-shape fashion. Branching intensity for principal mangrove species tend to increase with disturbance and decrease with time with heavily exploitation having maximum stem per tree of 10, moderate 11 and undisturbed 4 with mean stem density per tree of 1.2 whereas the proportion of multi-stemmed trees increases with diameter in a more determined mathematical fashion. All the stand parameters (stand density, basal area, volume and above ground biomass) had significant impact on tree form. There were only sites - tree form – disturbance regime level interactions in stand density. Generally contribution of multi-stemmed individuals to various stand attributes (stand density, basal area, volume and biomass) tends to increase with forest disturbance but decrease with census time. Contribution was generally higher for stems than trees. Average contribution for the 3-census for i) stand density for tree in heavily exploited regime (HE) was 12.5%, moderate exploitation 13.8%, undisturbed (UND) 6.2%; stems in HE 28.2%, ME 29.6%, UND 12.9% ii) basal area of trees in HE 31.4%, ME 19.3%, UND 18.3%; stems in HE 80.9%, ME 42.7%, UND 31.9% iii) volume/biomass for trees in HE 26.4%, ME 9.7%, UND 10.3%; stems in HE 66.8%, ME 34.4% and UND 23.8%. Forest disturbance had no significant impact on tree form in all the stand growth parameters considered or any interaction effects between tree form between zones, regimes or census. However, level of exploitation seems to favour tree/stem and stand growth which decreases with time. Stand growth mean values for all stems for different exploitation regimes were: i) diameter growth: heavily exploited regime 0.34cm/yr; moderate exploitation, 0.31cm/yr and undisturbed 0.28 ii) basal area growth: heavily exploited 0.38 m^2/yr/ha; moderate 0.35 m^2/yr/ha and undisturbed -0.01m^2/yr/ha iii) volume growth: heavy exploitation range: 3.41 m^3/yr/ha; moderate exploitation 2.80 m^3/yr/ha; undisturbed forests -0.87 m^3/ha/yr; and iv) above tree biomass growth: heavy exploitation 3.68 tons/ha/yr, moderate exploitation 3.68 tons/ha/yr; and undisturbed forests -0.94 tons/ha/yr. Significant differences in tree form in annual recruitment and mortality were observed between the zones and disturbance regimes with trees with generally higher rates than secondary stems. No significant tree form – time interactions effects on recruitment have been found but on mortality. Generally recruitment was above mortality. In most cases tree recruitment were generally higher than stem recruitment but stem mortality was higher. Mean annual recruitment values were: i) heavy exploitation 475 trees/ha (7.6%); sec. stems 63 stems/ha (2.6%); all stems 538 stems/ha (6.8%) ii) moderate exploitation; trees 475 trees/ha (7.1%), sec stems 140 stems/ha (5.0%); all stems 615 stems/ha (7.2%); iii) undisturbed forests, trees 333 trees/ha (6.0%); sec stems 18 stems/ha (2.1%), all stems 351 stems/ha (5.8%). Annual mortality values were: i) heavy exploitation: 153 trees/ha (2.4%), sec stems 225 stems/ha (9.3%), all stems 378 stems/ha (4.8%) ii) moderate exploitation: 116 trees/ha (1.7%), sec stems 152 stems/ha (5.5%), all stems 268 stems/ha (3.1%) iii) undisturbed forests: 95 trees/ha (1.7%), sec. stems, 44 stems/ha (5.2%), all stems 139 stems/ha (2.3%). Results of multivariate tests show that there were no site differences in invasive species level except Nypa palm. Forest disturbance had significant effect on invasive species level but no time or interactive effects except for ferns. These may be alternative strategies for survivorship in their constantly changing environments. Generally forest dynamics parameter values were comparatively higher than examples from upland forests, indicating higher recovery rate.

