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Effect of Thinning on Carbon Stocks in *Sonneratia apetala* Buch.-Ham Plantations: a Simulation Study

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APPROVAL

This is to certify that the present project thesis entitled "Effect of Thinning on Carbon Stocks in *Sonneratia apetala* Buch.-Ham Plantations: a Simulation Study" has been carried out by Md. Arifuzzaman Arif (Student Id: 130538) under my direct supervision at the Forestry and Wood Technology Discipline of Khulna University, Khulna-9208, Bangladesh.

I recommend that the content of the project thesis can be accepted in the partial fulfillment of the requirement for the Degree of B.Sc. (Honors) in Forestry.

4.3.18

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DECLARATION

I. **Md. Arifuzzaman Arif**, 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.

04.03.18

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DEDICATION

To my beloved ***Mom***, rest in peace

Mrs. Sufia Ashraf,

who was my heart and everything & who always inspired me to be a complete human being and an honest man from my childhood.

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First, I want to admire to Almighty ALLAH, the supreme creator and ruler of the university from the deepest corner of my heart for His blessings that keeps me alive and enable me to accomplish this project work successfully.

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Md. Arifuzzaman Arif

ABSTRACT

Forests are very important for sequestering atmospheric carbon and mangroves are amongst the most efficient carbon sequestering ecosystems. 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) was developed in order to analyze demographic processes of mangrove forests according to abiotic environmental factors, individual tree spacing, local tree-to-tree interactions and intra-specific competition. 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. Data obtained from the field monitors the output and parameterization of the model. Thinning normally avails more space and thus resources for growth, which leads to enhanced biomass increment. The objectives of this study were to identify the short- and long-term effects of thinning on carbon stocks in a mangrove plantation. Simulation experiments, tuned to observe configurations of the study sites, provided a forecast of the stand development to be expected in the future. In this study, two thinning were done at 15 year and 20 year with 0.5 m to 4.5 m radius while the annual sapling recruitment rate is kept zero during thinning. Among the different thinning radius, 3.5 m radius thinning shows maximum aboveground carbon stocks in *Sonneratia apetala*, which is comparable to 1.8 m stick radius thinning practiced in Matang Mangrove, Malaysia for Rhizophora apiculata. In case of Bangladesh coastal plantation, 2.5 m and 3.0 m thinning radius is perfect because 2.5 m and 3.0 m thinning radius contain adequate number of trees and also produce above ground carbon as same as 3.5 m thinning radius. This experiment strongly supports that the KiWi model can mimic real dynamic growth pattern and thinning has effect on carbon stock 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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CHAPTER 1: INTRODUCTION

1.1. Background and Justification of the Study

Mangroves appear among the most productive ecosystems on the earth and mangroves are keystone coastal ecosystems providing numerous environmental services viz. reduce global warming and critical ecological functions, affecting both upland and oceanic resources (Donato et al. 2011). Mangroves provide important goods and services to coastal population such as sequestrating carbon, filtering capacity of pollutants trap and stabilization of sediments (Fromard et al. 1998), indicator of sea level rise (Adame et al. 2013), storm protection (Doyle 1997), support of a diversity of animal species both within the forest and in offshore areas, direct benefits to local communities and indirect benefits to the economy of the region through the contribution to fisheries production and the development of the ecotourism industry (Primavera 2000, Primavera 2005).

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, Machiwa and Hallberg 2002, Mumby et al. 2004). Mangroves can be defined as an association of halophytic trees, shrubs and other plants growing in brackish to saline tidal waters of tropical and subtropical coastlines (Donato et al. 2011).

Mangrove forests have been traditionally used as a wide variety of products and services. In the world, many countries are managed the mangrove forest for various purposes such as poles, firewood, construction, timber, charcoal extraction and pulp. Non-timber forest products are recognized as important economic resources, particularly to rural, marginalized communities. The two most widespread uses of mangrove wood are for fuel and construction. Many common mangrove tree species e.g. *Sonneratia apetala* produce timber and fuel wood which is used in different industries. The production of the species recommends to make hardboard, pulpwood, packing boxes, bobbins, joinery, doors, windows, etc. (Iftekhar and Islam 2004).

