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Dedicated To...

My Beloved Friend

Shekh Muhammad Hadiul Islam

(Rest in Peace)

(1993-2011)

ABSTRACT

Monospecific mangrove stand development requires high-resolution temporal data. However, due to less availability of long-term monitoring, it is difficult to gather temporal data. In Bangladesh, several plantations of *Sonneratia apetala* have been raised with a large-scale plantation along the coastal belt. An individual-based model (KiWi 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. In this study we selected several sivilicultural approaches (with or without thinning and with or without recruitment) to compare the development of planted forest in terms of forest management. The output and parameterization of the model was evaluated based on monitoring data obtained in the field. The highest harvested aboveground biomass as well as basal area at 40-years-rotation was obtained through the silvicultural option 'with recruitment with thinning' and the lowest biomass and basal area were obtained through the option 'without recruitment without thinning'. This reveals that both thinning and natural regeneration has positive impact on yield in terms of biomass as well as basal area in *Sonneratia apetala*. Thinning normally avails more space and thus resources for growth, which leads to enhanced biomass increment. Simulation experiments, tuned to observe configurations of the study sites, provided a forecast of the stand development to be expected in the future.

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Atikur Rahman

APPROVAL

This is to certify that, Atikur Rahman, Student ID: 110521 has prepared this thesis entitled **"Effect of Thinning and Natural Regeneration on Yield in *Sonneratia apetala* Buch.-Ham Plantations Using Monte Carlo Simulation"** under my direct supervision and guidance. Project thesis submitted to the Forestry and Wood Technology Discipline, Khulna University, Khulna, Bangladesh in partial fulfilment of the requirements for the four years professional B.Sc. (Hons.) degree in Forestry. I have approved the style and format of the project thesis.

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DECLARATION

I, **Atikur Rahman**, hereby declare that this project thesis is based on my original work except 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 Khulna University or other institutions.

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10.05.2016

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CHAPTER 1: INTRODUCTION

1.1 BACKGROUND OF THE STUDY

Mangroves are the main forest cover and woody plants in the inter tidal zones, which grow between land and sea in the tropical and subtropical coasts where they exist or resist by developing highly physiological and morphological adaptations process in different extremes conditions i.e. strong winds, high salinity, extreme tides, high temperature and muddy, anaerobic soils (Alongi *et al.*, 2000; Kathiresan and Bingham, 2001; Machiwa and Hallberg, 2002; Mumby *et al.*, 2004). Mangroves play some important functions in the forest ecosystem which are associated with nearby marine environment and helps to atmospheric carbon sequestration (Eong, 1993; Alongi *et al.*, 2001; Khan *et al.*, 2007; Bouillon *et al.*, 2008; Kristensen *et al.*, 2008; Alongi, 2011; Donato *et al.*, 2011) and improve socio economic conditions of the neighbouring local community (Rönnbäck, 1999; Primavera, 2005; Kairo *et al.*, 2009b). There are many reasons for loss of mangrove forest in the global environment (Valiela *et al.*, 2001; Duke *et al.*, 2007). The possible reasons are habitat destruction through human encroachment, diversion of fresh water for irrigation and land reclamation and conversion for agriculture, aquaculture and urbanization (Primavera, 2000; Saenger, 2002; Primavera, 2005; Kristensen *et al.*, 2008). So it is imperative to find out the possible ways to control the loss of mangroves Therefore, mangrove management has been become an important issues in management of resource and economy in the coastal areas of Bangladesh.

The Bangladesh coastline extends over 710 km long along the Bay of Bengal (Miah *et al.*, 2014) and is comprised of various forms of accreted (char) lands and off-shore islands (Siddiqi, 2001). The coastal areas of Bangladesh have suffered severe cyclone damage almost annually since cyclone recordings began in 1584 (Saenger and Siddiqi, 1993). During 1966, for the protection from cyclone damage, Bangladesh Forest Department commenced a programme of planting mangroves outside the protective coastal embankments in order to provide greater protection for inhabited coastal areas (Rachid, 1977; Saenger and Siddiqi, 1993). The initial objective of the afforestation program was to create a shelterbelt to protect the lives and properties of the coastal communities (Saenger and Siddiqi, 1993; Siddiqi, 2002; Iftekhar and Islam, 2004).

The general intensity of natural regeneration and resultant sapling recruitments would play an important role in the yield development which is generally influenced by the growth and overall tree size distribution in the whole stand and also influence the management priorities of mangrove plantations (Khan *et al.*, 2012). Thinning schedule has some effects on the yield management in the mangrove plantation (Fontalvo-Herazo *et al.*, 2011). In such *Sonneratia apetala* dense plantations, 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 (Saenger and Siddiqi, 1993). However, an individual based model, which is mentioned above that explicitly, presents the effect of sapling recruitment patterns on quality and quantity of yield.

For mangrove stand development needs large scale regular data. But it is difficult to gather regular data because of less availability of long-term monitoring. In Bangladesh, several plantations of *Sonneratia apetala* have been raised with a large-scale plantation along the coastal belt. The species in highly suitable in the newly formed muddy land in the coastal belt. Coastal afforestation programme was first initiated along the coastal belt of Bangladesh in 1966 and it is still going on (Islam *et al.*, 2012). The development of monospecific stands, these data sets can be used to parameterize the KiWi model that starts from the conditions used for planting mangroves over a period of years. When the model is parameterized, some silvicultural options such as with or without recruitment and with and without thinning. A simulation experiment helps to experiment with long term monitoring and make suitable management decisions.

1.2 OBJECTIVES OF THE STUDY

The objectives of the study are given below:

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

CHAPTER 2: LITERATURE REVIEW

In literature review, objectives were set to have the broader idea about coastal afforestation in Bangladesh, success, importance and in depth information about *Sonneratia apetala* in coastal plantation projects and to understand the modelling for testing mangrove forest structure development and various forest management options in the coastal areas of Bangladesh. Thus, this chapter includes three sections each with several subsections. The first section gives the detailed information about coastal plantation status in Bangladesh. The second and third section represents the species description about *Sonneratia apetala* and the modelling testing for mangrove forest structure development and various forest management options using field data respectively.

2.1 COASTAL PLANTATION IN BANGLADESH

The coastal area of Bangladesh lies within the tropical zone between 21-23°N and 89-93°E (Saenger and Siddiqi, 1993). The coastline is approximately 710 kilometres long and the coastal zone covers an area of about 2.85 million hectares, which is 23 percent of the country's total area. The coastal region includes offshore islands, mudflats, chars and new accretions (Islam, 2012).

The coastal areas of Bangladesh have suffered severe cyclone damage almost annually since cyclone recordings began in 1584. During the period from 1960 to 1970, eight severe cyclones were recorded, with the intense cyclone and associated storm surge of November 1970 reported to have caused the deaths of about 300,000 people; current estimates of the April 1991 cyclone yield a similar figure (Saenger and Siddiqi, 1993).

The protection from cyclone damage afforded by the Bangladesh Sundarbans mangrove forests, a continuous natural mangrove forest of 5,800 km^2 in the southwest of Bangladesh, led the Forest Department in 1966 to commence a programme of planting mangroves outside the protective coastal embankments in order to provide greater protection for inhabited coastal areas. These initial mangrove plantings were highly successful and led to the development of a large-scale mangrove afforestation program. Now the coastal plantations established in the coastal areas are administered by four Coastal Afforestation Divisions namely, from east to west, Chittagong, Noakhali, Barisal and Patuakhali and subdividing into 28 forest Ranges and 198 beats (Drigo, 1987). Till 2010, an area of 170,000 ha coastal area has been planted, although there are plantation failures over a considerable area (Aziz, 2010). In this context, over the last four decades the Forest Department has successfully implemented several massive projects and has established some 148 000 hectares of mangrove plantations scattered over on and offshore areas mostly along the central part of the coast (Islam, 2012).