8.5. Dynamics of *Avicennia* and *Rhizophora* in balanced mixed stands

Stand height for *Avicennia* was 15.4m and *Rhizophora* 17.2m. Except in the proportion of multi-stemmed trees that showed significant differences between the two species with *Avicennia* between 20-100%, there were no other differences between species or their tree forms in other stand parameters. However mean stand density values in *Avicennia* for all stems were 4139 stems/ha, *Rhizophora 2*850 stems/ha, mixed species 6989 stems/ha; basal area for *Avicennia* 5.18m^2/ha, *Rhizophora* 4.86m^2/ha, mixed 10.04m^2/ha; volume for *Avicennia* 44.05m^3/ha, *Rhizophora* 33.97m^3/ha, mixed 78.02m^3/ha; above ground tree biomass *Avicennia* 31.28tons/ha, *Rhizophor*a 32.0 tons/ha, mixed 63.28tons/ha. There were significant association between tree form and species as well as between tree form and census in annual recruitment and mortality. Recruitment was generally above mortality in both species but higher in *Rhizophora* than *Avicennia* and vice versa in mortality. *Avicennia* recruited annually 92 trees/ha (3.5%), 183stems/ha (4.4%), all stems 275/ha (4.1%). *Rhizophora* 267 trees/ha (13.4%), 75 stems/ha (2.6%), all stems 342/ha (7.0%); mixed species 358 trees/ha (7.8%), 258stems/ha (3.7%), all stems 616/ha (5.3%). Mortality values were: *Avicennia* 125 trees/ha (4.8%), 300 stems/ha (7.2%), all stems 425/ha (6.3%). *Rhizophora* 4 trees/ha (0.2%), 71 stems/ha (2.5%), all stems 75/ha (1.5%); mixed species 129 trees/ha (2.8%), 371 stems/ha (5.3%), all stems 500/ha (4.3%). There were significant differences in diameter growth between the species. There were no other significant differences or interaction differences in neither tree form nor census time. Mean diameter growth for *Avicennia* was 0.29 cm/yr, *Rhizophora* 0.72cm/yr, mixed species 0.51 cm/yr; basal area growth for *Avicennia* 0.43m^2/ha/yr, *Rhizophora* 1.06 m^2/ha/yr, mixed 1.49m^2/ha/yr; Volume growth for *Avicennia* 3.55m^3/ha/yr, *Rhizophora* 7.81 m^3/ha/yr, mixed species 11.35m^3/ha/yr; above ground biomass growth of 2.64 tons/ha/yr for *Avicennia*, 7.35 tons/ha/yr for *Rhizophora* and mixed species 9.99 tons/ha/yr. Generally forest dynamics parameters were comparatively higher than examples from upland forests indicating higher recovery rate.

8.6. Modelling mangrove stand dynamics following different wood exploitation regimes

Regression and matrix models were used to model mangrove stand dynamics following various levels of disturbance with a disturbance scale based on proportion of basal area removed compared to average basal area of undisturbed subplots in each site. Linear and/or binary logistic regression analyses were used where appropriate to calibrate the model parameters of a) four year individual tree basal area increment models, b) four year individual tree mortality/survival models, c) four year regeneration models, d) stand volume projection models and eco-morphological models. Graphical stand structural dynamic and matrix models were also developed. The models were followed by independent benchmark tests on separate data set not used in model development.

- For basal area increment models, the dependent variable, ln (g+1) was highly dependent on reciprocal diameter, relative interaction term D^2/AMD, interaction between basal area and exploitation level. The model has a reasonable predictive accuracy with a prediction bias, mean percentage difference of 0.54%, mean % bias of -32.41% with a non significant t-value.
- The probability of tree survival was dependent on reciprocal diameter, relative diameter, residual dominant stand height and wood exploitation levels.
- The probability of recruitment was a function of inverse of stand density, direct function of site indicator and disturbance level. The amount of recruitment (natural log of four year recruitment) was a function of stand density and disturbance.
- Stand volume projection models were developed as time independent yield models with two different sets of predictor variables (Model 1-basal area, site indicator and proportion of basal area removed and Model 2-basal area and proportion of basal area removed) and short-term time dependent model (Model 3 – Basal area, proportion of basal area removed and time elapsed after disturbance).
- Some eco-morphological phenomena like branching habits and root sprouting in *Rhizophora* could be modelled. Probability of branching was dependent on tree diameter, relative tree status, interaction of basal area and disturbance, and time elapsed after disturbance. The model gives a reasonable good-fit at diameter classes above 3cm. The probability of root sprouting in *Rhizophora* was controlled by relative tree status, interaction of relative status and disturbance. The model gives a reasonable good-fit at all diameter classes.
- De Lieucourt q-ratios show no significant difference between tree form, regime, census nor their interactions. However, q-ratios were generally higher for all regimes for stems (2.43 – 4.70 mean 2.73 – 4.23) than trees (2.47 – 4.10 mean 2.39 – 3.72). The q-ratios were generally lower with decreasing disturbance and decreases with census probably towards equilibrium. Various shade of rotatory sigmoid shape to straight line indicating various

levels of disturbance were obtained also indicating mangrove forest in a continuous changing environment than upland forests.