Bangladesh coastline extends more than 710 km long along the Bay of Bengal which is comprised of various forms of accreted (char) lands and off-shore islands (Siddiqi 2001). The coastal areas of Bangladesh had 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 program of planting mangroves outside the protective coastal embankments in order to provide greater protection for inhabited coastal areas (Rachid et al. 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, Iftekhar and Islam 2004).

Among the different models which are generally used for the study of forest silviculture as well as yield modeling for tropical forests, Simulations model have been proven to be more efficient tools (Köhler and Huth 2004, Phillips et al. 2004). Simulations models are increasingly being used in problem solving and in management decision making. The models simulate ecological processes such as growth, mortality, competition and recruitment on the base of species groups (SYMFOR) (Phillips et al. 2004) or functional groups (FORMIND) (Köhler and Huth 2004). The models have been applied for analyzing wood harvesting management decisions showing changes on the forest structure over time due to repeated logging events among others (Fontalvo-Herazo et al. 2011). Individual based models simulate each individual tree as a unique entity in respect to establishment, growth and death (Liu and Ashton 1995). In dynamics of mangrove forest, some individual based models have been applied such as MANGRO (Doyle 1997, Doyle et al. 2003), FORMAN and KiWi (Berger and Hildenbrandt 2000). MANGRO, FORMAN and KiWi were developed to understand long-term dynamics of mangrove forests under different environmental and management settings (Berger et al. 2008). The Kiwi model was developed in order to analyze demographic processes of mangrove forests according to abiotic environmental factors, individual tree spacing, local tree-to-tree interactions and intra and inter species competition (Berger and Hildenbrandt 2000) and it was successfully applied for analyzing neo-tropical mangrove forest dynamics affected by environmental settings (pore water salinity and nutrient availability), natural disturbances (lighting and hurricane destruction), silviculture and yield management in mangrove plantations (Fontalvo-Herazo et al. 2011) and spatial pattern dynamics in mono specific mangroves (Khan et al. 2013). The MANGRO model was developed for assessing the impact of hydrologic restoration of freshwater flow in the Everglades and also focuses on landscape dynamics on larger spatial scale. But the FORMAN Models was developed to simulate the soil characteristics along the gradients of soil nutrient availability and salinity conditions on mangrove forest dynamics (Chen and Twilley 1998).

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. 2013). 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. The general objective of this study is to contribute to the ongoing research for mangrove silviculture management alternatives, estimate biomass as well as carbon sequestration. More specifically, this study aims at testing different harvesting cycles of mono-cultural plantations of *Sonneratia apetala*. For this purpose, the KiWi model needed to be adapted to *Sonneratia apetala*. Therefore, two steps were performed in this study (Gong and Ong 1995). The first one is the parameterization of the KiWi model to the mangrove species *Sonneratia apetala* basing on available data. In the second step, harvesting cycles having thinning schedules should be suggested for the mangrove plantation (Gong and Ong 1995) and simulation should be done in order to evaluate their potential ecological and economic impacts.

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 and fund. In Bangladesh, several plantations of *Sonneratia apetala* have been raised with a large-scale plantation along with the coastal belt. The species is highly suitable in the newly formed muddy land in the coastal belt. Coastal afforestation program was first initiated along the coastal belt of Bangladesh in 1966 and it is still going on (Iftekhar and Islam 2004). For the development of mono-specific 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 is done. A simulation experiment helps to experiment with long term monitoring and make suitable management decisions.

However, several studies have already done on biodiversity, biomass, vegetation type assessment and carbon stock in Mangrove plantation but current assessment with the simulation model in the mangrove plantation is a considerable issue. By this study, we can quantify the biomass as well as carbon sequestration rate with respect to thinning operation. In future, this study will help the Bangladesh Forest Department, Mangrove researchers and policy makers to take decisions about management of the Mangrove forest.

1.2. Objectives of the Study

- To investigate effect of thinning operation on carbon stocks in mangrove plantations.
- To observe the performance of various forest management options regarding sapling recruitment and thinning operations.

