Khulna University
Life Science School
Forestry and Wood Technology Discipline

Author(s): Md. Shanewas Hossain

Title: Effect of thinning and natural regeneration on yield in *Avicenia officinalis* L. plantation using monte carlo simulation

Supervisor(s): Dr. Md. Nabiul Islam Khan, Professor, Forestry and Wood Technology Discipline, Khulna University

Programme: Bachelor of Science in Forestry

EFFECT OF THINNING AND NATURAL REGENERATION ON YIELD IN *Avicenia officinalis* L. PLANTATION USING MONTE CARLO SIMULATION

Md. Shanewas Hossain
Student ID: 110531

FORESTRY AND WOOD TECHNOLOGY DISCIPLINE
LIFE SCIENCE SCHOOL
KHULNA UNIVERSITY
KHULNA – 9208
BANGLADESH

2016

Effect of Thinning and Natural Regeneration on Yield in *Avicennia officinalis* L. Plantation Using Monte Carlo Simulation

COUSRE TITLE: PROJECT THESIS

COURSE NO.: FWT-4114

[This thesis paper has been prepared for the partial fulfillment of the requirements of Four years B. Sc. (Hons.) degree in Forestry from Forestry and Wood Technology Discipline, Khulna University, Khulna, Bangladesh.]

Supervisor

30.5.16

Dr. Md. Nabiul Islam Khan
Professor
Forestry and Wood Technology Discipline
Khulna University
Khulna-9208
Bangladesh

Submitted By

Shanewas
30. 05. 16

Md. Shanewas Hossain
Student ID: 110531
Forestry and Wood Technology Discipline
Khulna University
Khulna-9208
Bangladesh

APPROVAL

This project thesis has been submitted to the Forestry and Wood Technology Discipline, Khulna University, Khulna, Bangladesh, in partial fulfillment of the requirements of Four (4) years professional B. Sc. (Hons.) degree in Forestry. I have approved the style and format of the project thesis.

Signature

20.05.16

Dr. Nabiul Islam Khan

Professor

Forestry and Wood Technology Discipline

Khulna University

Khulna, Bangladesh.

DECLARATION

I, Md. Shanewas Hossain, Student ID- 110531, hereby declare that this project thesis is based on my own research work except for quotations and citations, which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at other institutions.

Shanewas
30.05.16

Md. Shanewas Hossain

Date:

Dedicated
To
My Beloved Father

ACKNOWLEDGEMENT

First of all, I am very grateful to almighty Allah for successfully completion of my B. Sc. honor's project thesis. I would like to thank and express my gratitude to several people.

It is a great pleasure for me to express my gratitude, sincere appreciation, heart-felt indebtedness and profound respect to my honorable supervisor Prof. Dr. Md. Nabiul Islam Khan, Professor, Forestry and Wood Technology Discipline, Khulna University, Khulna for his continuous supervision, guidance, inspiration, valuable advices and thoughtful suggestions during the research period and for providing useful books and papers in preparing and writing up this thesis. Moreover, without his kind supervision and encouragement I could not come up with this paper.

I do express my thanks to my Parents, sister and my all family members.

I also Grateful to my entire classmates, especially Atikur Rahman and Suresh kumar Nath for helping me a lot about my research project. I also thankful to my two senior brothers Biplob and Jewel. They encouraged me and helped me a lot.

I also grateful to my loving junior Md. Shiddikur Rahman and his family. I am also grateful to ACF Mr. Altaf (ACF of Patuakhali coastal afforestation division) and beat officer of Rangabali, Patuakhali. They helped me a lot in data collection and staying in Rangabali.

Finally, I do express my thanks to all of my friends and well-wishers.

ABSTRACT

High resolution temporal data on mangrove stand development are rare because long-term monitoring data are generally lacking. However, in Rangabali, potuakhali (Bangladesh), several plantations of *Avicennia officinalis* L. have been established and monitored since 1991. We used KiWi, an individual-based model to hindcast the development of some of the monospecific stands planted at regular intervals, and applied field data on plant development and floristic recruitment under natural conditions to parameterize the KiWi model. We then compared the development of planted forests with or without recruitment and with or without thinning as a silvicultural approach to forest management. The model output and parameterization was evaluated based on monitoring data obtained in the field. The highest harvested biomass at 40-year-rotation was obtained through the option 'with recruitment and with thinning' in *A. officinalis* stands. The performance of various forest management options suggests that natural recruitment along with a periodic thinning offers higher biomass production. Thinning and recruitment play significant roles in the rotational yields having higher proportions of large diameter trees. The model output can be applied to explore a suitable method for restoration of degraded mangrove areas and to set a sound mangrove management strategy as well as to predict future stand development. The study has also relevance to studies on carbon sequestration potentials of mangroves through biomass prediction.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER ONE: INTRODUCTION

1.1 Background of the Study

Mangrove forests are widely distributed along the coasts of tropical and subtropical areas. As mangroves grow on muddy and anaerobic soils which suffer from tidal inundation, they show a unique pattern of biomass allocation (Das and Siddiqi 1985).

Mangrove forests grow in coastal settings of (sub) tropical climates characterized by freshwater runoff, multiple substrate conditions, prolonged hydro period, salinity, anoxic conditions, and accumulation of toxic substances (Berger et al. 2008). Species composition is strongly influenced by these coastal settings because they are linked to differences in mangrove tree species' capability to become established and grow. Mangroves should be viewed as woody vegetation in the intertidal zone that migrates up and down slope from the sea in relation to eustatic natural and human-induced changes in sea level. In their final remarks, (Saenger 2002) conclude that ''mangrove ecosystems are self-maintaining coastal landscape units that are responsive to long-term geomorphological processes and to continuous interactions with contiguous ecosystems in the regional mosaic''.

The Bangladesh coastline extends over 710 km long along the Bay of Bengal and is comprised of various forms of accreted (char) lands and off-shore islands (Siddiqi and Bisvabidyālaẏa 2001). Every year newly accreted lands are added in the coastal belt. Bangladesh Forest Department has created productive and protective mangrove vegetation in the coastal belt with the primary objective of saving lives and properties of coastal dwellers from cyclones and tidal bores(Das and Siddiqi 1985). The objectives of coastal afforestation were then expanded to stabilization of newly accreted lands and enhancement of accretions, and development of forest for timber and fuel wood. Initially, most of the commercial mangrove species were planted on newly accreted lands periodically inundated by tides. *Sonneretia appetela* (keora) is the most successful planted species along the shoreline and *Avicennia officinalis* L. (baen) is the second most successful species of the coastal mangrove plantations on newly accreted lands (Saenger and Siddiqi 1993). Approximately 190,000 ha of accreted lands have been brought under coastal mangrove plantations till 2010. *A. officinalis* alone accounts for about 5% of the total mangrove plantations and 22% in the eastern part (Chittagong and Cox's Bazar) of the shoreline (Siddiqi and Bisvabidyālaẏa 2001).

Simulation modeling is the process of creating and analyzing a digital prototype of a physical model to predict its performance in the real world. Simulation models have been proven to be efficient tools for both the study of forest silviculture and yield modelling for tropical forests (Köhler and Huth 2004). These models can simulate ecological processes such as growth, mortality, competition and recruitment in order to make management decisions on wood harvesting.

A suite of models have been developed independently by various academic and government institutions worldwide to understand the dynamics of mangrove ecosystems and to provide ecological forecasting capabilities under different management scenarios and natural disturbance regimes. The models have progressed from statistical tables representing growth and yield to more sophisticated models describing various system components and processes. Among these models are three individual-based models (IBMs) (FORMAN, KIWI, and MANGRO). A comparison of models' designs reveal differences in the details of process description, particularly, regarding neighbor competition among trees. Each model has thus its specific range of applications. Whereas FORMAN and KIWI are most suitable to address mangrove forest dynamics of stands, MANGRO focuses on landscape dynamics on larger spatial scale (Berger et al. 2002).However, none of the above mentioned individual based models explicitly presented the effect of sapling recruitment patterns on quality and quantity of yield.

Recurrent data on mangrove stand development are rare because long-term monitoring data are generally lacking. In Bangladesh, several plantations of *A. officinalis* have been established in the Patuakhali coastal zone, raised and monitoring by Forest research institute. These data sets can be used to parameterize the KiWi model to hind cast the development of monospecific stands starting from the conditions used for planting mangroves over a period of 40 years. When the model is parameterized, simulation experiments can be performed to compare the development of planted forests with or without recruitment and with or without thinning as silvicultural options in forest management.

1.2 Objectives

Objectives of the study were:

- To parameterize natural mangrove stand development using a combination of simulation experiments and field data;
- To investigate the performance of various forest management options regarding sapling recruitment and thinning operations;
- To predict future stand development.

CHAPTER TWO: LITERATURE REVIEW

2.1 KiWi Model

The KiWi model was developed for analyzing neotropical mangrove forest dynamics affected by environmental settings (pore water salinity and nutrient availability), inter- and intraspecific competition, natural disturbances (lightning and hurricane destruction), and tree cutting (Berger and Hildenbrandt 2000).