- From the matrix models used to describe changes in multi-stemmed tree status and structural dynamics of tree population, dominant eigen values for proportion of multi-stemmed trees were generally unity irrespective of the wood exploitation regime indicating a stable proportion. It could be that nature tends to maintain a stable proportion of single and multi-stemmed status in any given population irrespective of wood exploitation pressures on the ecosystem. Though there were spatial variations, the stable SS: MS ratio seems to indicate a tendency towards a greater proportion of single stemmed trees with exploitation pressures. Generally the multi-stem proportion dynamics matrix model made accurate predictions for overall total tree population followed by single stemmed trees and multi-stemmed trees across disturbance regimes. Predictions for diameter classes were generally over estimated irrespective of the regimes for lower classes (1-3 cm, 3-5 cm).The accuracy of the model in predicting diameter distribution greatly improved with decreasing disturbance status for both single stemmed, multi-stemmed and total tree population.
- Matrix models for structural dynamics of mangrove tree population show that the tree population structure was highly variable. Except for certain undisturbed forests, most regimes and pooled conditions have dominant eigen values (λ) greater than unity. These indicate actively growing population. There were significant differences between dominant eigen values across regimes and sites. Eigen values were significantly higher for disturbed than disturbed regimes. Stable stage distribution for all pooled regimes and zones will be 100:13:3:1:0:0 for size classes 1,2,3,4,5,6 and 7 respectively. This forest structure associated with the greatest latent root maximises the available yield from the forest. The stable stage distribution was highly variable between regimes and zones, in some cases with some classes having zero population. This shows that adequate regeneration is needed to sustain production and growth of the affected forest to forestall possible extinction while in other cases some harvests will be encouraged to stabilise the forest.
- The predictive harmony, consistency and convergence of the various models tested through stand table projection approach showed that the models generally predict diameter class distribution with varying accuracies with overestimation of lower diameter classes especially 1-7 cm. Like matrix models, the predictive accuracy of the regression models improved with decreasing forest disturbance with the undisturbed state being the best.

8.7. Management applications

These models can be used with simulations for sustainable mangrove forest management. A codification system amenable to eco-morphological structure of mangroves is proposed to facilitate field measurements, data processing and easy quantification of population dynamics parameters using spread sheet. The use of the models in setting rotations, planning harvests, yield projections/predictions, assessing impacts of wood extraction or deforestation, planning silvicultural or mangrove restoration operations, forest carbon stock assessments, research, and policy, legal and institutional frameworks for implementation are further elaborated.

9. ZUSAMMENFASSUNG

Mangrovenwälder, die an der Grenze zwischen Meer und Land in tropischen und subtropischen Ländern wachsen, sind von großer ökologischer und sozio-ökonomischer Bedeutung, zudem sind sie aus Klimaschutzgründen wichtig, jedoch sind sie zum Teil stark degradiert. Bewirtschaftungsmodelle für diese Wälder wurden entwickelt und sind gut dokumentiert. In den meisten Fällen wurden nicht bewirtschaftete Mangrovenwälder studiert, der Einfluss von Bewirtschaftungsmaßnahmen auf das Mangroven-Ökosystem wurde wenig untersucht. Modelle für Inventur und Monitoring von Mangrovenwäldern müssen die komplexen Stammstrukturen der Mangroven berücksichtigen, eine Übertragung von Modellen aus anderen Wäldern ist nicht möglich.

Die Zielsetzungen der vorliegenden Untersuchung war Inventur und Monitoringmodelle als Grundlage für die nachhaltige Bewirtschaftung von Mangrovenwäldern an der Atlantik Küste von Kamerun nach unterschiedlichen Störungsregimen zu entwickeln. Die Untersuchungen wurden auf der Grundlage von temporären Stichproben und zweimal wieder vermessenen Stichproben in stark degradierten Flächen, moderat genutzt und auf ungestörten Flächen durchgeführt.