CHAPTER 2: LITERATURE REVIEW

In literature review, objectives has set to 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 modeling for testing mangrove forest structure development, various forest management options and investigate carbon stocks as well as biomass in the coastal areas of Bangladesh. Thus, this chapter includes five sections each with several subsections. The first section gives the detailed information about coastal plantation status in Bangladesh. The second section represents the species description about *Sonneratia apetala*. The third section describes about thinning operations. The fourth and fifth sections gives an idea about carbon stocks and the modeling testing for mangrove forest structure development, various forest management options and investigate carbon as well as biomass using field data respectively.

2.1. Mangrove forest of Bangladesh

Sundarbans, the largest mangrove forest spans the border between Bangladesh and India, extending from the Hooghly River in India to the Baleswar River in Bangladesh. The forest lies on the delta of the Ganges, Brahmaputra, and Meghna Rivers on the Bay of Bengal. The area is intersected by a complex network of tidal waterways or channels, mudflats, and mangrove forests (Giri et al. 2007). The Sundarbans support an exceptional biodiversity with a wide range of flora and fauna including more than 27 mangrove species, 40 species of mammals, 35 species of reptiles, and 260 bird species. Wildlife species found in the area include the man-eating Royal Bengal tiger, the Indian python, sharks, crocodiles, spotted deer, macaque monkey and wild boar. The forests are characterized two main tree species Sundri, and Gewa. Other species that make up the forest assemblage include Avicenia, Xylocarpus, Sonneratia, Bruguiera, Rhizophora and Nypa palm. The area experiences exceptional ecological processes such as monsoonal rains, flooding, delta formation, tidal influence and mangrove colonization. Rainfall in the area is as high as 2800 mm, mostly during the monsoon season lasting from June to October. Storms, cyclones and tidal surges are quite common throughout Sundarbans. The forest is also a center for economic activities, such as the extraction of timber and fuel wood, fishing and collection honey and other forest products. Within the Sundarbans, there are three wildlife sanctuaries and one national park covering 27% of the area; all of these are listed as a World Heritage Site by the United Nations Educational, Scientific, and Cultural Organization (Mitra et al. 2012). Over 2.5

million people live in villages surrounding the Sundarbans and depend for much of their subsistence on products from mangrove forests. The forest provides a livelihood for some 300,000 people, working seasonally as wood-cutters, palm collectors, fisherman, and honey hunters. Population density in the vicinity of Sundarbans is among the highest in the world (Banerjee 1964).

2.2. 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 kilometers 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 accretion (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 program 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 et al. 1987). Till 2010, an area of 170,000 ha coastal area has been planted, although there are plantation failures over a considerable area (Aziz et al. 2012). 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).