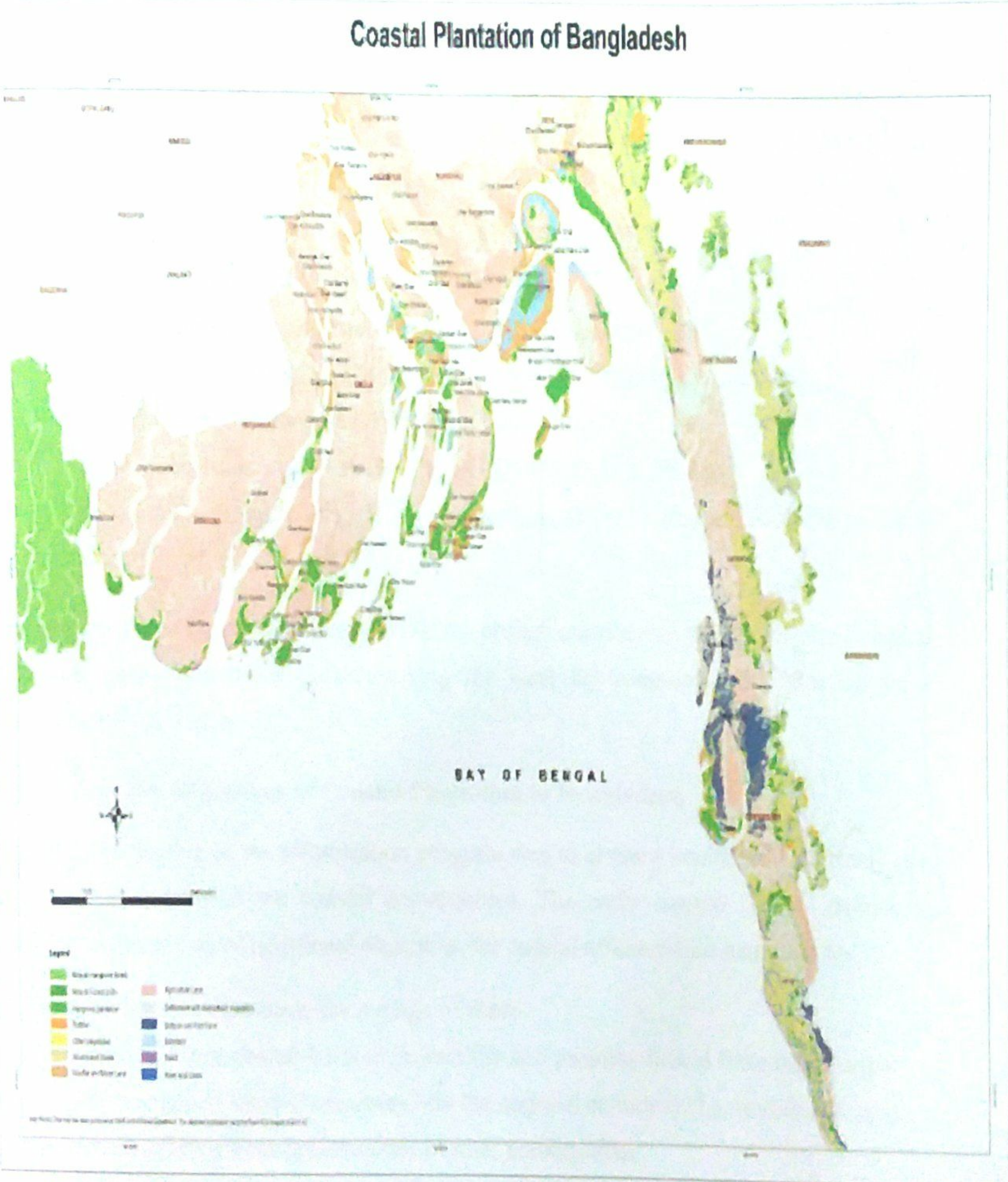

Figure 2.1: Map of Coastal plantations in Bangladesh (Source: Bangladesh Forest Department)

2.1.1 Coastal Plantation Projects executed by the Forest Department, Bangladesh

The coastal afforestation program was started in 1965-66 and the Government of Bangladesh has a unique afforestation program on the newly forming lands of the Bay of Bengal. The government has decided that all new accretions in the Bay will be afforested to ensure their stabilizations and to ensure further accretions (Rachid, 1977).

The list of coastal plantation projects executed by the forest department was given below:

- Afforestation in the coastal belt and offshore islands (1960–61 to 1964–65).
- Afforestation in the coastal belt and offshore islands (1965–66 to 1969–70).
- Afforestation Project in the coastal regions of Chittagong, Noakhali, Barisal and Patuakhali (1974–75 to 1979–80).
- Mangrove Afforestation Project (1980–81 to 1984–85).
- Second Forestry Project (1985–86 to 1991–92).
- Forest Resources Management Project (1992–93 to 2001–2002).
- Extended Forest Resources Management Project (2002–03 to 2003–04).
- Coastal Green Belt Project (1995–96 to 2001–02).
- Coastal Char Land Afforestation Project (2005–05 to 2009–10).
- Management Support Project for Sundarbans Reserve Forest (2005–06 to 2009 10).

Bangladesh forest department executed above project considering the condition of coastal area with some objectives for developing the rural environment and protection from environmental hazards.

2.1.2 Goals and Objectives of Coastal Plantation in Bangladesh

The initial objective of the afforestation program was to create a shelter belt to protect the lives and properties of the coastal communities. The early success of the plantations resulted in the setting of additional objectives for coastal afforestation including to-

- Provide forest products for a range of uses;
- Develop forest shelter-belts to protect life and property inland from tidal surges;
- Inject urgently needed resources into the national economy (i.e. timber and land);
- Create employment opportunities in rural communities;
- Create an environment for wildlife, fishes, and other estuarine and marine fauna.

- Conservation and stabilization of newly accreted land, and acceleration of further accretion with the ultimate aim of transferring a large part of this land to agriculture.

2.1.3 Commonly Used Species for Coastal Plantation Projects in Bangladesh

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 11 or so species occur frequently enough to sustain silviculture. Commercially important mangrove species, viz, *Sonneratia apetala, Avicennia officinalis, A. marina, A. alba, Amoora cucullata, Bruguiera sexangula, Excoecaria agallocha, Xylocarpu smekongensis, Heritiera fomes, Ceriops decandra and Nypa fruticans* were planted on new accretion. 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. 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 (Saenger and Siddiqi, 1993). For this study *S. apetala* was choosen for the better performance in monospecific stands.

2.1.4 Challenges of Coastal Plantation in Bangladesh

The shoreline of Bangladesh is about 700 km long. The coastal areas with mangrove plantations are regularly inundated during high tide. However, the forest floor of the older plantations is not submerged in the dry seasons during neap tides. Soil texture ranges from silty loam to silty clay loam. pH varies between 7.5 and 8.2. Afforestation is carried out on a very unstable environment. Thus, there will always be a risk of some plantation loss during the time it takes the trees to reach maturity. Both *S. apetala* and *A. officinalis* are pioneer species in the ecological succession in the natural mangroves of Bangladesh. These species grow well on new accretions with regular inundation. They are strong light demanding. These might be the reasons why these species have performed better. In the case of *S. apetala* plantation is carried out using seedlings, whereas, this is done by dibbling seeds into the mud for *A. officinalis* (Banglapedia., 2014).

2.2 KEORA (*Sonneratia apetala*)

2.2.1 Taxonomic Information

Kingdom: Plantae

Phylum: Tracheophyta

Class: Magnoliopsida

Order: Myrtales

Family: Lythraceae

Genus: Sonneratia

Species: *Sonneratia apetala*

Botanical name: *Sonneratia apetala* Buch.-Ham (Kathiresan, 2010).

2.2.2 Description

Sonneratia apetala is a small to medium size columnar tree, which can attain a height of about 20 m and a girth of about 2.5 m. The tree occurs on newly accreted soil in moderately to strongly saline areas and is considered as a pioneer species in ecological succession. The leaves are simple opposite, entire and leathery. Bark thin, light brown, irregularly fissured. Flowers apetalous, cream coloured, arranged in axillary 3-flowered of 7 flowered dichasial cyme. The flowers have no petals, but 4 prominent green sepals. Cream colored mass of stamens give the flowers a cream colored look. The most interesting part of the flower is the style, which consists of a white, 2-3 cm long, curved, stigma, falttened like umbrella or mushroom. The upper portion is reddish in color. Fruit is 1-2 × 2-2.5 cm in diameter. Seeds are typically U-shaped or sickle-shaped, 8-9.5 mm (FlowersofIndia., 2005).

2.2.3 Distribution

This species is found in Bangladesh, Myanmar, and India, including the Andaman and Nicobar islands. It has been introduced into Fujian and Guangdong provinces China (Kathiresan, 2010).

2.2.5 Habitat and Ecology

This species is found in the upstream estuarine zone in the low to mid-intertidal region (Robertson and Alongi, 1992). This species is fast-growing species and hardy, but the seed viability is low (less than three months). It can form monotypic stands, and is a pioneering species that colonizes on newly formed mudflats (Terrados *et al.*, 1997). It grows up to 20 m, but more commonly grows to between 12 and 15 m (Kathiresan, 2010).

2.2.5 Nursery and Planting Techniques

Mature green fruits of keora (*Sonneratia apetala*) are generally collected during September and they are heaped for 20 days to allow the pericarps to decay. They are then rubbed and washed in water to separate the small seeds from the rotted fleshy portion of the fruits. About 1 kg of green fruit will yield about 275 g or 7,500 seeds. These seeds maintain their viability for about one month (Saenger and Siddiqi, 1993).