9.1. Allometrische Gleichungen für Inventur und Monitoring von Mangrovenwäldern

Allometrische Gleichungen, die vom Durchmesser abhängen, wurden entwickelt, als Grundlage für die nachhaltige Nutzung von Mangrovenwäldern. Umrechnungsfaktoren für Volumen/Biomasse wurden auf der Grundlage von Literaturrecherchen ermittelt und die geeigneten Gleichungen und Tabellen abgeleitet.

9.2. Volumeninventur

Die Kosten zur Einrichtung und Aufnahme von permanenten Probeflächen mit Kluppschwelle 1,0 cm war 3 mal so hoch wie die für temporäre Probeflächen mit einer Kluppschwelle von 6,4 cm. Die Wälder, von Rhizophora dominiert, erreichen eine maximale Höhe von 59 m und Durchmesser von 131,7 cm mit einer durchschnittlichen Bestandesstammzahl von 651 Bäumen/ha, 784 Stämme/ha ($d \geq 6.4$cm), durchschnittlichen Grundfläche von 88,43 m^2/ha und einem Volumen von 1879 m^3/ha in gut bestockten Beständen.

Bestandesdichte, Grundfläche, Volumen und gesamte oberirdische Biomasse in ungestörten Wäldern variierten von 400 – 20100 Bäumen/ha (Mittel 5416.7, SE 1930.5), 400 - 22300 Stämme/ha (Mittel 5900.0, SE 2077.7) ($d \geq 1.0$cm); 25,43 – 49,62 m^2/ha (Mittel 36,85), 223-611 m^3/ha (Mittel 402,8) und 240,3 – 659 to/ha (Mittel 435,03).

Die oberirdische Biomasse nimmt, weltweit gesehen, sehr hohe Werte an, Durchmesser Verteilungen sind Log-Normal mit Weibull Parametern von 1,43 – 2,62 und 25,06 – 39,57. De-Liocourt q-Werte variierten von 0,3 – 5,0 (Mittel 1,5).

In den Mangroven-Reinbeständen erwies sich die Zufallsauswahl der Probeflächen als geeignet, eine stratifizierte Auswahl ergab nur eine Effizienzsteigerung von 10%.

9.3 Auswirkungen von Holznutzungen auf Struktur und Dynamik von Mangrovenwäldern

Die Bestandesparameter (Stammzahl, Anzahl von Stämmen/Baum, Bestandesgrundfläche) für die Standorte unterschieden sich signifikant. Für alle Bestandesparameter zeigten sich signifikante Unterschiede in Bezug auf die Störungsregime. Aufnahmezeiten hatten keine signifikanten Einflüsse auf die Parameter, die einzige Interaktion zeigte sich für Störungsregime und Auftreten von mehrstämmigen Bäumen. Keine signifikanten Effekte von Standort, Störung, Aufnahmezeiten oder Interaktion konnten in Bezug auf die räumliche Verteilung entdeckt werden. Die einzigen Standort-Unterschiede in Einwuchs und Störungsregime zeigten sich bei Grundflächenzuwachs. Der durchschnittliche Einwuchs in der Untersuchungsperiode war immer größer als die Mortalität. Nutzungen scheinen die Mortalität zu fördern, am größten war sie in Flächen mit großer Nutzung, mittel in mittlerer Nutzung und am geringsten in ungestörten Beständen. Wie zu erwarten, war die Mortalität am höchsten in den unteren Durchmesserklassen, vor allem in der Klasse 1-3 cm. Nutzung im allgemeinen hatte einen Effekt auf den Einwuchs, am höchsten war er bei mäßiger Nutzung, dann hohe Nutzung und dann bei ungestörten Beständen. Die Verteilung des Durchmesserzuwachses war annähernd normal verteilt.