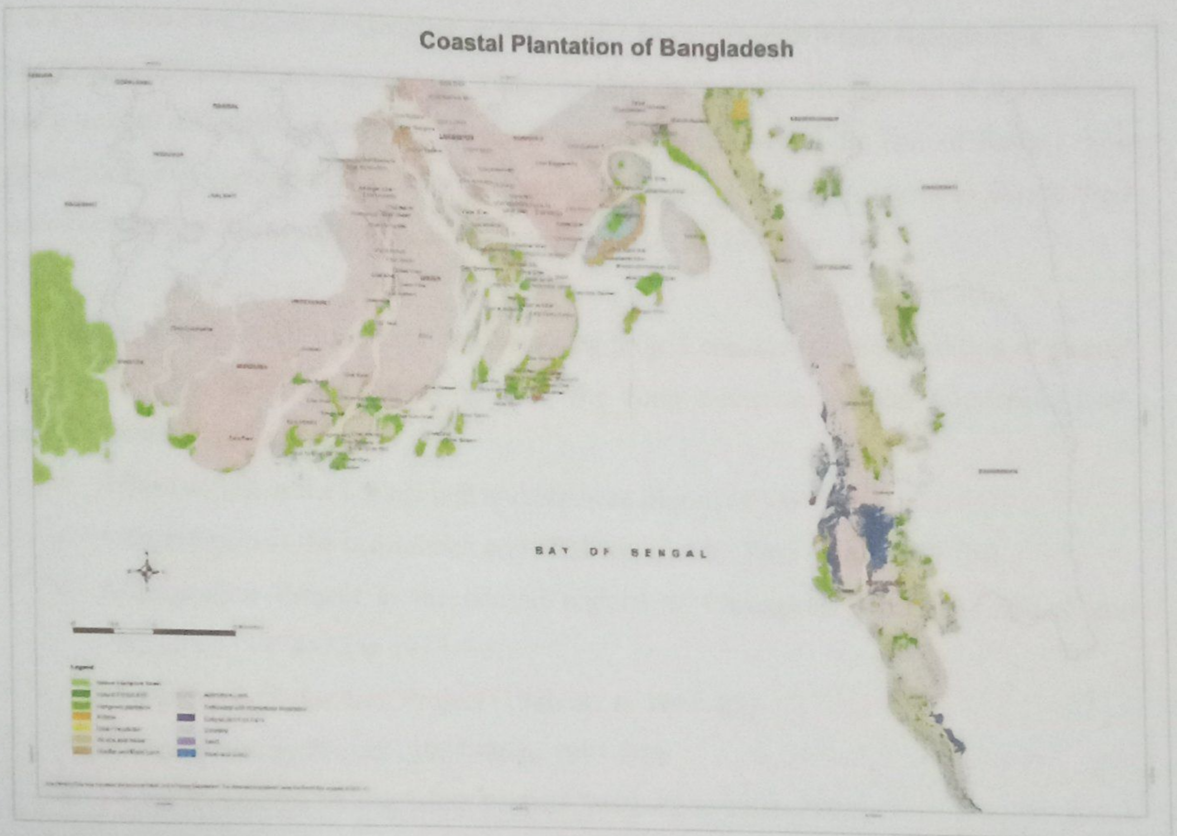

Figure 2.1: Map of Coastal plantations in Bangladesh (Source: Bangladesh Forest Department)

The coastal zone has extensive areas of both natural and planted mangrove forest. Natural forest includes the Sundarbans, the Chakaria Sundarbans and fringe mangroves along the eastern coast. The Sundarbans is the world's single largest tract of mangrove forest and in terms of mangrove biodiversity, the richest forest in the world; it is a Ramsar site, part of which has been designated as a World Heritage site. For about a century the Sundarbans has enjoyed the status of Reserved Forest and has been managed for its productive value.

After a cyclone devastated the coastal region in the 1960s — except for Khulna District, which is protected by the Sundarbans coastal afforestation with mangrove species was initiated to protect life and property from cyclones and tidal surges. Later, industrial raw material and fuelwood production, conservation of coastal ecosystem and the environment, protection of wildlife and aquatic resources, protection of agricultural land against salt intrusion, tourism, poverty reduction and enhancing land accretion were added to the objectives of development programs. 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.

2.2.1. 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 et al. 1977).

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

- ✓ 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).

2.2.2. 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.

2.2.3. Commonly Used Species for Coastal Plantation Projects in Bangladesh

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 mono-specific stands. These species are medium quality timbers used for fuel wood, constructions and furniture. About 80% by area of the early plantations consisted of mono-specific 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 chosen for the better performance in mono-specific stands.

2.2.4. Challenges of Coastal Plantation in Bangladesh

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. apeta*la plantation is carried out using seedlings, whereas, this is done by dibbling seeds into the mud for *A. officinalis (Alam and Rahman 2014)*.

2.3. Keora (*Sonneratia apetala* Buch.-Ham)

2.3.1. Taxonomic Information

Scientific classification

Kingdom: Plantae

Phylum: Tracheophyta

Class: Magnoliopsida

Order: Myrtales

Family: Lythraceae

Genus: Sonneratia

Species: *Sonneratia apetala*

Botanical name: *Sonneratia apetala* Buch.-Ham (Pattanaik et al. 2008)

2.3.2. 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 colored, arranged in axillary 3-flowered to 7-flowered di-chasial 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, flattened 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.