Approximately 7-8 kg of these seeds are broadcast onto intertidal nursery beds 1.2 m wide and 12 m long, slightly raised above the surrounding sediment. The beds are usually encircled by low (15 cm) earthen walls, which retain water pumped into the enclosures during unusually dry periods.

Germination onset and success is largely controlled by salinity, which needs to be maintained below 20ppt; above 20ppt germination performance declines rapidly.

The seedlings are allowed to grow for about 10 months and from each nursery bed about 2,350 seedlings of the desired height (30-60 cm) become available for the next suitable planting season i.e. from July to August. At this time, the seedlings are gently pulled out of the ground and packed for transport to selected afforestation sites. Generally, one such nursery bed provides sufficient seedlings to plant an area of 0.4 ha at the usual spacing of 1.2 x 1.2 m. The uprooted seedlings can be stored in the shade for up to six days without any significant losses. As discussed later, this approach results in adequate survival rates for a species that has not been cultivated elsewhere (Saenger and Siddiqi, 1993).

2.2.5 Traditional Uses

This species is sometimes used for fuel wood and construction. The fruits of this species are eaten (pickled), and in some places the flowers are local sources of honey (Kathiresan, 2010). Leaf decoction of the keora tree helps to cure stop haemorrhage and cures blisters. Fruits are also used to prevent in diarrhoea (Ray, 2014). Traditionally, the species is used as fuel wood, furniture making and boat building. However, it can be used for making packing boxes, panelling and other purposes (Islam *et al.*, 2011).

2.3 Mangrove Simulations Modeling

Model simulations have been useful in synthesizing current knowledge about mangrove forest dynamics (Berger *et al.*, 2008). The modelling approach is suitable for simultaneously evaluating the effects of environmental changes and disturbances on ecological processes such as tree recruitment, establishment, growth, productivity, and mortality. Such estimates on the sustainability of mangrove resources may contribute to evaluating impacts of mangrove degradation to socio-economic systems (Alongi *et al.*, 2002; Berger *et al.*, 2008). Consequently, simulation models have been proposed as tools for developing management plans for mangrove protection, rehabilitation and restoration (Field, 1999; Doyle *et al.*, 2003; Twilley and Rivera-Monroy, 2005). The first pioneers in mangrove simulation models were (Lugo *et al.*, 1976) who used a process-based model to simulate the effects of upland run-off and tidal flushing on the biomass production of an over-washed mangrove wetland. (Burns and Ogden, 1985) used a Leslie-Matrix model to predict the development of an *Avicennia marina* monoculture assuming an exponential population growth. (Clarke, 1995) used a Lefkovich matrix for predicting the recovery of an *Avicennia germinans* population following disturbances differing in strength. There are also a few static trophic models estimating matter and energy flow in mangrove ecosystems (Ray *et al.*, 2000; Vega-Cendejas and Arreguın-Sánchez, 2001; Wolff, 2006). Currently there are only three spatially explicit individual based simulation models (IBMs) describing Neotropical mangrove forests: FORMAN, KIWI, and MANGRO (Chen and Twilley, 1998; Berger and Hildenbrandt, 2000; Doyle *et al.*, 2003).

A model of mangrove forest dynamics, KiWi, which is based on the FON (Field of Neighbour) approach (Berger *et al.*, 2002). Both KiWi and FON are described in details **(Chapter 3 Section 3.4)**.

CHAPTER 3: MATERIALS AND METHODS

3.1 DESCRIPTION OF THE STUDY SITE

The study site was located in the newly accreted (char) lands at Madarbunia, Rangabali island of Patuakhali district, Bangladesh. Rangabali island is located at 21°92′ N and 90°45′ E. 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 (Miah *et al.*, 2014).

The area forms the lowest landmass and is part of the delta of the extended Himalayan drainage ecosystem. 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. Tides are semi-diurnal and mean tide ranges from 2.3–4.0 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 $dS{\cdot}m^{-1}$ in December and reaches its peak from April-May when average salinity is as high as 9 $dS{\cdot}m^{-1}$ (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).

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3.2 SAMPLE PLOT LAYOUT AND MAPPING PLOT

Field data were collected from 30 sample plots (10m×10m each) of *Sonneratia apetala* stands (14, 17, 22, 26 and 27 years old). Then proper identification of tree positions, DBH (diameter at breast height, i.e. 1.3m from the ground), height of each single trees were recorded in study site by using different instruments (i.e. Diameter tape; Measuring tape; Spiegel relaskop; Haga altimeter). Twenty sample trees having wide range of DBH were selected for measuring sectional diameter. In addition, for the parameterization of the KiWi model field investigations were made in *Sonneratia apetala* stands of different plantation ages.

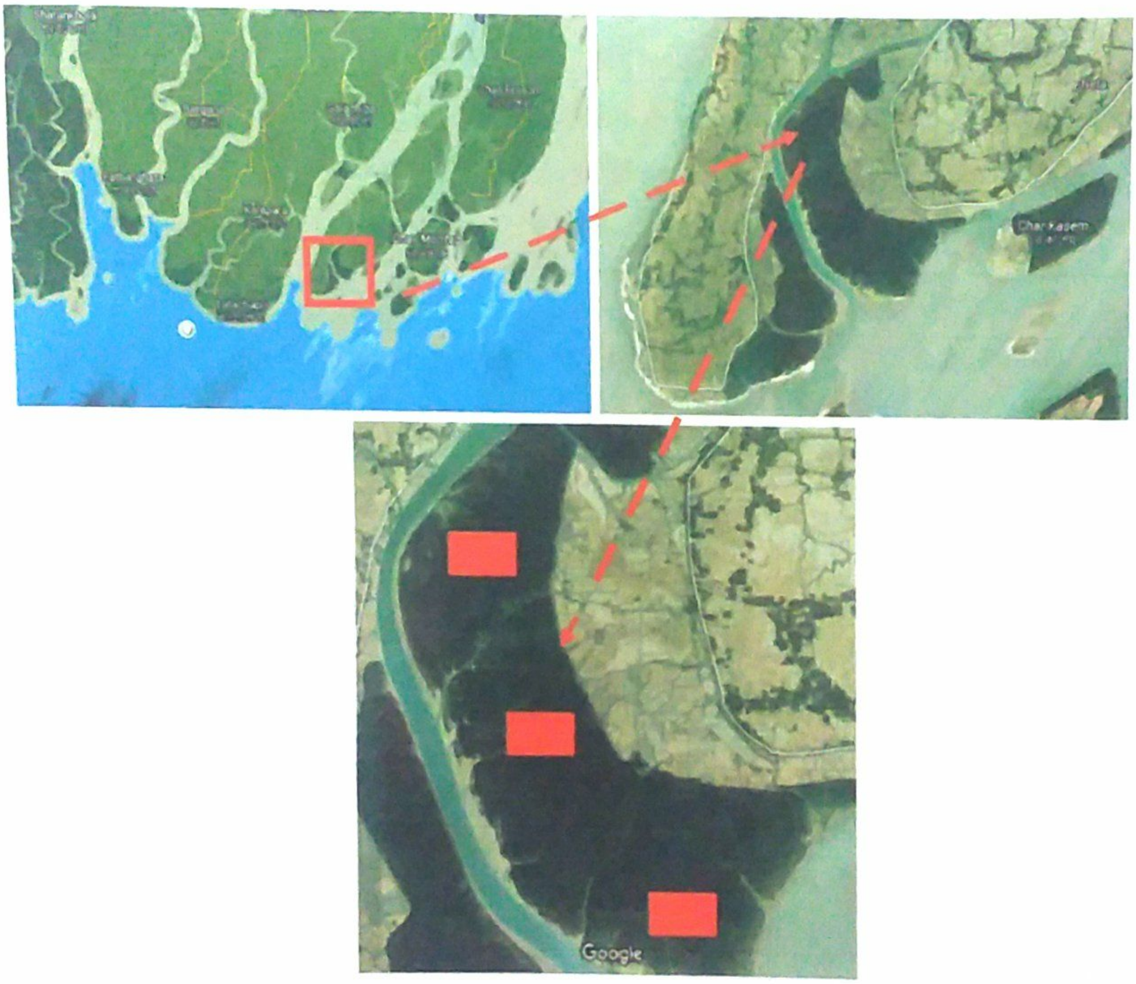

Figure 3.1: Map of the study site (Madarbunia, Rangabali, Patuakhali) and Location of sample plots (in Red colours) (Source: Google Map and Google Earth).