9.4. Auswirkungen von Störungen auf die Stammform

Die Bestandesstammzahl nimmt mit zunehmender Anzahl von Stämmen/Baum ab. Die Verästelungen nehmen mit dem Ausmaß der Störungen zu und nimmt mit Nutzungen ab, die hohe Nutzung zeigt 10 Stämme/Baum, moderate 11 und ungestört 4. Alle Bestandesparameter (Stammzahl, Grundfläche, Volumen, Biomasse) hatten einen signifikanten Einfluss auf die Baumform. Es zeigten sich nur Interaktionen von Bestand, Baumform, Nutzungshöhe und Bestandesdichte. Im Allgemeinen wird der Beitrag vom Bäumen mit multiplen Stämmen zu verschiedenen Bestandesparametern (Stammzahl, Grundfläche, Volumen und Biomasse) mit zunehmender Nutzung größer sein, jedoch mit der Beobachtungszeit abnehmen.

9.5. Dynamik von Avicennia und Rhizophora in Mischbeständen

Die Bestandeshöhe für Avicennia war 15,4 m und Rhizophora 17,2 m. Mit Ausnahme der Stammverzweigungen ergaben sich keine Unterschiede in den Bestandeswerten für beide

Baumarten. Die mittlere Stammzahl/ha für Avicennia war 4139/ha, für Rhizophora 2850/ha, in Mischbeständen 6989/ha. Die Grundfläche für Avicennia war 5,18 m^2/ha, Rhizophora 4,86 m^2/ha, Mischbestände 10,04 m^2/ha, die Biomasse war für Avicennia 31,28 to/ha, Rhizophora 32,0 to/ha und Mischbestand 63,28 to/ha.

Es wurden signifikante Unterschiede zwischen Stammform und Baumart und zwischen Recruitment und Mortalität für unterschiedliche Stammformen gefunden.

9.6. Modellierung der Bestandesdynamik von Magrovenwäldern für unterschiedliche Nutzungsregime.

Regressions- und Matrix-Modelle wurden zur Modellierung der Bestandesdynamik bei verschiedenen Störungsregimen formuliert. Die Störungsregime wurden definiert über das Verhältnis der ausgeschiedenen Grundfläche zu durchschnittlicher Grundfläche der ungestörten Probeflächen. Lineare und/oder binäre logistische Regression wurde angewendet, um die Modell Parameter zu kalibrieren für a) 4-Jahres Grundflächenzuwachsmodell für Einzelbäume, b) 4-Jahres Mortalitätsmodell für Einzelbäume, c) 4-Jahres Regenerationsmodell d) Bestandesvolumen Projektionsmodell. Zusätzlich wurden grafische Bestandes-Struktur Modelle und Matrix Modelle formuliert. Die Modelle wurden anhand von unabhängigen Datensätzen überprüft.

Für die Grundflächenzuwachsmodelle war die abhängige Variable ln (g+1) signifikant abhängig von 1/D, relativer Interaktionsterm D^2/AMD, Interaktion von Grundfläche und Nutzungshöhe. Das Modell hat akzeptable Vorhersagegüte (durchschnittliche Prozentdifferenz 0,54%, durchschnittlicher prozentualer Bias – 31,41%.

Die Überlebenswahrscheinlichkeit war abhängig von 1/D, relativer Durchmesser, Residual dominante Bestandeshöhe und Nutzungshöhe.

Die Wahrscheinlichkeit des Recruitments war eine Funktion der Bestandesdichte, Bonität und Nutzungshöhe.

Bestandesvolumen-Projektionsmodelle wurden als Zeit-unabhängige Ertragsmodelle mit 2 Sätzen von unabhängigen Variablen formuliert – Modell 1 – Grundfläche, Bonität und prozentuale Grundflächenentnahme und Modell 2 mit Grundfläche, und prozentuale Grundflächenentnahme. Ein drittes Modell wurde mit Grundfläche, prozentuale Grundflächenentnahme und Zeit seit der letzten Störung definiert.

Mehrere morphologische Gegebenheiten wie Verzweigungen und Wurzelausschläge wurden für Rhizophora modelliert. Die Wahrscheinlichkeit von Verzweigungen war abhängig von Durchmesser, relativem Baum Status, Interaktion von Grundfläche und Störungsregime und

Zeit seit der letzten Störung. Das Modell zeigt eine gute Anpassung für Durchmesserklassen über 3 cm. Die Wahrscheinlichkeit von Wurzelausschlägen von Rhizophora ist abhängig von relativem Baum-Status, Interaktion von relativer Status und Störungsregime. Das Modell zeigt eine gute Anpassung für alle Durchmesserklassen.