2.3.3. 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 (Duke et al. 2010).

2.3.4. 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.

2.3.5. 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 kilograms 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).

2.3.6. 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 (Duke et al. 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, paneling and other purposes (Islam et al. 2012).

2.4. Thinning

In forestry, thinning is the selective removal of trees, primarily undertaken to improve the growth rate or health of the remaining trees. Overcrowded trees are under competitive stress from their neighbours. Thinning is often the most important thing to influence the growth and health of your forest. Proper spacing and thinning can reduce overcrowding and relieve tree stress. This helps maintain the health and vigor of your forest. Thinning can reduce fire hazards, generate revenue, and increase the value of remaining trees. From an aesthetic perspective, thinning helps create a more open forest stand, which often increases the likelihood of wildlife through improved forest habitat. Unthinned sites were consistently dominated by a high density of small (≤10 cm DBH) stems and contained higher cover in the mid-storey (2–6 m) and sub-canopy (6–14 m) than all other forest management treatments (McElhinny et al. 2005)

2.5. Carbon Stock

Carbon stock refers to the quantity of carbon contained in a "pool", meaning a reservoir or system which has the capacity or release carbon. In the context of forests, the FAO defines as the amount of carbon stored in the world's forest ecosystem, mainly in living biomass and soil, but to a lesser extent also in dead wood and litter. At present, carbon stock is valued as a function of credit emission reductions (CREs), based on the difference between the amount of carbon stored in scenario projects and baseline, current amount of carbon stored in the system (UNFCCC 2004).

2.5.1. Carbon Stock in Forest

As they grow, trees absorb CO2 and through Photosynthesis, sequester carbon to produce wood. Newly established forests (on reforested or afforested sites) and forest re-growth can sequester carbon quickly and will store it for the life of the forest. When trees are harvested efficiently, a large part of the sequestered carbon can be used to produce wood products such as house frames and thus stored in the medium to long term (IPCC 2007). The high rate of carbon allocation in belowground with aboveground carbon makes mangroves as the densest carbon-rich ecosystem in the tropics and contains one an average 937 Mg C ha-1 (Donato et al. 2011, Alongi 2012).

The carbon stored in the aboveground living biomass of trees is typically the largest pool and the most directly impacted by deforestation and degradation. Thus, estimating aboveground forest biomass carbon is the most critical step in quantifying carbon stocks and fluxes from

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2.5.1. Carbon Stock in Forest

As they grow, trees absorb CO2 and through Photosynthesis, sequester carbon to produce wood. Newly established forests (on reforested or afforested sites) and forest re-growth can sequester carbon quickly and will store it for the life of the forest. When trees are harvested efficiently, a large part of the sequestered carbon can be used to produce wood products such as house frames and thus stored in the medium to long term (IPCC 2007). The high rate of carbon allocation in belowground with aboveground carbon makes mangroves as the densest carbon-rich ecosystem in the tropics and contains one an average 937 Mg C ha-1 (Donato et al. 2011, Alongi 2012).

The carbon stored in the aboveground living biomass of trees is typically the largest pool and the most directly impacted by deforestation and degradation. Thus, estimating aboveground forest biomass carbon is the most critical step in quantifying carbon stocks and fluxes from tropical forests (Brown and Masera 2003, Pearson et al. 2013).The most direct way to quantify the carbon stored in aboveground living forest biomass (hereafter referred to as forest carbon stocks) is to harvest all trees in a known area, dry them and weigh the biomass.

2.6. Mangrove Simulations Modelling

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 Neo-tropical mangrove forests: FORMAN, KIWI, and MANGRO (Chen and Twilley 1998, Berger and Hildenbrandt 2000, Doyle et al. 2003).

Both KiWi and FON are described in details (**Chapter 3 Section 3.4**).

2.6.1. Purpose of Mangrove Simulations Modelling

The Mangrove Simulations Modelling was developed for analysing 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.

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 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).

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) (Figure 3.1). 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.