3.3 MODELING STAND GROWTH AND DEVELOPMENT

An individual-based, spatially explicit model is the KiWi model originally developed to study mangrove forest dynamics (Berger *et al.*, 2004) and simulation experiments were performed using this model to investigate the stand development in the monospecific mangrove plantation stands (Berger and Hildenbrandt, 2000). KiWi model has also been used to address theoretical issues of self-thinning trajectories and dynamics of size distributions in even-aged stands (Berger and Hildenbrandt, 2003); asymmetric competition (Bauer *et al.*, 2004) and cyclic population dynamics in perennials (Berger *et al.*, 2004). 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 4.1)**. The values of the model parameters were obtained according to the procedure of pattern oriented modelling (POM) (Grimm *et al.*, 1996; Grimm *et al.*, 2005; Fontalvo-Herazo *et al.*, 2011; Khan *et al.*, 2013) considering the observed density, basal area and biomass at known stand age of *Sonneratia apetala.*

The KiWi model was particularly developed for analyzing the influence of local tree-to-tree interactions on mangrove forest dynamics (Berger and Hildenbrandt, 2000). The model has been successfully used for studying trajectories of secondary mangrove succession (Berger *et al.*, 2006) and recovery after hurricane occurrence (Piou *et al.*, 2008). 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 neighbourhood (FON) defining the area within which a tree influences its neighbours and is influenced by them. Tree growth depends on nutrients, neighbour competition (FON overlap), tree ages and environmental conditions at stem position. Tree mortality due to growth suppression and growth reduction. 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).

3.4 INDIVIDUAL-BASED MANGROVE SIMULATION MODELLING (KIWI MODEL)

Individual-based models became widely accepted in ecology during the, 1990s and are recognized as suitable tools for simulating the variability of individual plants or animals and its influence on complex life systems (DeAngelis and Gross, 1992; DeAngelis and Mooij, 2005). These models integrate different hierarchical levels of ecological processes, and they can be directly and relatively simply parameterized. They have an intrinsic ability to include both temporal and spatial scales. All these features make them powerful "virtual laboratories", which help testing hypotheses about specific behaviours and traits of individuals, and advance ecological principles for both basic ecological knowledge and the restoration of biological diversity (Berger *et al.*, 2008).

3.4.1 The FON Modeling Approach

FON is the abbreviation for 'field of neighbourhood.' This particular approach is based on the description of a 'zone of influence' (ZOI) according to which an individual is firstly characterized in terms of its (stem-) position. A circular zone whose diameter increases with the size of the individual surrounds this position. This zone defines the area within which the individual interacts with its environment and with potential neighbours. The extension of the FON approach as compared to the ZOI approach consists in a competition function of field that is defined within the ZOI. This field describes the location-dependent competition strength exerted by the individual on its neighbours and its environment. Assuming that the neighbourhood fields of all individuals superimpose, two quantities are important (Figure: 3.2): F(x, y) quantifies the competition strength exerted by the established individuals at position (x, y), whereas FA is a measure of the competition which an individual encounters from its neighbours. It is summarized from the overlapping parts of the neighbourhood fields of all competitors and is related to the ZOI of the individual in focus, i.e., is normalized by the ZOI area A of the target plant. F(x, y) and FA thus indicate the neighbourhood situation for a point and/or an individual defined in terms of the number of neighbours, their size and their spatial configuration (Berger *et al.*, 2002).

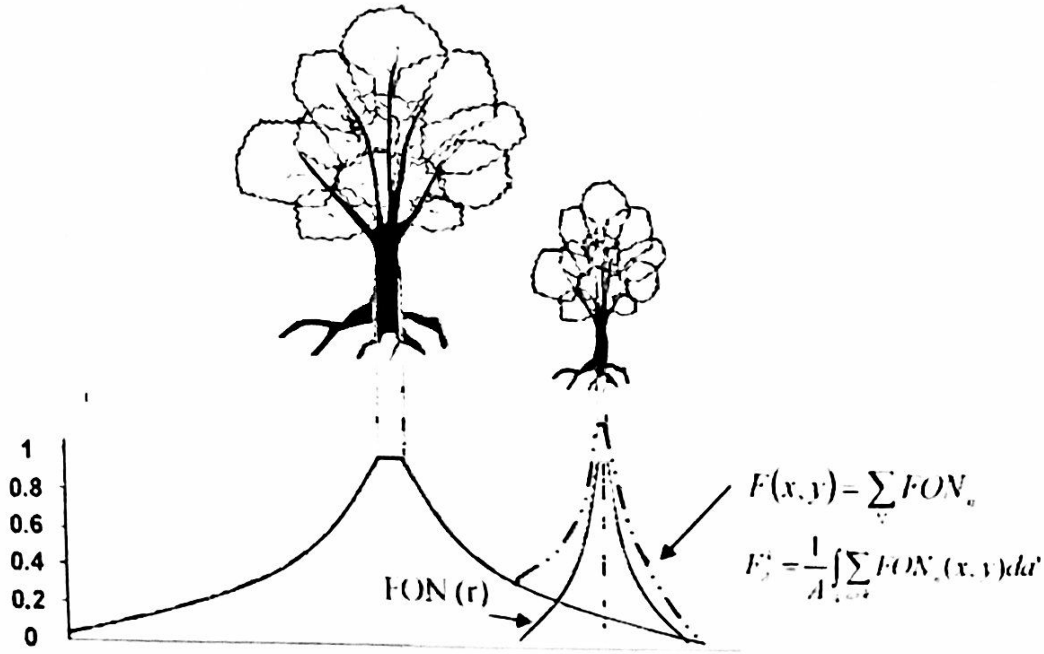

Figure 3.2: The Field of Neighborhood describes the competition strength that an individual exerts on its neighbors or on its environment. F(x, y) indicates the competition strength of all established trees at the location (x, y). FA records the competition that an individual encounters from its neighbors. A is the area of the zone of influence of the target plant.

3.4.2 Description of KiWi Model

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

3.4.2.1 Overview

3.4.2.1.1 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 neighbours for spatially limited resources such as space and light.

3.4.2.1.2 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-neighbourhood (FON), used to describe local neighbourhood 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.

3.4.2.1.3 Process overview and scheduling

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, neighbourhood 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 neighbourhood 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 (Figure 3.3). Each time step, a sequence of processes is operated following the three biological sub-models (see sub-models part for details):

1. establishment of new trees,
2. growth of trees,
3. 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 D130 of all trees are updated synchronously and the derived parameters such as tree height and FON radius are re-calculated.

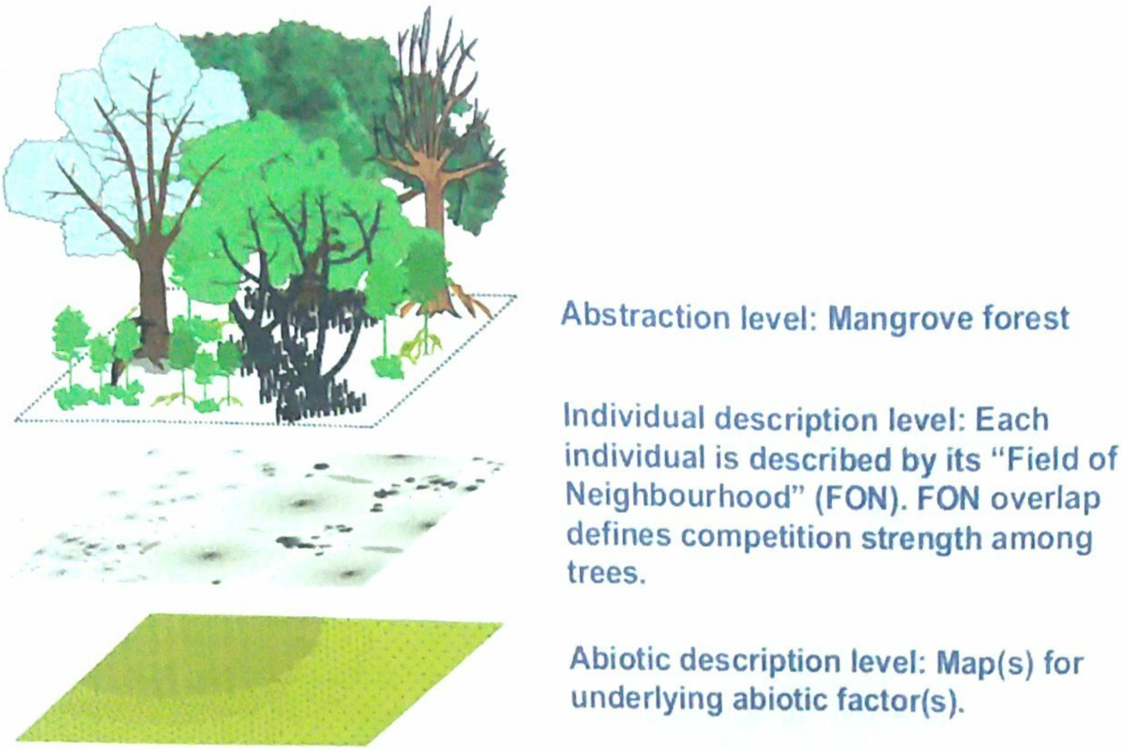

Figure 3.3: Scheme of KiWi Model

3.4.2.2 Design concepts

3.4.2.2..1 Emergence

The growth of each tree depending on neighbourhood 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 behaviour, (4) the distribution of mortality size classes, (4) species zonation, and (5) vertical canopy zonation.