Die Liocourt q-Werte zeigen signifikante Differenzen zwischen Baumform, Nutzungslevel und die Interaktionen. Die q-Werte waren höher für alle Nutzungsregime für Stämme im Vergleich zu Bäumen. Die q-werte waren i.a. niedriger bei geringerer Störung und nehmen mit zunehmenden Aufnahmeprozenten zu.

Die Matrix Modelle, die Veränderungen bei multiplen Stammformen und der strukturellen Dynamik der Baum Population zeigten, dass die dominanten Eigenwerte für den Anteil von multiplen Stammformen i.a. eins waren, unabhängig von den Nutzungslevels. Dies könnte darauf zurückzuführen sein, dass von Natur aus, ein stabiler Anteil von einzelnen- und multiplen Stämmen, unabhängig von der Nutzung vorhanden ist. Es gab dabei räumliche Variationen, das stabile SS:MS Verhältnis zeigt, dass die Tendenz zu einzelnen Stämmen mit zunehmender Nutzungsintensität steigt. Im Allgemeinen ergab das dynamische Matrix-Modell für multiple Stämme gute Ergebnisse, gefolgt von Einzelstamm-Bäumen und multiplen Stamm Bäumen für die Nutzungsregimes. Die Vorhersagen für die Durchmesserklassen waren Überschätzungen für die unteren Durchmesserklassen, unabhängig von den Nutzungsregimen. Die Genauigkeit der Modelle für die Vorhersage der Durchmesser-Verteilungen war für geringe Störungsregime genauer als für höhere sowohl für Einzelstamm- als auch für multiple Stamm-Modelle.

Matrix Modelle der strukturellen Dynamik der Mangroven Bestände zeigten, dass die Struktur sehr variabel war. Mit der Ausnahme von wenigen ungestörten Wäldern haben die meisten Störungsregime und Aggregierungen Eigenwerte größer als 1. Dies weist auf wachsende Populationen hin. Es ergaben sich signifikante Unterschiede zwischen den Eigenwerten von Störungsregimen und Bonitäten. Eigenwerte waren signifikant höher für gestörte Regime als für ungestörte. Stabile Verteilungen für alle Regime und Zonen sind 100.13.3:1:0:0 für die Größen-Klassen 1,2,3,4,5,6,7. Diese Waldstruktur, die mit der größten latenten Wurzel assoziiert ist, maximiert den Waldertrag. Die stabilen Verteilungen waren sehr variabel für Regime und Zonen, in manchen Fällen hatten manche Klassen Nullwerte. Dies zeigt, dass eine ausreichende Verjüngung notwendig ist, um Produktion und Zuwachs des Waldes zu garantieren, während in anderen Fällen Nutzungen den Waldzustand stabilisieren können.

Die Vorhersagen der verschiedenen Modelle, die durch die Tabellenkalkulationsprogramme getestet wurden, zeigen, dass die Durchmesserklassen-Verteilungen mit unterschiedlicher

Genauigkeit vorhergesagt werden konnten, die unteren Klassen von 1-7 cm jedoch überschätzt wurden. Ähnlich wie bei den Matrix-Modellen ist die Vorhersagegenauigkeit der Regressionsmodelle besser für ungestörte Wälder.

9.7. Anwendungen für die Bewirtschaftung von Mangrovenwälder

Diese Modelle können für Simulationen der nachhaltigen Bewirtschaftung von Mangrovenwäldern verwendet werden. Ein Klassifizierungssystem wird vorgeschlagen, um Geländeaufnahmen, Datenverarbeitung und Quantifizierung der Populationsdynamik mit einem Tabellenkalkulationsprogramm zu erleichtern. Die Anwendung der Modelle für die Festlegung der Umtriebszeit, der Planung von Erntemassnahmen, der Projektion/Vorhersage des Ertrags, für die Bestimmung des Einflusses von Holzernten oder Abholzungen, für die Planung von waldbaulichen Massnahmen oder der Wiederbegründung von Mangrovenbeständen, für die Abschätzung der Kohlenstoffspeicherung und für Forschungsarbeiten wird diskutiert, die forstpolitischen, rechtlichen und institutionellen Rahmenbedingungen für die Implementierung werden beschrieben.