The KiWi model has two hierarchical levels: individual trees and simulated area. At individual level, tree establishment, growth, mortality, and competition are considered. The simulated area defines abiotic conditions by mean of maps of local pore water salinity, nutrient availability or any other variable thought to interact with individual trees (Berger and Hildenbrandt 2000, Grimm and Railsback 2005).

An individual tree is described by its stem position (x and y), its age (Age) its stem diameter (dbh), and its annual stem increment (dbh).

The size of the simulation area can be arbitrarily attributed (x_{max},y_{max}). A typical size is 1-5 ha. The maps are set to cover the entire simulation area but their resolutions depend on their pixel sizes (Grimm and Railsback 2005).

2.1.1 Process overview and scheduling of KiWi

The trees life cycle is described by three biological sub-models operating at yearly time step. The first sub-model predicts the stem increment of the trees depending on their current stem diameter, neighborhood competition, pore water salinity, and nutrient availability. The second simulates tree mortality depending on the growth realized within a certain time span by the focal tree. The third sub-model incorporates the establishment of new trees depending on the available space (described by the neighborhood competition exerted by the existing trees at a certain location), and the abiotic conditions. The biological sub-models are linked to the simulated area through the maps describing the abiotic conditions (Berger and Hildenbrandt 2000). Each time step, a sequence of processes is operated following the three biological sub-models:

1) Establishment of new trees,

2) Growth of trees,

3) Mortality of trees

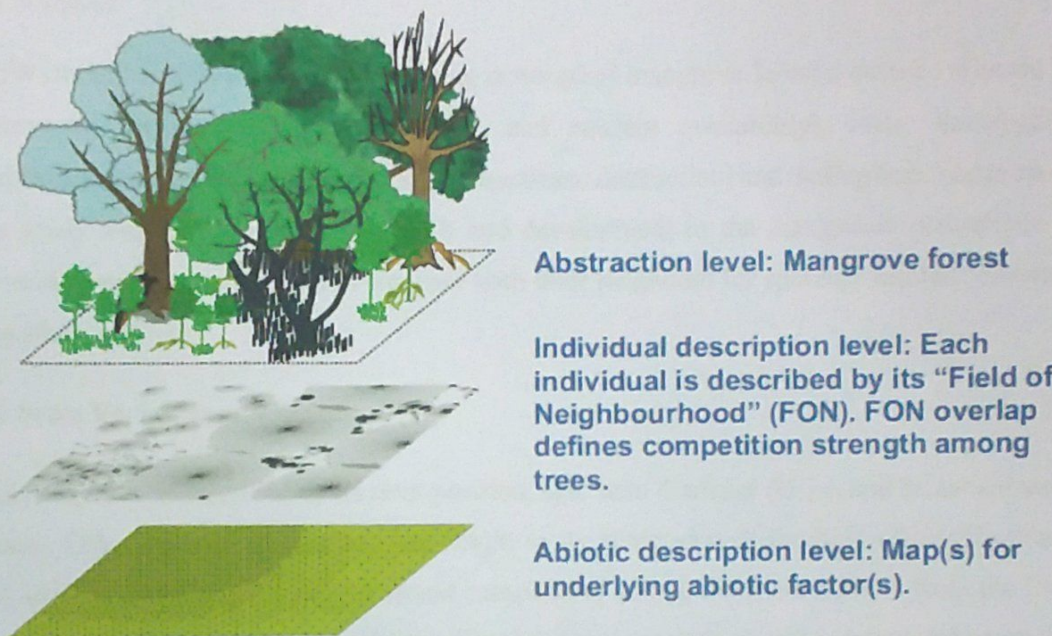

Fig. 1. Scheme of the KiWi model (Berger and Hildenbrandt 2000)

The concrete realization of growth, tolerance to pore water salinity, effectiveness of nutrient use, thresholds for tree establishment, and mortality are species-specific.

2.1.2 Description of KiWi Model

Model description following the ODD protocol (Grimm et al. 1996, Grimm and Railsback 2005, Grimm et al. 2006).

2.1.2.1 Purpose

The KiWi model was developed for analyzing neotropical mangrove forest dynamics affected by environmental settings (pore water salinity and nutrient availability), inter- intraspecific competition, natural disturbances (lighting and hurricane destruction) and cutting tree. The purpose of this study was to analyze stand growth and development in the mangroves plantations of *Sonneratia apetala*, where the trees compete with their neighbors for spatially limited resources such as space and light.

2.1.2.2 State Variables and Scales:

An individual tree is described by its stem position, age, stem diameter (D_{130}), and its annual stem increment. Other descriptors such as stem height or the dimension of the field-of-neighborhood (FON), used to describe local neighborhood competition among trees, are derived from the D_{130} as shown in the growth function (see below). Species-dependent tree growth is calculated annually. The spatial dimension and shape of the forest stand are variable.

2.1.2.3 Process overview and scheduling

The trees life cycle is described by three biological sub-models operating at yearly time step.

- Establishment of new trees,
- Growth of trees,
- Mortality of trees.

The concrete realization of growth, tolerance to pore water salinity, effectiveness of nutrient use, thresholds for tree establishment, and mortality are species-specific. The stem D_{130} of all trees are updated synchronously and the derived parameters such as tree height and FON radius are re-calculated.

2.1.3 Design concepts

2.1.3.1 Emergence

The growth of each tree depending on neighborhood competition and abiotic conditions, and the resulting mortality. Emergent system dynamics include (1) the size structure of the forest, (2) species composition, (3) self-thinning behavior, (4) the distribution of mortality size classes, (4) species zonation, and (5) vertical canopy zonation.

2.1.3.2 Interactions

Trees compete with one another for spatially distributed resources. This competition is phenomenologically described using the so-called Field of Neighborhood (FON) approach. According to this approach, each tree has a circular, size-dependent FON around its stem position where the tree influences its neighbors and is influenced by them. The FON is derived from the philosophy of the Zone of Influence (ZOI) models. However, a scalar field exponentially decreasing from the stem to the boundary defines the strength of competition the tree exerts at each location. Trees with overlapping FONs are neighbors. The sum of the neighboring FONs on the FON area of a focused tree mark the neighborhood competition the later "receives".

2.1.3.3 Sensing

Individual trees are "informed" about the abiotic conditions at their stem position and the local neighborhood situation via FON overlapping.

2.1.3.4 Stochasticity

The KiWi model includes several stochastic processes related to the establishment of trees and the occurrence of additional mortality. However, the tree growth and density dependent mortality are both completely deterministic.

2.1.3.5 Observations

KiWi allows registering continuously the state variables such as stem positions, and stem diameter but also derived variables such as neighborhood competition for each tree. The output files can easily be imported to a spreadsheet for analysis and visualization. In addition, we use the run time visualization of the forest for visual debugging. Using empirical regressions among stem diameter, tree biomass, or tree height provide further analysis in terms of self-thinning and stand development.2.1.4 Details

2.1.4.1 Initialization

Stand development based on random tree positions, an initial height of 1.37 m and a stem D_{130} of 2.5 ± 0.25 cm, and 1 year as starting stand age.

2.1.4.2 Input

Yearly recruitment rates define the establishment of new saplings. Recruitment was set to zero in order to implement the artificial thinning at 15 and 20 years stand ages. Abiotic factors such as topography, inundation height, inundation frequency, pore water salinity and nutrient availability can be addressed explicitly by user-supplied maps corresponding to the simulated forest stand; but for the purpose of this study they were considered to be optimal for the whole forest.

2.1.5 Sub models

2.1.5.1 Description of a single tree

A tree is described by its x-y position, D_{130}, and FON. The latter describes the area within which a tree influences its neighbors and is influenced by its neighbors. The radius R of the FON increases with D_{130}: $R = a. (D_{130}/ 2)^{b}$, where a and b are species specific scaling factors (Table 1). The intensity of FON (r) = $e^{-(r-(D130/2))}$.

2.1.5.2 Recruitment and establishment

Seedling growth is not explicitly modelled due to the lack of field data. Seedling growth and mortality, however, are implicitly included in the sapling recruitment rates. Saplings can establish if tree density and the resulting intra-specific competition are below a certain threshold at the potential, randomly chosen location. This threshold mimics a given shade tolerance of the species.

2.1.5.3 Tree growth

The model uses a JABOWA-type growth function, where the annual stem increment is a function of D_{130} and stem height H

$$\frac{\Delta dbh}{\Delta t} = \left[\frac{G \cdot dbh \cdot \left(1 - \frac{dbh \cdot H}{dbh_{max} \cdot H_{max}}\right)}{274 + 3b_2.dbh - 4b_3.dbh^2}\right].(1 - \varphi.C_{FON} \quad with\ H = 274 + 3b_2.dbh - 4b_3.dbh^2$$

This function is parameterized for optimal growth conditions. The growth multiplier $((1 - \varphi.C_{FON})$corrects the stem increment depending on tree neighbourhood competition, where φ represents the resource sharing capacity and C_{FON} represents the FON intensity in each individual tree. The growth multiplier stands one for no neighboring trees.