3.4.2.2..2 Interactions

Trees compete with one another for spatially distributed resources. This competition is phenomenologically described using the so-called Field of Neighbourhood (FON) approach. According to this approach, each tree has a circular, size-dependent FON around its stem position where the tree influences its neighbours 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 neighbours. The sum of the neighbouring FONs on the FON area of a focused tree mark the neighbourhood competition the later "receives".

3.4.2.2.3 Sensing

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

3.4.2.2.4 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.

3.4.2.2.5 Observations

KiWi allows registering continuously the state variables such as stem positions, and stemming diameter but also derived variables such as neighbourhood 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.

3.4.2.3 Details

3.4.2.3.1 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.

3.4.2.3.2 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 yr 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.

3.4.2.4 Submodels

3.4.2.4.1 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 neighbours and is influenced by its neighbours. 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 4.1**). The intensity of FON (r) = $e^{-c(r-(D130/2))}$.

3.4.2.4 .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.

3.4.2.4 .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:

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

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 neighbouring trees.

3.4.2.4.4 Competition

The intensity of the FONs of all neighbouring 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.

3.4.2.4.5 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 neighbouring trees. This procedure assures that a tree has a chance to recover when conditions improve, e.g. when a neighbouring tree dies. Additional mortality was incorporated in order to implement the artificial thinning in the simulation experiments at 15 and 20 yr. stand ages.

3.4.3 Advantages of KiWi Model

The advantages of the KiWi model are that the parameters are easy to obtain even with limited availability of data. KiWi model has been successfully used for studying recovery after hurricane occurrence, lighting disturbance, and trajectories of secondary mangrove succession, silviculture yield management in mangrove plantations and spatial pattern dynamics in monospecific mangroves (Berger *et al.*, 2006; Fontalvo-Herazo *et al.*, 2011; Kautz *et al.*, 2011).

3.4.4 Simulations Model for *Sonneratia apetala* in Coastal plantations

Forest department was started coastal plantation with different mangrove species. Among them *Sonneratia apetala* dominates the mangrove plantations generally as a monospecific stands by showing higher survival rate. About 80% by area of the early plantations consisted of monospecific stands of *Sonneratia apetala* (Saenger and Siddiqi, 1993). Thinning of *S. apetala* 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. So thinning has a good positive impact on yield in terms of biomass as well as basal area. For the reason in this study *S. apetala* was choose for simulation modelling to prove that it shows better performance in monospecific stands.

3.5 SILVICULTURAL TREATMENTS

According to the (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. Simulations were performed in the monospecific stands of *Sonneratia apetala* with a rotation age of 40 years.

The seedlings are left to grow till around 15 years when the first thinning was carried out using a 1 .2 m stick circumference radius so that any tree within a 1.2 m radius of a selected central tree is removed (and the bigger trees sold as poles). In practice, seedling densities are increased considerably by natural recruitment even after manual planting which results in a harvest of about half of the trees during the first thinning. A second thinning takes place at about 20 years when a 1.8 m stick circumference radius was used. This thinning also removes about half of the trees (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).

3.6 ABOVE-GROUND WEIGHT

Above-ground weight was calculated using the following formulae:

According to (Komiyama *et al.*, 2005)

$$W_{top} = 0.247 \times \rho \times (D^2)^{1.23} \quad (1)$$

Here, ρ = wood density ($gmcm^{-3}$) (*Sonneratia apetala* = 0.537) (Zanne, 2009) and D = Diameter (cm).

According to (Chave *et al.*, 2005)

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

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

According to allometric equation obtained from field data

$$Stem\ Weight = \rho \times \{(0.383 \times (\frac{D}{100})^2 \times H)^{0.9205}\} \quad (3)$$

Here, ρ = wood density, D = Diameter (cm), H = Height (m).

CHAPTER 4: RESULTS AND DISCUSSION

4.1 RESULTS

To get the desire result in our works, firstly select some parameters which were used for running simulation in the KiWi model. KiWi parameters used for the simulations of the mangrove *Sonneratia apetala* obtained according to procedure of pattern oriented modelling (POM) (Grimm *et al.*, 1996; Grimm *et al.*, 2005; Fontalvo-Herazo *et al.*, 2011; Khan *et al.*, 2013) and field data.

Table 4.1: KiWi Parameters for Simulation in *Sonneratia apetala*:

Description	Parameters	Value	References
FON scaling factor	a	8.209	Field Data, Fontalvo-Herazo et al. 2011
FON scaling factor	b	0.5352	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}	0.7793	Field data, Gong and Ong 1995
Maximum annual growth increment (cm/yr)	ΔD_{max}	1.50	Field Data, Gong and Ong 1995
Growth constant	G	250	Botkin et al. (1972)
Maximum D_{130}* (cm)	D_{max}	250	Field Data, POM
Maximum height (cm)	H_{max}	3500	Field Data, POM
Constant in height to D_{130}	b_2	26.9	Botkin et al. (1972)
Constant in height to D_{130}	b_3	0.0538	Botkin et al. (1972)
Mortality threshold	ΔD_{crit}	0.289	Fontalvo-Herazo et al. 2011
Resource sharing capacity	φ	0.95	POM (Fontalvo-Herazo et al. 2011)

Note: FON: Field of Neighbourhood (Berger and Hildenbrandt, 2000); D_{130}- Tree diameter at 130 cm height from the ground (Brokaw and Thompson, 2000).

In the field work, we have taken the total Height, DBH, Collar dia and Sectional dia of the *Sonneratia apetala* 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 ($R^2 = 0.9948$) for estimating the trunk volume (**Fig. 4.1**) used in this study was established based on wide ranges of tree diameter and height which offers better predictions of volume for *Sonneratia apetala.*

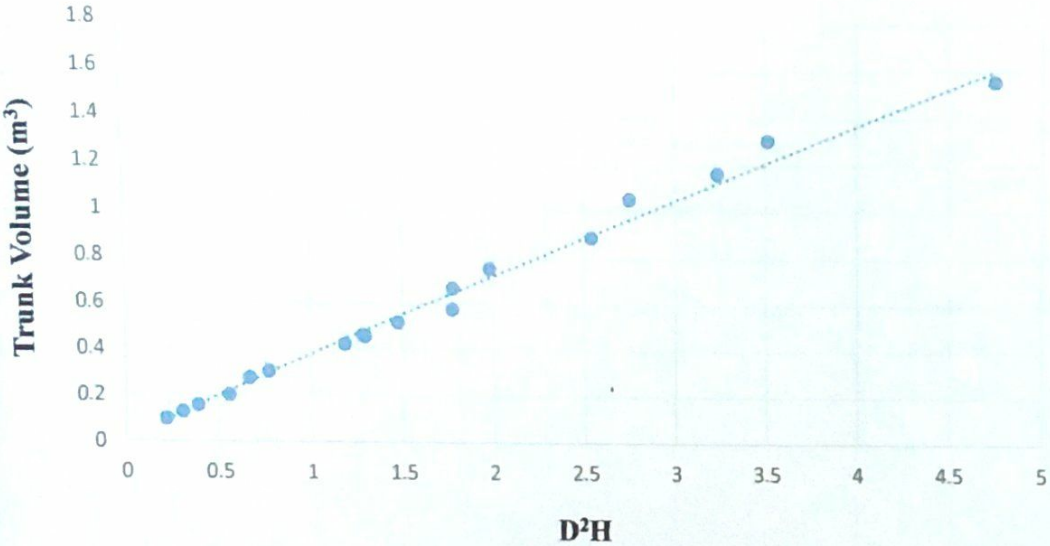

Figure 4.1: Allometric relationship of trunk volume (m^3) in relation to tree diameter and height in Sonneratia apetala using field data ($y = 0.382x^{0.920}$, $R^2 = 0.994$)

The output and parameterization of the model was evaluated based on monitoring data obtained in the field. The observed frequency distributions of diameter (D_{130}) in the *Sonneratia apetala* stands showed no remarkable differences to that in the simulated results at stand ages of 27 years as revealed by the median values in the box plot (**Fig 4.2**). There was no significant difference in the mean diameter between observed and simulated trees at 27 years old (**P > 0.05**) as tested with t test (such as Two way sample t test). This suggests that the model can mimic real dynamic growth pattern.