10. RESUME

Les forêts de mangrove situées à l'interface entre la mer et le continent dans les zones intertidales des régions tropicales et sous tropicales du monde jouent un rôle très important sur le plan écologique, socio-économique et de la régulation climatique du globe terrestre. Pendant des années, ces forêts ont été fortement dégradées due principalement aux facteurs anthropiques.

Les efforts visant à gérer ces forêts ont largement été consentis et documentés. Bien que les états non perturbés de ces forêts aient particulièrement été étudiés, les informations pertinentes sur les stocks et la résilience de ces écosystèmes aux facteurs causés par l´homme sont souvent manquantes pour développer les stratégies de gestion durable. En plus, les systèmes de suivi et d'évaluation appliqués aux forêts continentales sont souvent inadaptés à ces mangroves aux formes d´arbres à tiges multiples et à structures éco-morphologiques diverses.

L'objectif principal de cette étude est de développer les modèles appropriés d'évaluation, de suivi et de la gestion durable de ces forêts de mangrove suivant différentes pressions d'extraction du bois dans la zone côtière atlantique du Cameroun (Afrique centrale). C'est une contribution à la compréhension des dynamiques de récupération et de la résilience des mangroves à divers sytèmes de perturbation.

Les résultats obtenus sont basés sur les données collectées dans les placettes temporaires et permanentes établies dans les forêts de mangrove fortement, modérément et non exploitées de la réserve de Douala-Edéa sur la côte atlantique du Cameroun; ceci durant quatre années d´observations avec deux remesures à intervalle de deux ans.

10.1. Relations allométriques établies pour faciliter l´évaluation et le suivi des ressources forestières des mangroves

Les relations allométriques à base des diamètres des arbres ont été developées pour faciliter la gestion durable des forêts de mangrove y compris la hauteur, les courbes de peuplement, les équations de tarifs avec des tests statistiques et graphiques appropriés. Les équations de facteurs ou des constantes d'expansion/conversion de la biomasse ont également été élaborées sur la base des ratios entre le volume des arbres et la biomasse totale obtenus à partir des équations génériques de biomasse publiées. Des tables sont préparées des meilleurs modèles.

10.2. Evaluation des stocks

Ces mangroves estuariennes dominées par *Rhizophora* (*Rhizophora* fréq. rel. 89,9%, *Avicennia germinans* fréq. rel. 0,25%) atteignent une hauteur maximale de 59 m et un diamètre maximum de 131,7 cm avec une densité moyenne de peuplement, une surface terrière et un volume brut sur pied respectifs de 651 arbres/ha, 784 tiges/ha (d≥6,4 cm), 88,43 m^2/ha et 1879m^3/ha dans les peuplements bien stockés. La densité de peuplement, la surface terrière, le volume et la biomasse totale au dessus du sol mesurés dans les parcelles non perturbées varient de 400 à 20100 arbres/ha (moyenne 5416,7; SE 1930,5), 400 à 22300 tiges/ha (moyenne 5900,0; SE 2077,7) (d≥ 1,0 cm), 25,23 à 49,62 m^2/ha (moyenne de 36,85; SE 3,23), 223 à 611 m^3/ha (moyenne 402,8; SE 49,4) et 240,3 à 659,3 tonnes/ha (moyenne 435,03 ; SE 53,4) respectivement.

Les valeurs de la biomasse sur pied sont parmi les plus élevées des mangroves du monde. La distribution du diamètre tend à se rapprocher au type log-normal. L'échantillonnage aléatoire simple a donné une efficacité d´échantillonnage de 1,1 comparativement aux autres plans stratifiés et peut économiquement se subtituer à ces derniers vu la nature monospécifique des forêts de mangrove.