2.1.5.4 Competition

The intensity of the FONs of all neighboring trees on the FON of a focal tree is taken as a measure of the competition strength the focal tree suffers. This value is related to the area of the FON of the focal tree, assuming that the influence of larger trees on smaller ones is stronger than vice versa.

2.1.5.5 Mortality

The model considers mortality due to a prolonged period of growth depression. Since there is no field data available on that process, the model describes it phenomenologically. A tree dies if its mean stem increment over a specified time range (here 5 years) is less than half of the average increment under optimal conditions. This occurs when the stem diameter approaches its maximum, or results from salinity stress, nutrient limitation, or competition among neighboring trees. This procedure assures that a tree has a chance to recover when conditions improve, e.g. when a neighboring tree dies. Additional mortality was incorporated in order to implement the artificial thinning in the simulation experiments at 15 and 20 years stand ages.

2.2 Coastal Afforestation

The term coast is used to indicate the zone of contact between land and the sea (Blasco and Aizpuru 2002). It is an intermediate zone that extends land ward from the shore. A coast may be a gently sloping plain; it may terminate abruptly in a stiff cliff or it may be characterized by other types of topography (Bandyopadhyay 1998). The raising plantation with suitable mangrove species on the newly accreted land in any coastal area is defined as coastal afforestation. The area where no forest exist before.

2.2.1 Benefits of Coastal Afforestation

2.2.1.1 Protective benefits

- Shoreline and river bank protection
- Reduced disaster-induced non-material losses (injuries, deaths)
- Reduced disaster-induced indirect (long-term) losses (reduced productivity due to saltwater intrusion or injuries)
- Shoreline stabilization (reduction of soil erosion)
- Reduced costs in sea-dyke maintenance and repair
- Reduced disaster-induced material losses (public infrastructure, buildings, crops, livestock, aquaculture) (Pathak and Mehta 2011).

2.2.1.2 Ecological benefits

- Carbon sequestration
- Nutrient retention
- Sediment retention
- Biodiversity habitat
- Flood attenuation
- Wastewater treatment
- Water supply and recharge (Pathak and Mehta 2011).

2.3 Coastal Afforestation in Bangladesh

Bangladesh is a low-lying deltaic country at the confluence of mighty river systems, namely the Ganges the Brahmaputra and the Meghna. The land is deep, fertile and flat. Most parts are less than 12 m above the sea level while the highest point is about 1,052 m. Very often the country faces natural disasters, especially cyclones and tidal bores (Das and Siddiqi 1985). Bangladesh has 710 Kilometer long coast line. The coastal zone covers 19 coastal districts (153 Upozilas) & Exclusive Economic Zone (EEZ) in the Bay of Bengal. Out of 19 districts, 12 (51 Upozilas) are 'exposed coast' subject to natural calamities. The landward distance of the delineated coastal zone from the shore is between 30 and 195 km whereas the exposed coast up to 57 km. Coastal zone constitutes 32 percent of the area and 28 percent of the population of Bangladesh. Land of coastal area is used mainly for agriculture, shrimp and fish farming, forestry, salt production, ship-breaking yards, ports & industries (Siddiqi and Khan 1990, Islam et al. 2013).

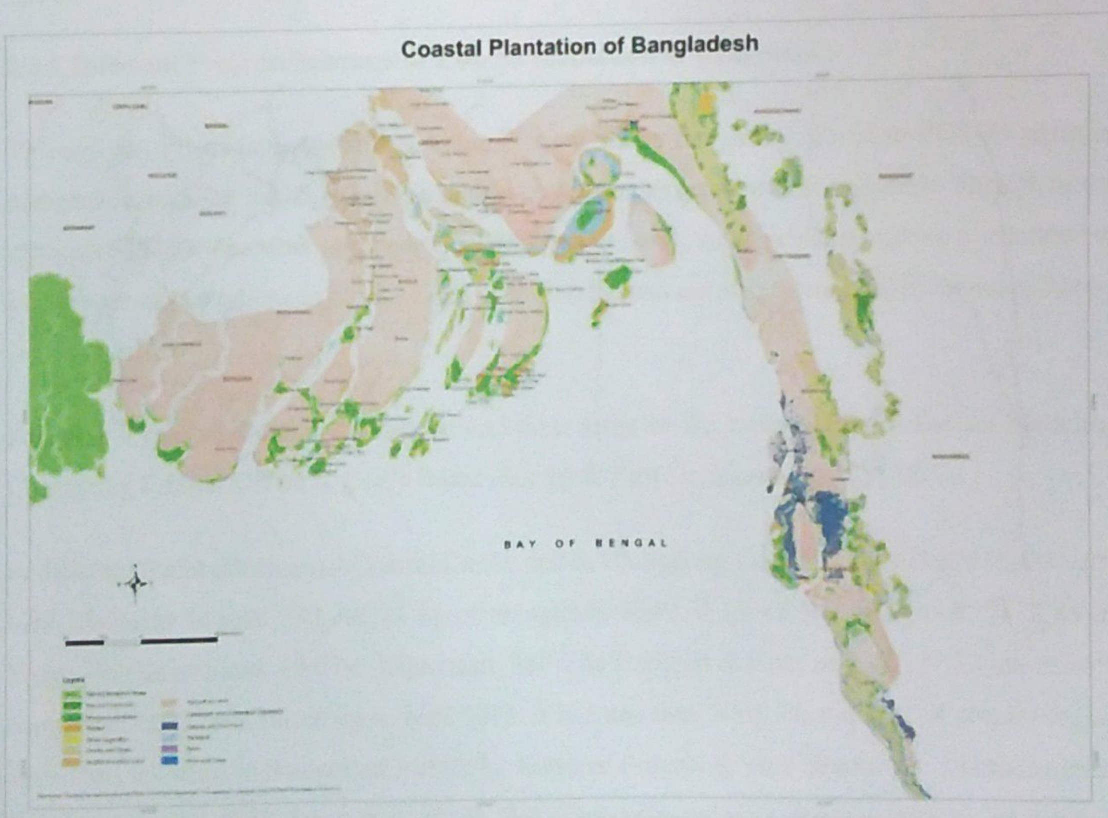

Fig. 2. Coastal Plantation in Bangladesh (Bangladesh Forest Department)

Although roughly 27 species of mangroves and a similar number of mangrove associates occur in Bangladesh most are rare, or of little economic importance. Only 10 or so species occur frequently enough to sustain silviculture. As a result of the early 'trial and error' approach to plantations, only two species - *Sonneratia apetala* and *Avicennia officinalis* - showed encouraging survival rates, and as a consequence, these two species dominate the mangrove plantations generally as monospecific stands. These species are medium quality timbers used for fuel wood, constructions and furniture (Siddiqi and Bisvabidyālaẏa 2001). About 80% by area of the early plantations consisted of monospecific stands of *Sonneratia apetala*, about 15% consisted of stands of *Avicennia officinalis* with the remaining areas consisting of *Excoecaria agallocha, Bruguiera* spp. and *Ceriops decandra*, more valuable species for timber or paper pulp production. Polybag culture of a range of other mangrove species has been experimentally developed although field assessments of the performance of these species are as yet incomplete (Siddiqi 2002, Miah et al. 2014).

2.3.1 Different Projects/Schemes of Coastal plantation in Bangladesh

Through the 'Pilot Mangrove Afforestation Project' during the years 1965-66 to 1974-75 artificial mangrove plantation initiative has been taken by Forest Department of Bangladesh. Though major mangrove plantations were undertaken by different projects, small scale mangrove plantations or other types of plantations in coastal areas or in Sundarbans are also carried out by revenue budget (Islam et al. 2013).

Different Types of Coastal Plantations and their areas in the Coastal Circle, Barisal including Chittagong Coastal Division, Cox's Bazar (South) & Feni Division upto 2011-2012.

In different forest divisions of Coastal Circle, and in Chittagong Coastal, Cox's Bazar (south) and Feni Divisions in total 192,395.24 ha of mangrove, 8689.53 ha of non-mangrove, 2872.88 ha Nypa, 10.0 ha coconut, 40.0 ha Arica palm, 280.0 ha Bamboo & Cane and 12127.13 km of strip plantations have been raised up to June 2013. It is noted that 'Strip Plantations' of coastal region have been included in homestead forests by National Forests & Tree Resources Assessment in Bangladesh, 2005-2007 (Miah et al. 2014). Out of total plantations more than 94% are mangroves (mostly *Sonneratia apetala*) and rests are negligible. 'Ditch-dyke' and 'Mount' plantations that are done under 'Community Based Adaptation to Climate Change through Coastal Afforestation in Bangladesh' project have been included in 'Non-mangrove' plantations. BCCRF funded 'Climate Resilient Participatory Afforestation and Reforestation (CRPAR) Project that has been started this year (2013), going to implement 'Enrichment Plantation' with mangrove species like Kankra (*Rhiziphora mucronata*), Geoa (*Bruguiera gymnorrhiza*), Baen (*Avicennia officinalis*), Passur (*Xylocarpus mekongensis*), Sundri (*Heritiera fomes*), Khalshi (*Aegiceras Corniculatum*) etc (Saenger and Siddiqi 1993, Siddiqi and Bisvabidyālaẏa 2001). In the forests that are comparatively less dense, older and raised sites of different Coastal Divisions that was not tried much in the past. Plantation of Nypa has been also considered in this project which is a species of good soil binder and can effectively resist tidal and storm surges (Latif and Islam).