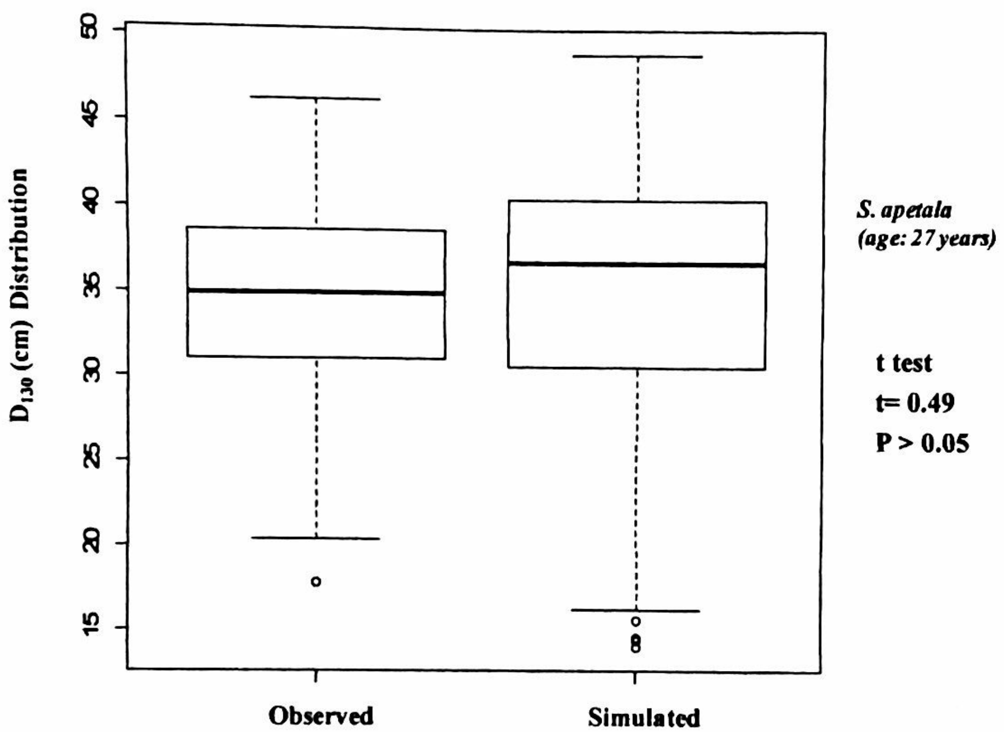

Figure 4.2: Box plot of observed and simulated distribution of tree diameter (D_{130}) in *Sonneratia apetala* stands

The highest harvested above-ground biomass as well as basal area at 40-years-rotation was obtained through the silvicultural option 'with recruitment with thinning' and the lowest biomass and basal area were obtained through the option 'without recruitment without thinning (**Fig. 4.3**). This suggests that in *Sonneratia apetala*, 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.

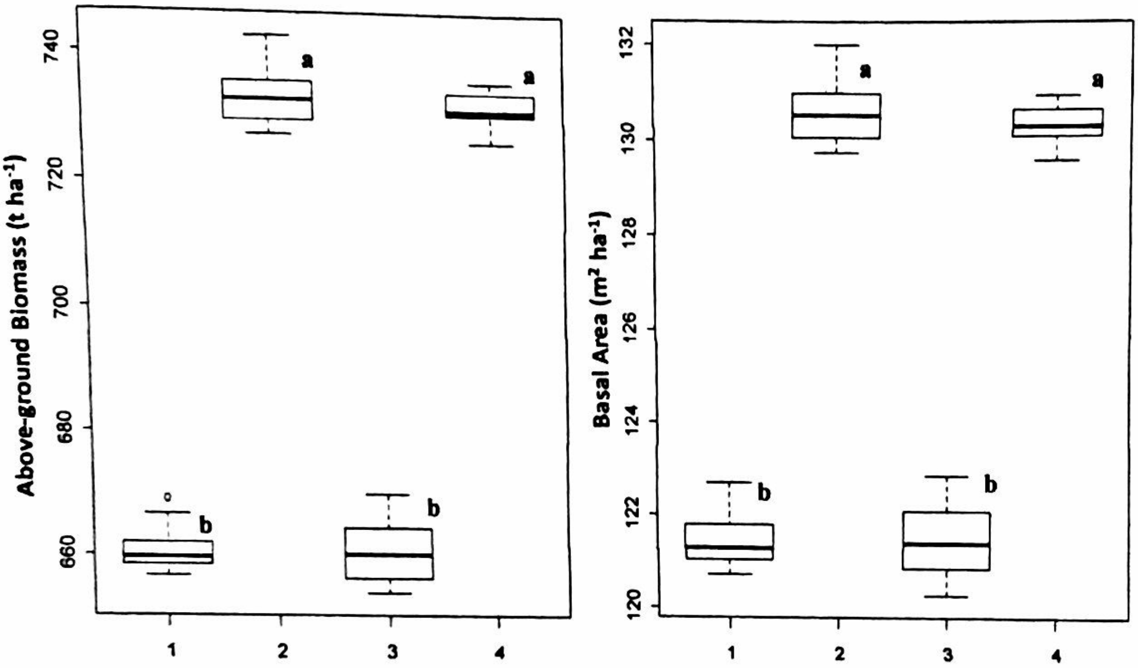

Figure 4.3: Above-ground biomass and basal area in *Sonneratia apetala* over 40 year's rotation period. Note: 1= with recruitment without thinning; 2= with recruitment with thinning; 3= without recruitment without thinning; 4= without recruitment with thinning. Same letters (a, b) indicate no significant difference (P < 0.001) 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 weight at 40 years of stand age.

Table 4.2: Above-ground biomass and Mean annual increment calculated using different formulae---

Stand Age	Above-ground biomass (ton/ha)		Stem Weight (ton/ha) (Field Data)	Mean annual increment (MAI) (t/ha/yr)		Mean annual stem increment (t/ha/yr)
	AGB 1 (Komiyama et al., 2005)	AGB 2 (Chave et al., 2005)		MAI 1 (AGB1/Stand age)	MAI 2 (AGB2/Stand age)	MAI 3 (Stem Weight /Stand age)
14	117.356	79.551	65.091	8.383	5.682	4.649
17	244.727	161.239	132.935	14.396	9.485	7.820
22	388.720	248.573	204.036	17.669	11.299	9.274
26	674.169	418.251	365.877	25.930	16.087	14.072
27	892.914	545.910	446.721	33.071	20.219	16.545

Table 4.3: Comparison of standing biomass in *Sonneratia apetala* and different mangrove species at different places and stand ages

Location	Stand Ages (yrs.)	Species	Above-ground Biomass (t ha^{-1})	Mean annual increment (MAI) (t/ha/yr)	Source
Potuakhali, Bangladesh	27	*Sonneratia apetala*	545.91	20.22	Present Study
Thailand	15	*Rhizophora apiculata*	159.0	10.6	(Christensen, 1978)
Matang mangrove, Malaysia	23	*Rhizophora apiculata*	185.30	8.06	(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)

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}>40 cm were obtained through the silvicutural treatment B (with recuritment with thinning) (Fig 4.4.) followed by silvicultural treatment D (without recuritment with thinning) in *Sonneratia apetala* (**Fig. 4.4**). Then the largest proportions of D_{130} 30-40 were obtained through the silvicultural treatment C (without recuritment without thinning) and treatment A (with recuritment without thinning).