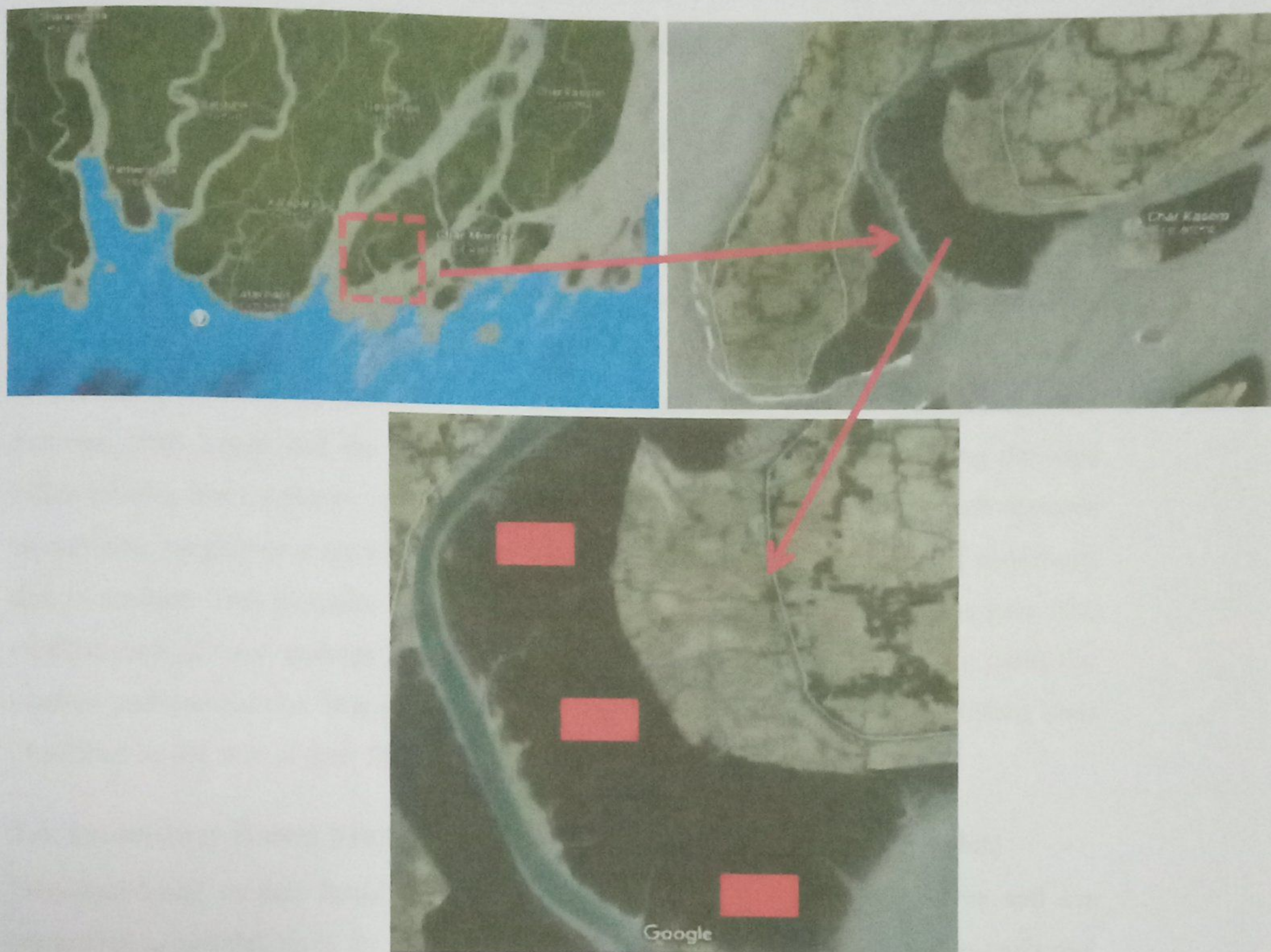

Figure 3.1: Map of the study site (Madarbunia, Rangabali, Patuakhali) and Location of sample plots (in Red colors) (Source: Google Map and Google Earth).