2.4 About *Avicennia officinalis*

This species is widespread and common within its range. It is threatened by the loss of mangrove habitat throughout its range, primarily due to extraction and coastal development, and there has been an estimated 24% decline in mangrove area within this species range since 1980 (Barik and Chowdhury 2014). Mangrove species are more at risk from coastal development and extraction at the extremes of their distribution, and are likely to be contracting in these areas more than in other areas. It is also likely that changes in climate due to global warming will further affect these parts of the range. Although there are overall range declines in many areas, they are not enough to reach any of the threatened category thresholds. This species is listed as Least Concern (Polidoro et al. 2010, Barik and Chowdhury 2014).

2.4.1 Scientific Classification

Avicennia officinalis Linn. is found sporadically on the banks of rivers and rarely found near the sea. It prefers clay soil and usually found inland. The plant can be found in Bangladesh, Brunei, Cambodia, India, Indonesia, Malaysia, Myanmar, Papua New Guinea, Philippines, Singapore, Sri Lanka, Thailand, and Vietnam (Erdtman and Sorsa 1971).

Kingdom:	Plantae
Division:	Magnoliophyta
Class:	Magnoliopsida
Order:	Lamiales
Family:	Acanthaceae
Genus:	*Avicennia*
Species:	*A. officinalis*

2.4.2 Description

Evergreen tree, sometimes to 25 m, trunk to 1 m in diameter. Numerous upright pneumatophores rise above soil from long shallow, horizontal roots. Bark brownish-gray, thin, becoming rough and blackish, or outer bark yellowish-green and inner bark whitish. Leaves opposite obviate or broadly oblong, 4–12 cm long, 2–6 cm wide, rounded at tip, acute or rounded at base, thick, leathery, edges slightly rolled under, upper surfaces shiny green and hairless, underneath with fine gray-green hairs and resin dots (Lemmens and Lemmens 1991). Cymes head like in panicles, upright near ends of twigs, to 15 cm long and wide. Flowers many 2–12 together, sessile, malodorous, 7–10 mm long, 12–15 mm across. Calyx 5-lobed, hairy on edges, with resin dots; corolla bell-shaped, tubular, yellow or yellow-brown, turning orange, with 4 unequal spreading lobes, stamens 4, inserted in notches of corolla tube; ovary conical, hairy, imperfectly 4-celled with 4 ovules, style threadlike; stigma 2-forked. Capsule broadly ovoid, flattened, 2.5 cm long. Seed 1, large, flattened, without seed coat, germinating in water (Little 1984).

2.4.3 Nursery and Planting Techniques of *Avicennia officinalis*

The crypto-viviparous propagules of species of *Avicennia* are usually collected from around the base of mother trees in August to September. When kept in air, these propagules lose their viability within a few days. These propagules may be directly planted into sheltered areas by 'dibbling' - where the propagule is gently pushed into the soft sediment until firmly wedged. 'Dibbling' is usually undertaken during neap tide periods to allow the seedling to develop roots. Pre-treatment of the propagules has also been used to decrease the establishment time (Little 1984, Khare 2008). Such treatment consists of placing the propagules in small nets and exposing them to daily tidal inundation to hasten the decay of the pericarp. Removal of the pericarp by pre-treatment reduces the establishment time to 2-3 days compared with the 5-6 days required where no pre-treatment is used. Alternately, propagules may be raised in nursery beds that are exposed to daily tidal inundation. Seedlings are raised for about 1-2 months after which they are gently pulled out of the ground and packed for transport to afforestation sites where they are usually planted out into holes of 3 cm diameter at a spacing of 1.0 x 1.0 m. Recent experiments using one year old seedlings (ranging in height from 70-90 cm) raised in nursery beds and planted out at Chittagong and Barisal, showed high survival rates, and may prove to be more suitable for areas where larger seedlings are required (Saenger and Siddiqi 1993).

2.4.4 Survival of *Avicennia officinalis*

Because of the highly dynamic nature of the Bangladesh coastline, survival of mangroves is generally poor and replacement planting often needs to be undertaken for up to 3 years. In sheltered localities, however, survival is usually around 70%. Long-term survival (i.e. between 5 and 15 years) is also highly variable but in experimental plots at Barisal, survival in 5-year old *Avicennia officinalis* ranged from 30-60%. (Saenger and Siddiqi 1993).

2.4.5 Optimal Planting Season:

Quantitative field trials of *Avicennia officinalis* have not yet been carried out with, maximal survival of this species also appears to occur during June to August. In some areas such as the Chittagong and Noakhali Divisions, winter planting is considered to result in higher survival rates but, to date, no experimental data support this view (Saenger and Siddiqi 1993).

2.4.6 Optimal Initial Spacing and Thinning Schedules

At 1.2 m x 1.2 m spacing, the trees become congested within 4 or 5 years. In such dense *Avicenna* plantations, thinning is carried out after 9-10 years when up to 50% of the stems may be removed. Thinning of these plantations largely consists of removing stunted trees and cutting smaller stems from multi-stemmed trees, and results in slightly reduced natural mortality together with marginal annual increases in height and girth (Khare 2008). In more widely spaced plantations, thinning is generally not required because of the relatively slow rate of tree growth and the loss of some trees in plantations due to stem borer attack ; the products of thinning yield low economic returns (Little 1984).

2.4.7 Distribution

Coasts of southern Asia to Australia and Oceania. From East Pakistan, Tanasserim, Andaman Islands, and Sri Lanka through coasts of Vietnam, Thailand, and Peninsular Malaysia to the Philippines, Sumatra, Madura, Java, Borneo, Celebes, Sunda Islands, Molucca Islands, and New Guinea; south in Australia to New South Wales (Khare 2008). Near sea level, to 50 m in Papua. Not widely introduced elsewhere (Little 1984).

2.4.8 Ecology

Estimated to range from Tropical Moist to Wet through Subtropical Moist to Wet Forest Life Zones, Indian mangrove is estimated to tolerate annual precipitation of 10 to 45 dm, annual temperature of 20 to 26°C, and pH of 6 to 8.5. Mostly on brackish or saline silts of depositing shores and marshes (Perry and Metzger 1980).

2.4.9 Uses

The wood, used to construct boats, houses, and wharves has been studied as a pulp source, and the bark and roots are used for tanning. The bark is used for dying cloth, the ash for washing it in India (Watt and Breyer-Brandwijk 1962). Javanese and others may consume the bitter fruits and seeds after rather elaborate processing. Branches are lopped and given to cattle for fodder. The wood has been recommended for creosoted paving blocks. Its wood is attractive enough of grain to be useful in cabinetry (Watt and Breyer-Brandwijk 1962, Perry and Metzger 1980, Grosvenor et al. 1995).

2.4.10 Folk Medicine

The fruits are plastered onto tumors in India. Indian mangrove is a folk remedy for boils and tumors (Duke et al. 2007). (Khare 2008) suggested that the roots are aphrodisiac. Unripe seeds are poulticed onto abscesses, boils, and smallpox sores. Indochinese use the bark for skin afflictions, especially scabies. According to (Perry and Metzger 1980), quoting other sources, "A resinous substance exuded from the bark acts as a contraceptive, and apparently can be taken all year long without ill effects. Philippines use the seed for ulcers, the resin for snakebite."(Perry and Metzger 1980)

2.4.11 Chemistry

Tanganyikan wood specimens (zero moisture basis) contained 54.7% cellulose, 2.3% ash (Scientific and Organization 1959). The wood ash is said to be rich in alkali. A green, bitter, medicinal resin oozes from the bark. Bark contains tannin and lapachol (Perry and Metzger 1980), but the tannin content may be only 2.5% (Scientific and Organization 1959, Rabe and Van Staden 1997).

CHAPTER THREE: METHODOLOGY

3.1 Description of the study site

The Plantation Trial Unit Division of Bangladesh Forest Research Institute established an experiment in the newly accreted (char) lands at Madarbunia, Rangabali island of Patuakhali district, Bangladesh with *Avicennia officinalis*. The total area of the experiment was 1.54 hectare. Rangabali island is located at 21°92′ N and 90°45′ E. The area forms the lowest landmass and is part of the delta of the extended Himalayan drainage ecosystem (Miah et al. 2014). The landscape has been formed by the combined actions of rivers Meghna, Brahmaputra and Ganges. The landscape is low-lying land, estuaries and inlands along the seacoast. The tidal floodplain has a distinctive, almost level landscape crossed by innumerable interconnecting tidal rivers and creeks. The estuarine islands are constantly changing shape and position as a result of river erosion and new alluvial deposition. The area is subject to flooding in the monsoon season (Das and Siddiqi 1985, Miah et al. 2014).