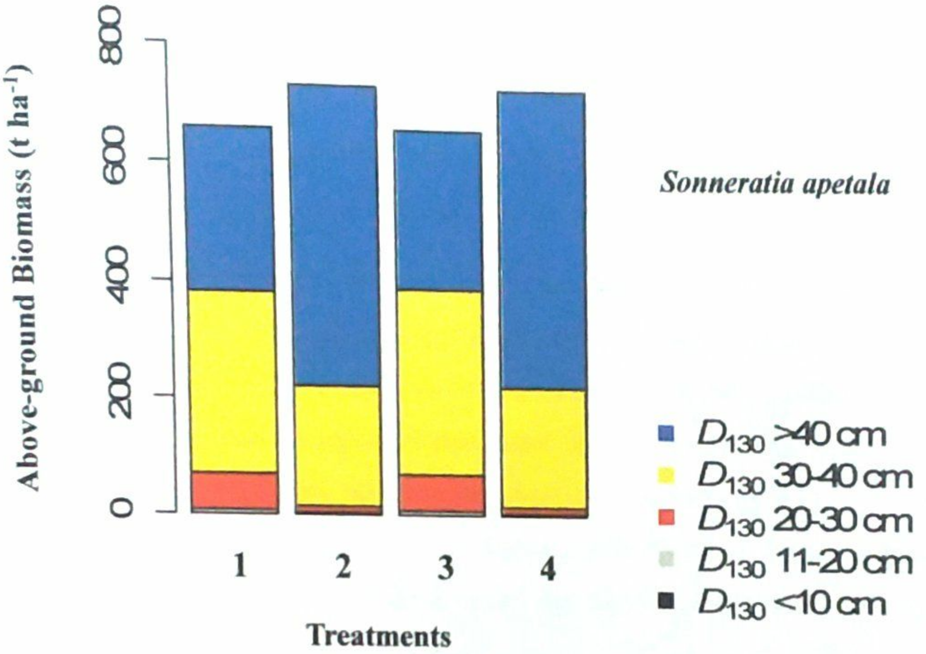

Figure 4.4: Above-ground biomass in relation to utilization class of tree diameter (D_{130}) in 40 year old stand. Note: Different silvicultural treatments (1: With recruitment without thinning; 2: With recruitment with thinning; 3: Without recruitment without thinning; 4: Without recruitment with thinning).

4.2 DISCUSSION

In this study, trunk volume of different trees of Sonneratia apetala was best estimated by power curves. The best estimate of trunk volume (R^2 = 0.9948) was obtained using a combination of tree height and diameter at breast height (D^2H) as the independent variables (Kairo *et al.*, 2009a). The strength of the reported allometric relationships of Sonneratia apetala (R^2 = 0.9948) in particular was probably due to the wide ranges of D_{130} classes (8.65~46.24 cm) of the datasets used. Hence, the maximum D_{130} in Sonneratia apetala was 46.24 cm only and the stand was very eldest (27 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 Sonneratia apetala 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. 4.2**). There was no significant difference in the mean diameter between observed and simulated trees at 27 years old ($P > 0.05$). This suggests that the model can mimic real dynamic growth pattern.

In *Sonneratia apetala* the highest harvested above-ground biomass and basal area were obtained when there is availability of sapling recruitment and a periodic thinning is practiced at 15 and 20 yr stand ages (**Fig. 4.3**) and the lowest biomass and basal area were obtained when there is an absence of sapling recruitment and there are no thinning operations. This reveals that both thinning and natural regeneration has positive impact on yield in terms of biomass as well as basal area in *Sonneratia apetala.* 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 no sapling recruitments but having a 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. 4.4**).

The species *S. apetala* shows strong potential for biomass accumulation (545.91 t/ha in a 27 year old stands) which is higher than other mangrove species (**Table 4.3**).

CHAPTER 5: CONCLUSION

Bangladesh is a pioneer country in raising successful plantations with *S. apetala* along the shoreline and offshore islands. This study is based on a combination of field and simulated data to describe the success, importance and performance of *S. apetala* for the development of monospecific stands in the coastal areas. The performance of different management options or silivicultural treatments suggests that recuritment with a periodic thinnig offers a higher yield than that with no silvicultural treatment. A periodic thinning and recruitment play significant roles in the ratational yields having different proportions of tree diameter utilization classes. Simulation experiments, tuned to observed configurations of the study sites, provided a forecast of the stand development to be expected in the future. Finally the results suggests that *S. apeatala* is more suitable for coastal plantation in terms of higher yield, performance and devlopment of monospecific stands. On the basis of this model, future research would foucs finding an appropriate thinning intensity (radius), which would ensure maximum yield at harvesting period.

REFERENCES

Alongi, D., Trott, L., Wattayakorn, G., Clough, B., 2002. Below-ground nitrogen cycling in relation to net canopy production in mangrove forests of southern Thailand. Marine Biology 140, 855-864.

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., Tirendi, F., Clough, B.F., 2000. Below-ground decomposition of organic matter in forests of the mangroves Rhizophora stylosa and Avicennia marina along the arid coast of Western Australia. Aquatic Botany 68, 97–122.

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

Aziz, A., 2010. Coastal and marine plant resources of Bangladesh: management and exploitation. Keynote paper, Annual Bot. Conf., Univ. Chittagong, Chittagong., P. 14.

Banglapedia., 2014. Coastal Plantation. http://en.banglapedia.org/index.php?title=Coastal_Plantation, (Accessed on 27th February).

Bauer, S., Wyszomirski, T., Berger, U., Hildenbrandt, H., Grimm, V., 2004. Asymmetric competition as a natural outcome of neighbour interactions among plants: results from the field-of-neighbourhood modelling approach. Plant Ecology (formerly Vegetatio) 170, 135–145.

Berger, U., Adams, M., Grimm, V., Hildenbrandt, H., 2006. Modelling secondary succession of neotropical mangroves: Causes and consequences of growth reduction in pioneer species. Perspectives in Plant Ecology, Evolution and Systematics 7, 243–252.

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

Berger, U., Hildenbrandt, H., Grimm, V., 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., Hildenbrandt, H., Grimm, V., 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., Rivera-Monroy, V. H., Doyle, T. W., Dahdouh-Guebas, F., Duke, N. C., Fontalvo-Herazo, M. L., ... & Twilley, R. R. (2008). Advances and limitations of individual-based models to analyze and predict dynamics of mangrove forests: A review. Aquatic Botany, 89(2), 260-274.

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

Bosire, J.O., Dahdouh-Guebas, F., Kairo, J.G., Wartel, S., Kazungu, J., Koedam, N., 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.

Bouillon, S., Borges, A. V., Castañeda-Moya, E., Diele, K., Dittmar, T., Duke, N. C., ... & Rivera-Monroy, V. H. (2008). Mangrove production and carbon sinks: a revision of global budget estimates. Global Biogeochemical Cycles, 22(2)..

Brokaw, N., Thompson, J., 2000. The H for DBH. Forest Ecology and Management 129, 89–91.

Burns, B., Ogden, J., 1985. The demography of the temperate mangrove [Avicennia marina (Forsk.) Vierh.] at its southern limit in New Zealand. Australian journal of ecology 10, 125-133.

Chave, J., Andalo, C., Brown, S., Cairns, M. A., Chambers, J. Q., Eamus, D., ... & Lescure, J. P. (2005). Tree allometry and improved estimation of carbon stocks and balance in tropical forests. Oecologia, 145(1), 87-99.

Chen, R., Twilley, R.R., 1998. A gap dynamic model of mangrove forest development along gradients of soil salinity and nutrient resources. Journal of Ecology 86, 37–51.

Christensen, B., 1978. Biomass and primary production of Rhizophora apiculata Bl. in a mangrove in southern Thailand. Aquatic Botany 4, 43-52.

Clarke, P.J., 1995. The population dynamics of the mangrove Avicennia marina; demographic synthesis and predictive modelling. In, Asia-Pacific Symposium on Mangrove Ecosystems. Springer, pp. 83-88.

DeAngelis, D.L., Gross, L.J., 1992. Individual-based models and approaches in ecology: populations, communities and ecosystems. Chapman & Hall.

DeAngelis, D.L., Mooij, W.M., 2005. Individual-based modeling of ecological and evolutionary processes. Annual Review of Ecology, Evolution, and Systematics, 147-168.

Donato, D. C., Kauffman, J. B., Murdiyarso, D., Kurnianto, S., Stidham, M., & Kanninen, M. (2011). Mangroves among the most carbon-rich forests in the tropics. *Nature Geoscience*, *4*(5), 293-297.

Doyle, P., 1997. Modeling Hurricane Effects on Mangrove Ecosystems. USGS Fact Sheet 200, 95–97.

Doyle, T.W., Girod, G.F., Books, M.A., 2003. Modeling mangrove forest migration along the southwest coast of Florida under climate change. In, Integrated Assessment of the Climate Change Impacts on the Gulf Coast Region. GRCCC and LSU Graphic Services, Baton Rouge, LA, pp. 211–221.

Drigo, D., Latif, M.A., Chowdhury, J. A., and Shaheduzzaman, M., 1987. The Maturing Coastal Plantations of the Coastal Afforestation Project. UNDP project BGD/85/085, Dhaka., Field Document No.2. P. 3.

Duke, N. C., Meynecke, J. O., Dittmann, S., Ellison, A. M., Anger, K., Berger, U., ... & Koedam, N. (2007). A world without mangroves?. Science, 317(5834), 41-42.