3.3. Modelling 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 mono-specific 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 mono-specific 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 analysing 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 is seen. 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 Louis 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 Modelling 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)

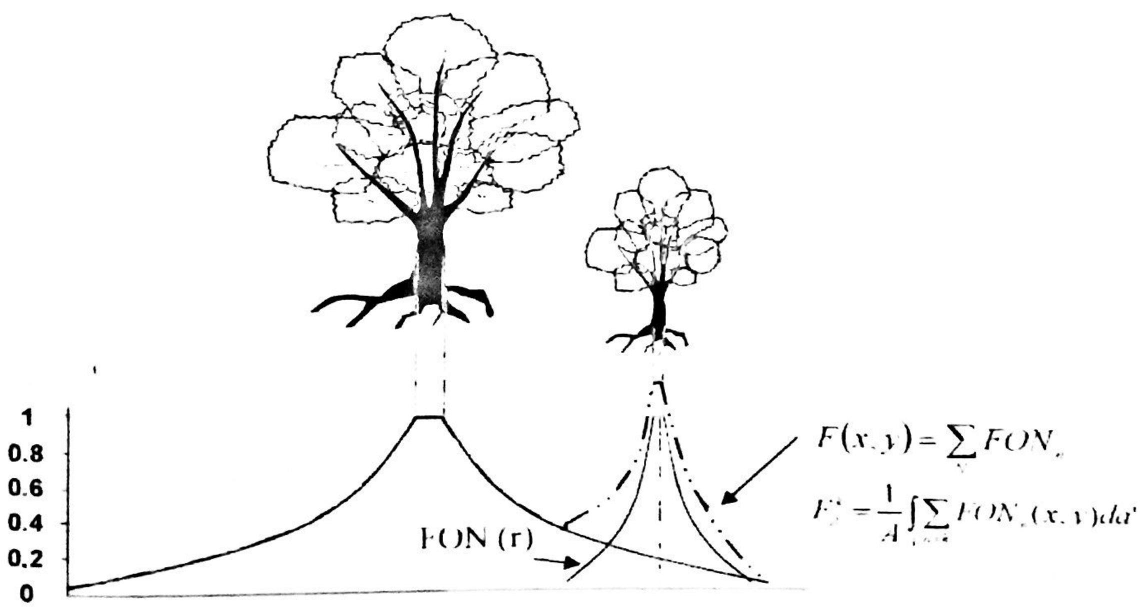

Figure 3.2: The Field of Neighborhood describes the competition strength that an individual exerts on its neighbors or on its environment. F(x, y) indicates the competition strength of all established trees at the location (x, y). FA records the competition that an individual encounters from its neighbours. A is the area of the zone of influence of the target plant. (Adapted from Berger et al. 2000)

3.4.2. Description of KiWi Model

Model describes the following 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 analysing 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 analyse 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 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.

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, 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 (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.