Tides are semi-diurnal and mean tide ranges from 2.2–4.0 m. In monsoon, water salinity ranges from 0.3–2.7% while in the dry season it ranges from 1.0–3.3% (Siddiqi and Khan 1990). Soil salinity varies remarkably between the monsoon and dry seasons. Soil salinity ranges from 0.3–4.2 dS·m-1 in December and reaches its peak from April-May when average salinity is as high as 9 dS·m-1 (Hasan 1987). Soil pH is slightly or moderately alkaline (7.5–8.0). Soil of the site is non-calcareous, grey floodplain and silt-clay-loam. Mean organic carbon in the soil is 1.4% and mean nitrogen content is 0.09%. The climate is humid. Temperatures range between 18 and 32°C. Annual rainfall varies from 2500–3000 mm (Siddiqi 2002). The experimental site was plain and gentle slope on the canal bank and the site was inundated throughout the year when the experiment was initiated.

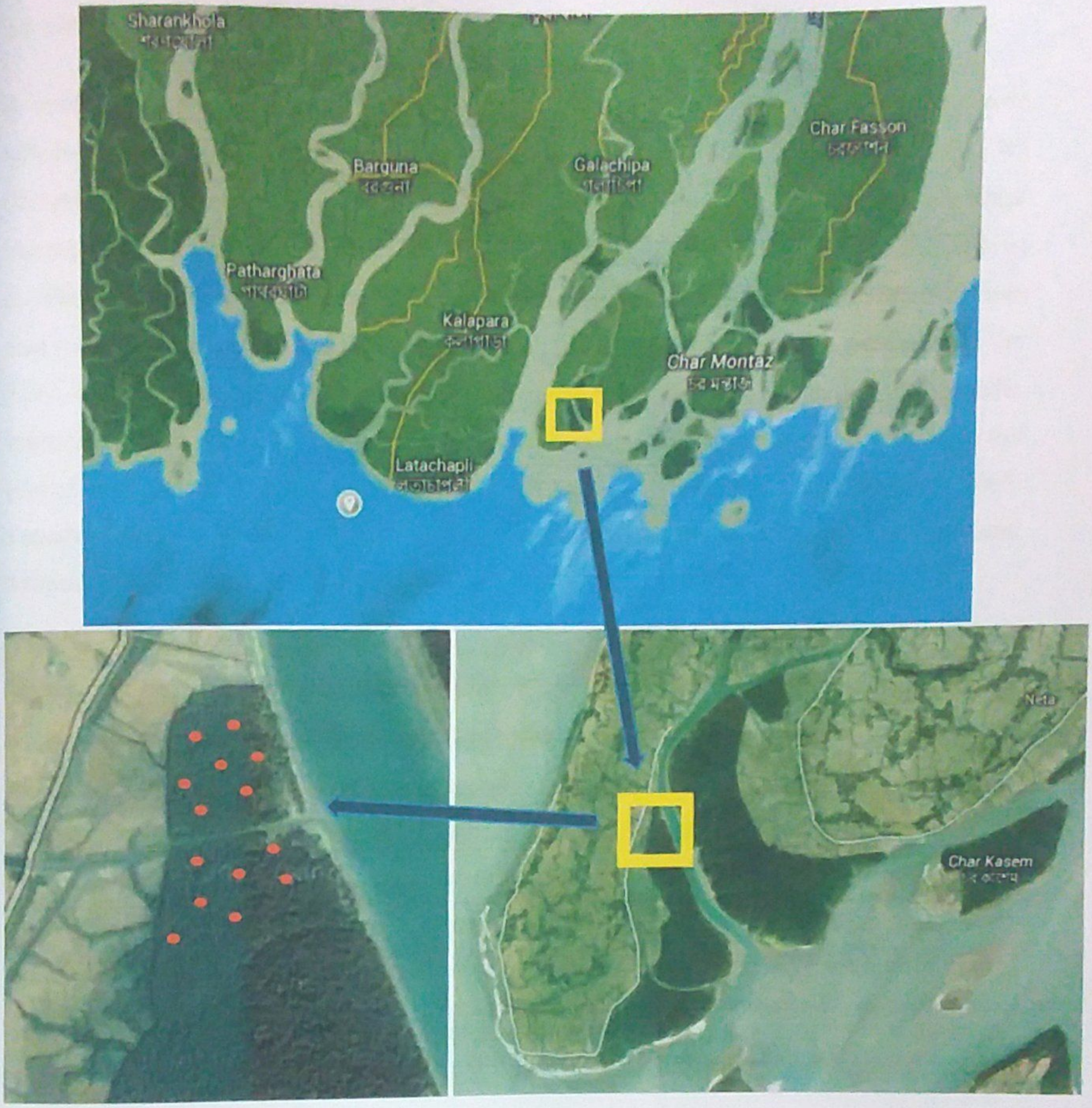

Fig. 3. Map of the Study Site (Madarbunia, Rangabali, Patuakhali) (Source: Google map)

3.2 Method

In order to investigate stand development in the monospecific mangrove stands of *Avicennia officinalis*, simulation experiments were performed using the individual-based model KiWi (Berger and Hildenbrandt 2000), which was originally applied for a neotropical mangrove forest but was found suitable for studying mangrove vegetation dynamics in various regions (Berger et al. 2004, Grimm et al. 2006, Berger et al. 2008, Piou et al. 2008, Khan et al. 2013). We used field data on plant development and floristic recruitment under natural conditions to parameterize the KiWi model so that the model actually mimics the dynamic stand growth in the monospecific mangrove stands (Table 1). The values of the model parameters were obtained according to the procedure of pattern oriented modelling (POM) (Grimm et al. 1996, Grimm and Railsback 2005, Fontalvo-Herazo et al. 2011, Khan et al. 2013) considering the observed density, basal area and biomass at known stand age of each species.

The KiWi model serves as a useful tool for the studies of stand growth and dynamics in mangroves, provided that the model parameters are tuned based on observed data from those particular mangroves. The advantage of the KiWi model is that the parameters are easy to obtain even with limited availability of data. This model is spatially explicit and it describes individual trees by their stem position, stem diameter, stem height and the so-called field of neighborhood (FON) defining the area within which a tree influences its neighbors and is influenced by them. The growth of trees depends on a tree's age, environmental conditions at stem position and neighborhood competition. Mortality generally increases with growth reduction (Berger and Hildenbrandt 2003).

The establishment of new saplings depends on both environmental conditions at the particular location and competition strength at this location exerted by the already established trees (described by the sum of their FONs).

Above-ground biomass was estimated using the allometric equations established using the data obtained through field data of *Avicennia officinalis* which was collected from Madarbunia, Rangabali island of Patuakhali district, Bangladesh.

Table 1. KiWi parameters used for the simulations of the mangrove *Avicennia officinalis* obtained according to procedure of pattern oriented modelling (POM) (Grimm et al. 1996, Fontalvo-Herazo et al. 2011, Khan et al. 2013).

Description	**Parameters**	**Value**	**References**
FON scaling factor	a	13.7	Field Data, Fontalvo-Herazo et al. 2011
FON scaling factor	b	0.72	Field Data, Fontalvo-Herazo et al. 2011
Minimum value of the FON	F_{min}	0.1	Berger & Hildenbrandt (2000)
Maximum value of the FON	F_{max}	1	Berger & Hildenbrandt (2000)
Average annual growth increment (cm/yr)	ΔD_{ave}	0.7605	Field data, Gong and Ong 1995
Maximum annual growth increment (cm/yr)	ΔD_{max}	1.6900	Field Data, Gong and Ong 1995
Growth constant	G	250	Botkin et al. (1972)
Maximum D_{130}* (cm)	D_{max}	150	Field Data, POM
Maximum height (cm)	H_{max}	2500	Field Data, POM
Constant in height to D_{130}	b_2	31.51	Botkin et al. (1972)
Constant in height to D_{130}	b_3	0.1050	Botkin et al. (1972)
Mortality threshold	ΔD_{crit}	0.3802	Fontalvo-Herazo et al. 2011
Resource sharing capacity	φ	**1.0**	POM

3.2.1 Above-ground Weight

Above-ground weight was calculated using the following formulas:

According to (Komiyama et al. 2005)

$$W_{top} = 0.247 \times \rho \times (D^2)^{1.23}$$

Here, ρ = wood density (gm cm^{-3}) (*Avicennia officinalis*= 0.59) [source: Global wood density database] and D = Diameter (cm).

According to (Chave et al. 2005)

$$AGW = \rho \times e^{(-1.349+1.98\ln(D)+0.207\ln(D^2)-0.0281\ln(D^3)}$$

Here, AGW= Above-ground weight, ρ= wood density and D= Diameter (cm).

3.3 Silvicultural treatments

Inspired by the suggestions of Gong and Ong (1995) four different types of silvicultural treatments were incorporated in the simulation experiments: (A) with recruitment without thinning, (B) with recruitment with thinning, (C) without recruitment without thinning, (D) without recruitment with thinning (Gong and Ong 1995). Simulations were performed in the monospecific stands of *Avicennia officinalis* with a rotation age of 40 years.