10.3. Impact de l'extraction du bois sur les dynamiques et la structure des forêts de mangrove

Il y avait des différences significatives de sites sur tous les paramètres de peuplement évalués (nombre d'arbres, nombre d'arbres à tiges multiples, surface terrière totale), à l'exception de l'incidence d'arbres à problème. Il y avait également un effet significant de pertubation sur tous les paramètres de peuplement. Les modèles spatiaux des étapes de développement des arbres (plantule, perche, adultes) étaient variés, avec une domination des structures d'agrégation. A l'exception de la mortalité et des arbres à tiges multiples, il n'y avait pas de différences significatives entre les sites, la perturbation des forêts et le temps de recensement ou d´interaction sur les modèles spatiaux de tous les stages de développment des arbres. Il n'y avait que des différences significatives de sites en recrutement et les différences significatives entre les différents régimes de perturbation des forêts en accroissement de surface terrière. La moyenne de recrutement au cours de cette période était généralement au dessus de la mortalité. La mortalité était plus élevée dans les forêts fortement exploitées. Les régimes de perturbations encourageaient la croissance, les plus élevés étant les systèmes d'exploitation modérée.

10.4. Impact des perturbations sur les formes de l´arbre (modèle de branchaison)

La densité du peuplement diminue avec l'augmentation de la densité des tiges par arbre suivant la forme de L. L'intensité de la branchaison des arbres des espèces principales de mangrove a tendance à augmenter avec la perturbation et diminuer avec le temps de recensement tandis que la probabilité de branchaison des arbres augmente avec le diamètre. Tous les paramètres du peuplement (densité, surface terrière, volume sur pied et de la biomasse au dessus du sol) avaient un impact significatif sur la forme de l´arbre contrairement aux paramètres de croissance du peuplement. Le recrutement d'arbre était généralement plus élevé que celui du recrutement de tige secondaire mais ce dernier avait une mortalité plus élevée. Les paramètres de la dynamique forestière étaient comparativement plus élevés que ceux des forêts continentales indiquant ainsi une résilience plus élevée des forêts de mangrove aux perturbations.

10.5. Dynamiques d´*Avicennia* et *Rhizophora* dans les peuplements mixtes et équilibrés

La dynamique des espèces d'*Avicennia* et *Rhizophora* observée dans les peuplements mixtes et équilibrés a montré que sauf dans la proportion d'arbres à tiges multiples qui ont montré des différences significatives entre les deux espèces, il n'y avait pas autres différences entre les espèces ou leurs formes d'arbres concernant les autres paramètres de peuplement. *Rhizophora* avait généralement de meilleurs résultats qu´*Avicennia* dans les peuplements mixtes et équilibrés.

10.6. Modélisation des forêts de mangrove suivant différents régimes d'extraction du bois

Les résultats de cette étude montrent également que la croissance des forêts de mangrove, la mortalité, le recrutement ainsi que des phénomènes éco-morphologiques tels que la probabilité de branchaison des arbres et l'enracinement aérien chez *Rhizophora* peuvent être modélisés avec les approches de la régression linéaire et binaire avec une échelle de perturbations basé sur la proportion de la surface terrière extraite avec comme base de référence les régimes adjacents non pertubés. Le développement de la matrice basé sur l´approche dynamique à tiges multiples était meilleur que celui basé sur l'approche traditionnelle de distribution de diamètre. La cohérence de prédiction, la consistance et la convergence des différents modèles testés par l'approche de projection de table de peuplement a montré que les modèles prédisent généralement la distribution des classes de diamètre avec des précisions variables et une surestimation des basses classes de diamètre 1 - 7 cm en particulier. Comme les modèle-matrices, la précision prédictive des modèles de régression s´est améliorée avec la diminution de la perturbation des forêts, les forêts non perturbées étant les meilleures.

10.7. Applications de gestion durable des forêts de mangrove

Un système de codification basé sur la structure éco-morphologique des mangroves est proposé pour faciliter les mesures sur le terrain, le traitement des données et la quantification facile des paramètres de la dynamique du peuplement utilisant la feuille de calcul. L'usage des modèles dans la gestion durable des mangroves surtout la détermination de la période de rotation; la planification des coupes; la projection des rendements; l'évaluation de l'impact d'extraction du bois ou de la déforestation; la planification des opérations sylvicoles et la restauration des mangroves; l'évaluation des stocks de carbone de forêt; la recherche; la politique et les cadres juridiques et institutionnels de mise en œuvre sont davantage élaborés.

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