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

Field, C., 1999. Rehabilitation of mangrove ecosystems: an overview. Marine Pollution Bulletin 37, 383-392.

FlowersofIndia., 2005. Sonneratia Mangrove. http://www.flowersofindia.net/catalog/slides/Sonneratia%20Mangrove.html (Accessed on 27th February).

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

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

Grimm, V., Berger, U., Bastiansen, F., Eliassen, S., Ginot, V., Giske, J., ... & Huth, A. (2006). A standard protocol for describing individual-based and agent-based models. Ecological modelling, 198(1), 115-126.

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

Grimm, V., & Railsback, S. F. (2013). Individual-based modeling and ecology. Princeton university press.

Grimm, V., Revilla, E., Berger, U., Jeltsch, F., Mooij, W.M., Railsback, S.F., Thulke, H.-H., Weiner, J., Wiegand, T., DeAngelis, D.L., 2005. Pattern-oriented modeling of agent-based complex systems: lessons from ecology. Science 310, 987–991.

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.

Hossain, M., Othman, S., Bujang, J.S., Kusnan, M., 2008. Net primary productivity of Bruguiera parviflora (Wight & Arn.) dominated mangrove forest at Kuala Selangor, Malaysia. Forest ecology and management 255, 179-182.

Iftekhar, M., Islam, M., 2004. Managing mangroves in Bangladesh: A strategy analysis. Journal of Coastal Conservation 10, 139-146.

Islam, M., 2012. Coastal forest rehabilitation and management in Bangladesh. Retrieved July 11.

Islam, M., Ashaduzzaman, M., Islam, M., Karim, M., Hannah, M., 2011. Preservative Treatment of Keora (*Sonneratia apetala)* Poles by Full Cell Method of Wood Preservation with CCA Preservative. Bangladesh Journal of Scientific and Industrial Research 46, 425-428.

Islam, S.S., Azad, A.K., Kabir, J., Hossain, M.A.T., 2012. Financial Analysis of Keora (Sonneratia apetala) Plantations in Bangladesh. Open Journal of Statistics 2, 124.

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

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

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

Kathiresan, K., Bingham, B.L., 2001. Biology of mangroves and mangrove ecosystems. Advances in marine biology 40, 81-251.

Kathiresan, K., Salmo III, S.G., Fernando, E.S., Peras, J.R., Sukardjo, S., Miyagi, T., Ellison, J., Koedam, N.E., Wang, Y., Primavera, J., Jin Eong, O., Wan-Hong Yong, J. & Ngoc Nam, V. , 2010. Sonneratia apetala. The IUCN Red List of Threatened Species 2010: e.T178841A7623713. . Downloaded on 27 February 2016.

Kautz, M., Berger, U., Stoyan, D., Vogt, J., Khan, N.I., Diele, K., Saint-Paul, U., Triet, T., Nam, V.N., 2011. Desynchronizing effects of lightning strike disturbances on cyclic forest dynamics in mangrove plantations. Aquatic Botany 95, 173–181.

Khan, M.N., Koedam, N., Berger, U., Bosire, J.O., Kairo, J.G., Dahdouh-Guebas, F., 2012. Testing mangrove forest structure development and various forest management options in Gazi (Kenya) by combining KiWi individual-based modelling with> 20 years of field data. VLIZ Special Publication.

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

Khan, M.N.I., Suwa, R., Hagihara, A., 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.

Khan, M.N.I., Suwa, R., Hagihara, A., 2009. Biomass and aboveground net primary production in a subtropical mangrove stand of Kandelia obovata (S., L.) Yong at Manko Wetland, Okinawa, Japan. Wetlands Ecology and Management 17, 585–599.

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

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

Komiyama, A., Havanond, S., Srisawatt, W., Mochida, Y., Fujimoto, K., Ohnishi, T., ... & Miyagi, T. (2000). Top/root biomass ratio of a secondary mangrove (Ceriops tagal (Perr.) CB Rob.) forest. Forest Ecology and Management, 139(1), 127-134.

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

Liu, J., Ashton, P.S., 1995. Individual-based simulation models for forest succession and management. Forest Ecology and Management 73, 157-175.

Lugo, A.E., Sell, M., Snedaker, S.C., 1976. Mangrove ecosystem analysis. Systems analysis and simulation in ecology 4, 113-145.

Machiwa, J.F., Hallberg, R.O., 2002. An empirical model of the fate of organic carbon in a mangrove forest partly affected by anthropogenic activity. Ecological Modelling 147, 69–83.

Miah, M.A.Q., Islam, S.A., Habib, M.A., Moula, M.G., 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.

Mumby, P. J., Edwards, A. J., Arias-González, J. E., Lindeman, K. C., Blackwell, P. G., Gall, A., ... & Wabnitz, C. C. (2004). Mangroves enhance the biomass of coral reef fish communities in the Caribbean. Nature, 427(6974), 533-536.

Norhayati, A., Latiff, A., 2001. Biomass and species composition of a mangrove forest in Pulau Langkawi, Malaysia. Malaysian Applied Biology 30, 75-80.

Phillips, P.D., de Azevedo, C.P., Degen, B., Thompson, I.S., Silva, J.N.M., Van Gardingen, P.R., 2004. An individual-based spatially explicit simulation model for strategic forest management planning in the eastern Amazon. Ecological Modelling 173, 335–354.

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

Primavera, J.H., 2000. Development and conservation of Philippine mangroves: institutional issues. Ecological Economics 35, 91–106.

Primavera, J.H., 2005. Mangroves, Fishponds, and the Quest for Sustainability. Science 310, 57–59.

Rachid, M., 1977. Instruction Manual for Planting on Coastal Area Departmental instruction manual., P.76.

Rahman, M.M., Khan, M.N.I., Hoque, A.F., Ahmed, I., 2015. Carbon stock in the Sundarbans mangrove forest: spatial variations in vegetation types and salinity zones. Wetlands Ecology and Management 23, 269-283.

Ray, S., Ulanowicz, R.E., Majee, N., Roy, A., 2000. Network analysis of a benthic food web model of a partly reclaimed island in the Sundarban mangrove ecosystem, India. Journal of Biological Systems 8, 263-278.

Ray, T., 2014. Customary use of mangrove tree as a folk medicine among the Sundarban resource collectors. International Journal of Research in Humanities, Arts, and Literature 2, 43-48.

Robertson, A.I., Alongi, D.M., 1992. Tropical Mangrove Ecosystems. American Geophysical Union, Washington, DC.

Rönnbäck, P., 1999. The ecological basis for economic value of seafood production supported by mangrove ecosystems. Ecological Economics 29, 235–252.

Saenger, P. (2002). Mangrove ecology, silviculture and conservation. Springer Science & Business Media.

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

Sargent, R.G., 2005. Verification and validation of simulation models. In, Proceedings of the 37th conference on Winter simulation. Winter Simulation Conference, Orlando, Florida, pp. 130-143.

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

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

Siddiqi, N.A., 2001. Mangrove Forestry in Bangladesh. Institute of forestry and Environmental Sciences, University of Chittagong, Chittagong., P.201.

Terrados, J., Thampanya, U., Srichai, N., Kheowvongsri, P., Geertz-Hansen, O., Boromthanarath, S., ... & Duarte, C. M. (1997). The Effect of Increased Sediment Accretion on the Survival and Growth ofRhizophora apiculataSeedlings. Estuarine, Coastal and Shelf Science, 45(5), 697-701.

Twilley, R.R., Rivera-Monroy, V.H., 2005. Developing performance measures of mangrove wetlands using simulation models of hydrology, nutrient biogeochemistry, and community dynamics. Journal of Coastal Research, 79-93.

Valiela, I., Bowen, J.L., York, J.K., 2001. Mangrove forests: one of the world's threatened major tropical environments. Bioscience 51, 807–815.

Vega-Cendejas, M., Arreguın-Sánchez, F., 2001. Energy fluxes in a mangrove ecosystem from a coastal lagoon in Yucatan Peninsula, Mexico. Ecological Modelling 137, 119-133.

Walters, B. B., Rönnbäck, P., Kovacs, J. M., Crona, B., Hussain, S. A., Badola, R., ... & Dahdouh-Guebas, F. (2008). Ethnobiology, socio-economics and management of mangrove forests: a review. Aquatic Botany, 89(2), 220-236.

Wolff, M., 2006. Biomass flow structure and resource potential of two mangrove estuaries: insights from comparative modeling in Costa Rica and Brazil. Rev. Biol. Trop 54, 69-86.

Zanne, A. E., Lopez-Gonzalez, G., Coomes, D. A., Ilic, J., Jansen, S., Lewis, S. L., ... & Chave, J. (2009). Global wood density database.