The first thinning was performed at 15 years using a 1.2 m stick circumference radius (Gong and Ong 1995) to determine the cutting area around a selected remaining tree and a second thinning was performed at 20 years with a 2 m stick circumference radius (Gong and Ong 1995). In the simulation experiments thinning operation was implemented using a virtual ecologist approach: trees having the maximum diameter within a circular area (based on the above-mentioned stick circumference radius) become the remaining trees and all other trees are removed at 15 and 20 years of stand ages, while the annual sapling recruitment rate is kept zero during thinning. The annual rate of sapling recruitment in the simulation runs was determined through field data on natural recruitments and relevant literatures (Kairo et al. 2002, Bosire et al. 2003, Bosire et al. 2006, Kairo et al. 2008).

CHAPTER FOUR: RESULTS AND DISCUSSION

4.1 Results

In the field work, we have taken the total height, DBH, Collar dia and Sectional dia of the *Avicennia officinalis* tree from the sampling plot for calculating the trunk volume. After calculation, tested many regression equations for estimating the relationship between calculated trunk volume and D^2H of different trees. From different regression analysis, chosen the best fitted according to the best R^2 value. The allometric equations having strong non-linear relationships (**R^2 = 0.9781**) for estimating the trunk volume (**Fig: 4**) used in this study was established based on wide ranges of tree diameter and height which offers better predictions of volume for *Avicennia officinalis.*

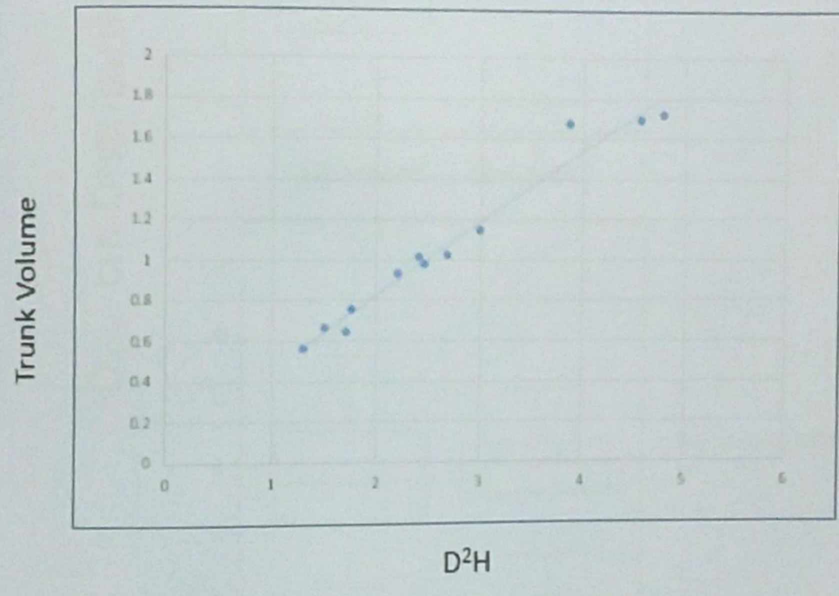

Fig. 4. Allometric relationship of trunk volume (m^3) in relation to tree diameter and height in Avicennia officinalis using field data (**$y = 0.4457x^{0.8946}$, $R^2 = 0.9781$**)

The model output and parameterization was evaluated based on monitoring data obtained in the field. The observed frequency distributions of D_{130} in the *A. Officinalis* stands showed no remarkable differences to that in the simulated results at stand ages of 23 and 24 years as revealed by the median values in the boxplot (Fig. 5). The mean differences between the observed and simulated D_{130} were, however, highly significant ($P < 0.001$) as tested with multiple comparison test (such as Tukey's HSD Post Hoc Test, LSD – Least Significant Difference test).

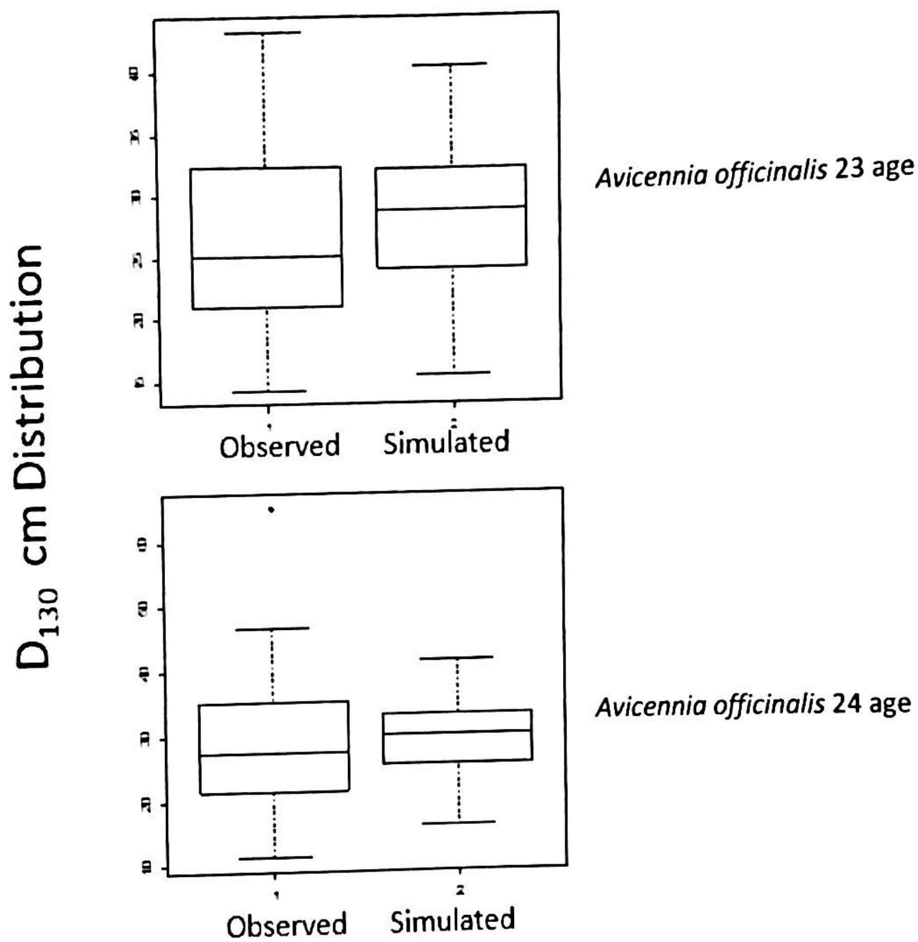

Fig. 5. Box plot of observed and simulated distribution of tree diameter (D_{130}) in Avicennia officinalis stands

The highest harvested above-ground biomass at 40-years-rotation was obtained through the silvicultural option 'with recruitment with thinning' and the lowest biomass obtained through the option 'without recruitment without thinning (**Fig. 6**). Highest basal area obtained through the silvicultural option 'with recruitment without thinning' and the lowest biomass obtained through the option 'without recruitment with thinning'. This suggests that in *Avicennia officinalis*, both thinning and recruitment provide significantly ($P < 0.001$) higher rotational yield as tested with multiple comparison test (such as Tukey's HSD Post Hoc Test; LSD – Least Significant Difference test) after a one-way-ANOVA test the above-ground biomass and basal area at 40 years of stand age

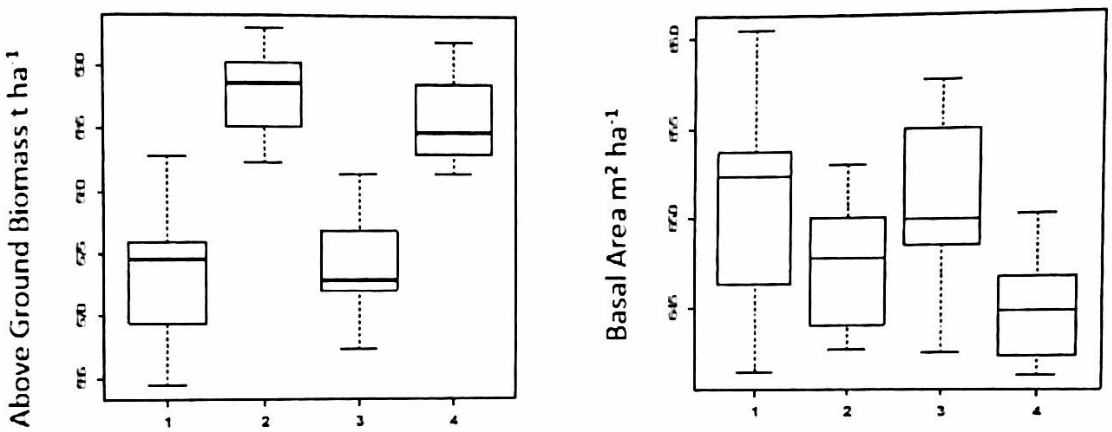

Fig. 6. Above-ground biomass and basal area in *Avicennia officinalis* over 40 year's rotation period

[Note: 1= *Avicennia officinalis* with recruitment without thinning; 2= *Avicennia officinalis* with recruitment with thinning; 3= *Avicennia officinalis* without recruitment without thinning; 4= *Avicennia officinalis* without recruitment with thinning]

Table 2. Comparison of standing biomass in aboveground components of different mangrove species at different places

Location	Stand Age	Species	Above Ground Biomass (t ha^{-1})	Mean annual increment (t/ha/yr)	Source
Potuakhali, Bangladesh	23	*Avicennia officinalis*	285.5042	12.41323	Present Study
Thailand	*15*	*Rhizophora apiculata*	159.0	10.6	(Christensen 1978)
Matang mangrove, Malaysia	*23*	*Rhizophora apiculata*	185.30	8.057	(Gong and Ong 1995)
Satun, Thailand		*Ceriops tagal*	92.24	-	(Komiyama et al. 2000)
Pulau langkawi, Malaysia		*Rhizophora mucronata*	115.56	-	(Norhayati and Latiff 2001)
Okinawa, Japan	*10*	*Kandelia obovata*	80.5	8.05	(Khan et al. 2009)
Kuala Selangor, Malaysia		Bruguiera parviflora	144.47	-	(Hossain et al. 2008)
Thailand		*Avicennia marina*	281.0	-	(Tamai et al. 1981)

For the purpose of the utilization, mangroves trees are classified into different utilization classes based on the tree diameter (D_{130}) such as (D_{130}>40 cm; D_{130} 30-40; D_{130} 20-30; D_{130} 10-20 and D_{130} <10). Among utilization classes, the highest proportions D_{130} 30-40 cm were obtained through the silvicutural treatment **B** (with recruitment with thinning) (Fig. 7) followed by silvicultural treatment D (without recruitment without thinning) in *Avicennia officinalis* (Fig. 7). Then the largest proportions of D_{130} 20-30 were obtained through the silvicultural treatment **C** (without recruitment without thinning) and treatment **A** (with recruitment without thinning).

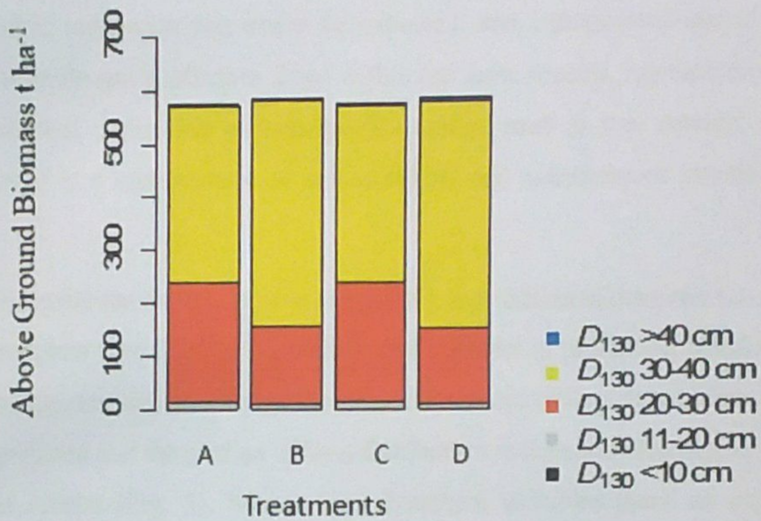

Fig. 7. Above-ground biomass in relation to utilization class of tree diameter (D_{130})

[Note: Different silvicultural treatment (**A:** With recruitment without thinning; **B:** With recruitment with thinning; **C:** Without recruitment without thinning; **D:** Without recruitment with thinning)]

4.2 Discussion:

In this study, trunk volume of different trees of *Avicennia officinalis* was best estimated by power curves. The best estimate of trunk volume ($R^2 = 0.9781$) was obtained using a combination of tree height and diameter at breast height (D^2H) as the independent variables (Kairo et al. 2009b). The strength of the reported allometric relationships of *Avicennia officinalis* ($R^2 = 0.9781$) in particular was probably due to the wide ranges of D_{130} classes (11.2-46.8 cm) of the datasets used. Hence, the maximum D_{130} in *Avicennia officinalis* was 46.8 cm only and the stand was eldest (23 yr old), a strong allometric regression can easily be expected, and extrapolated use of that regression becomes more reliable and applicable. Even within the same species, regression models will vary at different localities, depending on site-specific factors such as tree density, location on the ground, whether it is a monoculture or mixed forest, and management practices (Kairo et al. 2009a).

In *Avicennia officinalis* stands, the observed frequency distribution of diameter (D_{130}) well imitated and simulated patterns revealing the suitability of the model in predicting stand development of monospecific mangroves stands. Though the mean differences of D_{130} distribution in the simulated results were significant and the median of D_{130} distribution in the simulated results were very close to the observed results (Fig. 5). Some stand dynamics variables (such as mortality, sapling recruitments, and initial tree positions) in the simulated forest are probably responsible for the significant mean difference between the observed and simulated frequency distribution of diameter (Berger and Hildenbrandt 2000, 2003, Khan et al. 2013) and also due to the approximation of the model parameters according the procedure of pattern oriented modeling (Grimm et al. 1996, Grimm and Railsback 2005, Fontalvo-Herazo et al. 2011, Khan et al. 2013).

In *Avicennia officinalis* the highest harvested above-ground biomass obtained when there is availability of sapling recruitment and a periodic thinning is practiced at 15 and 20 yr stand ages (Fig. 6), and the lowest biomass obtained when there is an absence of sapling recruitment and there are no thinning operations. Highest basal area obtained when there is availability of sapling recruitment and no thinning operation. The lowest biomass obtained when there is absence of sapling recruitment and periodic thinning. This reveals that both thinning and natural regeneration has positive impact on yield in terms of biomass in *Avicennia officinalis*. Thinning normally avails more space and thus resources for growth, which leads to enhanced biomass increment, while continuous recruitment (natural regeneration) guarantees forest restocking.

The results also suggest that if high density mangrove plantations are raised upto the rotation age having sapling recruitments and periodic thinning, the dominant utilization class would be the second largest D_{130} 30-40 category and the overall yield of the largest D_{130}>40 cm category would be diminished (Fig. 7). D_{130} 20-30 category also found remarkably.

The species *A. officinalis* shows strong potential for biomass accumulation (453.603 t/ha in a 23 years old stands), which is higher than other species, such as *Rhizophora apiculata* (185.30 t/ha) in 23 year old stands (Gong and Ong 1995).

CHAPTER FIVE: CONCLUSION

This study has illustrated how mangrove simulation models can become a helpful tool for management forest practices. The potentiality of the KiWi simulation model as a tool for management might be further confirmed by the gathering of field data (i.e. species-specific data, monitoring of recruitment rates, forest plantation growth parameters, etc.) that permit a more precise parameterization and validation of model scenarios. This study is based on a combination of empirical and simulated data describing stand development of one of the major mangrove species in Bangladesh. Simulation experiments were used for providing a forecast of future stand development. The performance of various forest management options suggests that natural recruitment along with a periodic thinning offers higher yield than that with no silvicultural treatments. Generally thinning acts positively for most plant species. This study focused on a comprehensive analysis of stand development processes in the monospecific mangrove forests. Simulation experiments, tuned to observed configurations of the study sites, provided a forecast of the stand development to be expected in the future. The model output can be applied to explore a suitable method for restoration of degraded mangrove areas and to set a sound mangrove management strategy based on expected utilization classes as well as to predict future stand development. The findings of this study also has relevance to the studies on estimating carbon sequestration potentials of mangroves through converting the biomass to amount of carbon, which is ca. 50% of the biomass.

REFERENCES

Alongi, D. M. 2011. Carbon payments for mangrove conservation: ecosystem constraints and uncertainties of sequestration potential. Environmental Science & Policy 14:462–470.

Alongi, D. M., G. Wattayakorn, J. Pfitzner, F. Tirendi, I. Zagorskis, G. Brunskill, A. Davidson, and B. Clough. 2001. Organic carbon accumulation and metabolic pathways in sediments of mangrove forests in southern Thailand. Marine Geology 179:85–103.

Bandyopadhyay, A. 1998. Coastal soils and their management. International Book Distributors.

Barik, J., and S. Chowdhury. 2014. True mangrove species of Sundarbans delta, West Bengal, Eastern India. Check List 10:329-334.

Berger, U., and H. Hildenbrandt. 2000. A new approach to spatially explicit modelling of forest dynamics: spacing, ageing and neighbourhood competition of mangrove trees. Ecological Modelling 132:287–302.

Berger, U., and H. Hildenbrandt. 2003. The strength of competition among individual trees and the biomass-density trajectories of the cohort. Plant Ecology 167:89–96.

Berger, U., H. Hildenbrandt, and V. Grimm. 2002. Towards a standard for the individual-based modeling of plant populations: self-thinning and the field-of-neighborhood approach. Natural resource modeling 15:39-54.

Berger, U., H. Hildenbrandt, and V. Grimm. 2004. Age-related decline in forest production: modelling the effects of growth limitation, neighbourhood competition and self-thinning. Journal of Ecology 92:846–853.

Berger, U., V. H. Rivera-Monroy, T. W. Doyle, F. Dahdouh-Guebas, N. C. Duke, M. L. Fontalvo-Herazo, H. Hildenbrandt, N. Koedam, U. Mehlig, C. Piou, and R. R. Twilley. 2008. Advances and limitations of individual-based models to analyze and predict dynamics of mangrove forests: A review. Aquatic Botany 89:260–274.

Blasco, F., and M. Aizpuru. 2002. Mangroves along the coastal stretch of the Bay of Bengal: present status. Indian Journal of Marine Sciences 31:9-20.

Bosire, J. O., F. Dahdouh-Guebas, J. G. Kairo, and N. Koedam. 2003. Colonization of non-planted mangrove species into restored mangrove stands in Gazi Bay, Kenya. Aquatic Botany 76:267–279.

Bosire, J. O., F. Dahdouh-Guebas, J. G. Kairo, S. Wartel, J. Kazungu, and N. Koedam. 2006. Success rates of recruited tree species and their contribution to the structural development of reforested mangrove stands. Marine Ecology Progress Series 325:85–91.

Chave, J., C. Andalo, S. Brown, M. Cairns, J. Chambers, D. Eamus, H. Fölster, F. Fromard, N. Higuchi, and T. Kira. 2005. Tree allometry and improved estimation of carbon stocks and balance in tropical forests. Oecologia 145:87-99.

Das, S., and N. Siddiqi. 1985. The mangroves and mangrove forests of Bangladesh. Bulletin-Bangladesh Forest Research Institute. Mangrove Silviculture Division (Bangladesh). No. 2.

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

Duke, N. C., J. O. Meynecke, S. Dittmann, A. M. Ellison, K. Anger, U. Berger, S. Cannicci, K. Diele, K. C. Ewel, C. D. Field, N. Koedam, S. Y. Lee, C. Marchand, I. Nordhaus, and F. Dahdouh-Guebas. 2007. A world without mangroves? Science 317:41–42.

Eong, O. J. 1993. Mangroves - a carbon source and sink. Chemosphere 27:1097–1107.

Erdtman, G., and P. Sorsa. 1971. Pollen Morphology and Plant Taxonomy: An Introduction to Palynology. Pteridophyta. Almqvist & Wiksell.

Fontalvo-Herazo, M. L., C. Piou, J. Vogt, U. Saint-Paul, and U. Berger. 2011. Simulating harvesting scenarios towards the sustainable use of mangrove forest plantations. Wetlands Ecology and Management 19:397–407.

Gong, W., and J. Ong. 1995. The use of demographic studies in mangrove silviculture. Hydrobiologia:255–261.

Grimm, V., U. Berger, F. Bastiansen, S. Eliassen, V. Ginot, J. Giske, J. Goss-Custard, T. Grand, S. K. Heinz, G. Huse, A. Huth, J. U. Jepsen, C. Jørgensen, W. M. Mooij, B. Müller, G. Pe'er, C. Piou, S. F. Railsback, A. M. Robbins, M. M. Robbins, E. Rossmanith, N. Rüger, E. Strand, S. Souissi, R. A. Stillman, R. Vabø, U. Visser, and D. L. Deangelis. 2006. A standard protocol for describing individual-based and agent-based models. Ecological Modelling 198:115–126.

Grimm, V., K. Franka, F. Jeltsch, R. Brandla, J. Uchmariskib, and C. Wissela. 1996. Pattern-oriented modelling in population ecology. Science of the Total Environment 183:151–166.

Grimm, V., and S. Railsback. 2005. Individual-based Modelling and Ecology.

Grosvenor, P. W., A. Supriono, and D. O. Gray. 1995. Medicinal plants from Riau Province, Sumatra, Indonesia. Part 2: antibacterial and antifungal activity. Journal of Ethnopharmacology 45:97-111.

Hasan, M. 1987. Preliminary report on coastal afforestation site. Drigo, R., Latif, MA, Chowdhury, JA and Shahaduzzaman, M., The Maturing Mangrove Plantations of the Coastal Afforestation Project. Field Document:64-66.

Islam, S., M. Miah, M. Habib, M. Moula, and M. Rasul. 2013. Growth performance of underplanted mangrove species in Sonneratia apetala (Keora) plantations along the western coastal belt of Bangladesh. Bangladesh Journal of Forest Science 32:26-35.

Kairo, J. G., J. Bosire, J. Langat, B. Kirui, and N. Koedam. 2009a. Allometry and biomass distribution in replanted mangrove plantations at Gazi Bay , Kenya. Aquatic Conservation: Marine and Freshwater Ecosystems 19:63–69.

Kairo, J. G., F. Dahdouh-Guebas, P. O. Gwada, C. Ochieng, and N. Koedam. 2002. Regeneration status of mangrove forests in Mida Creek, Kenya: a compromised or secured future? Ambio 31:562–568.

Kairo, J. G., J. K. S. Lang'at, F. Dahdouh-Guebas, J. Bosire, and M. Karachi. 2008. Structural development and productivity of replanted mangrove plantations in Kenya. Forest Ecology and Management 255:2670–2677.

Kairo, J. G., C. Wanjiru, and J. Ochiewo. 2009b. Net Pay: Economic Analysis of a Replanted Mangrove Plantation in Kenya. Journal of Sustainable Forestry 28:395–414.

Khan, M. N. I., S. Sharma, U. Berger, N. Koedam, F. Dahdouh-Guebas, and A. Hagihara. 2013. How do tree competition and stand dynamics lead to spatial patterns in monospecific mangroves? Biogeosciences 10:2803–2814.

Khan, M. N. I., R. Suwa, and A. Hagihara. 2007. Carbon and nitrogen pools in a mangrove stand of *Kandelia obovata* (S., L.) Yong: vertical distribution in the soil–vegetation system. Wetlands Ecology and Management 15:141–153.

Khare, C. P. 2008. Indian medicinal plants: an illustrated dictionary. Springer Science & Business Media.

Köhler, K., and A. Huth. 2004. Simulating growth dynamics in a South-East Asian rainforest threatened by recruitment shortage and tree harvesting. Climatic Change 67:95–117.

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

Kristensen, E., S. Bouillon, T. Dittmar, and C. Marchand. 2008. Organic carbon dynamics in mangrove ecosystems: A review. Aquatic Botany 89:201–219.

Latif, M., and S. Z. Islam. Growth, yield, volume, and biomass equation and tables for important trees in bangladesh.

Lemmens, R., and R. Lemmens. 1991. Plant resources of South-East Asia. Pudoc Wageningen.

Little, E. L. 1984. Common fuelwood crops. A handbook for their identification. Common fuelwood crops. A handbook for their identification.

Miah, M. A. Q., S. A. Islam, M. A. Habib, and M. G. Moula. 2014. Growth performance of Avicennia officinalis L. And the effect of spacing on growth and yield of trees planted in the Western coastal belt of Bangladesh. Journal of Forestry Research 25:835-838.

Pathak, K. D., and I. Mehta. 2011. Socio-Economic and Ecological Benefits of Mangrove Plantation: A Study of Community Based Mangrove Restoration Activities in Gujarat. Esocialsciences.

Perry, L. M., and J. Metzger. 1980. Medicinal plants of East and Southeast Asia: attributed properties and uses. MIT Press: Cambridge, Mass. & London, England.

Piou, C., U. Berger, H. Hildenbrandt, and I. C. Feller. 2008. Testing the intermediate disturbance hypothesis in species-poor systems: A simulation experiment for mangrove forests. Journal of Vegetation Science 19:417–424.

Polidoro, B. A., K. E. Carpenter, L. Collins, N. C. Duke, A. M. Ellison, J. C. Ellison, E. J. Farnsworth, E. S. Fernando, K. Kathiresan, and N. E. Koedam. 2010. The loss of species: mangrove extinction risk and geographic areas of global concern. Plos one 5:e10095.

Rabe, T., and J. Van Staden. 1997. Antibacterial activity of South African plants used for medicinal purposes. Journal of Ethnopharmacology 56:81-87.

Saenger, P. 2002. Mangrove ecology, silviculture and conservation.

Saenger, P., and N. Siddiqi. 1993. Land from the sea: the mangrove afforestation program of Bangladesh. Ocean & Coastal Management 20:23-39.

Scientific, C., and I. R. Organization. 1959. Annual Report of the Commonwealth Scientific & Industrial Research Organization. Csiro.

Siddiqi, N. 2002. Development and sustainable management of coastal plantations in Bangladesh. Journal of Asiatic Society of Bangladesh (Science) 28:144-166.

Siddiqi, N., and M. Khan. 1990. Growth performance of mangrove trees along the coastal belt of Bangladesh. Mangrove Ecosystems Occasional Papers 8:5-14.

Siddiqi, N. A., and C. Bisvabidyālaẏa. 2001. Mangrove forestry in Bangladesh. Institute of Forestry & Environmental Sciences, University of Chittagong.

Watt, J., and M. Breyer-Brandwijk. 1962. The Medicinal and Poisonous Plants of Southern and Eastern Africa (2nd. Edn.) E and S Livingstone Ltd. Edinburgh and London:1457.