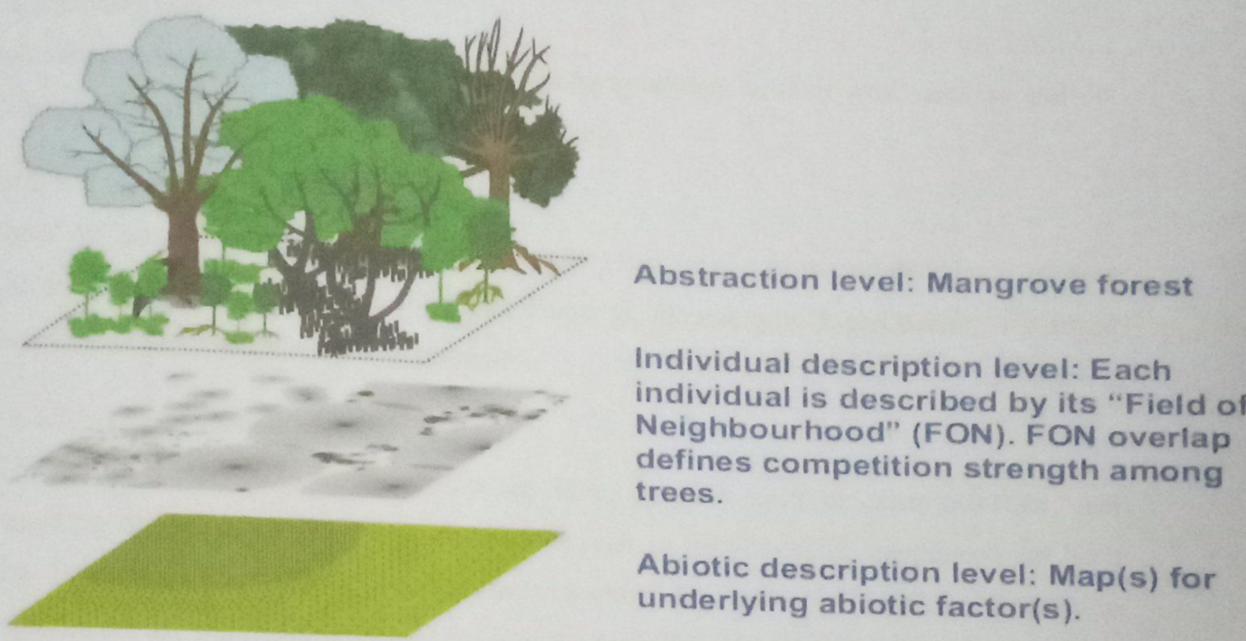

Figure 3.3: Scheme of KiWi Model (Adapted from Berger et al. 2000)

3.4.2.2. Design concepts

3.4.2.2..1. Emergence

The growth of each tree depends 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.

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 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 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 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.

3.4.2.3.1. Initialization

Stand development based on random tree positions, an initial height of 1.37 m and a stem D130 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 year 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. Sub-models

3.4.2.4.1. Description of a single tree

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 $(r) = e^{-c\,(r-(D_{130/2}))}$.

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 D130 and stem height H:

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

This function is parameterized for optimal growth conditions. The growth multiplier $((1-\varphi.CFON$)corrects the stem increment depending on tree neighbourhood competition, where φ represents the resource sharing capacity and CFON 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 mono-specific 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 mono-specific 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 modeling to prove that it shows better performance in mono-specific stands.

3.5. Silvicultural Treatments

According to the (Khoon and Eong 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 mono-specific stands of *Sonneratia apetala* with a rotation age of 60 years.

The seedlings are left to grow till around 15 years when the first thinning was carried out using various stick circumference radius so that any tree within a 0.5m radius to 4.5m 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 with 0.5m to 4.5m radius was used. This thinning also removes a lot of the trees. 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. 2006, Kairo et al. 2009).

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 et al. 2009), and D = Diameter (cm).

According to (Chave et al. 2005)

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

According to (Chave et al. 2005) especially for Mangrove:

$$AGW = 0.0509 \times \rho \times D^2 \times H \quad (3)$$

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

3.7. Conversion of Biomass to Carbon

Estimated biomass from the allometric relationship was multiplied by the wood carbon content (47%). As almost a carbon measurement projects in the tropical forest assume all tissues (Live biomass, dead wood) consist of 47% carbon on a dry mass basis (Hengeveld et al. 2015)

According to IPCC (2006):

Carbon = Biomass estimated by allometric equation × Wood carbon content %

= Biomass estimated by allometric equation × 0.47

3.8. Statistical Analysis

The normality of distribution of carbon stock and rates (aboveground) for the entire data sets were tested R programming. When and if distributions were approximately normally distributed, One-Way ANOVA was performed to explore the significant difference between aboveground carbon stocks in different ages. Descriptive analysis was done to explore minimum, maximum and mean value of different parameters. Analysis was performed using R programming (R Studio), Microsoft Excel 2010.

CHAPTER 4: RESULTS AND DISCUSSION

4.1. Results

4.1.1. KiWi Parameters for Simulation in *Sonneratia apetala*

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 4.1.1: 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).

4.1.2. Analysis of Field Data & Comparison between Field Data and Simulated Data

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 ($R^2 = 0.9945$) 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*.

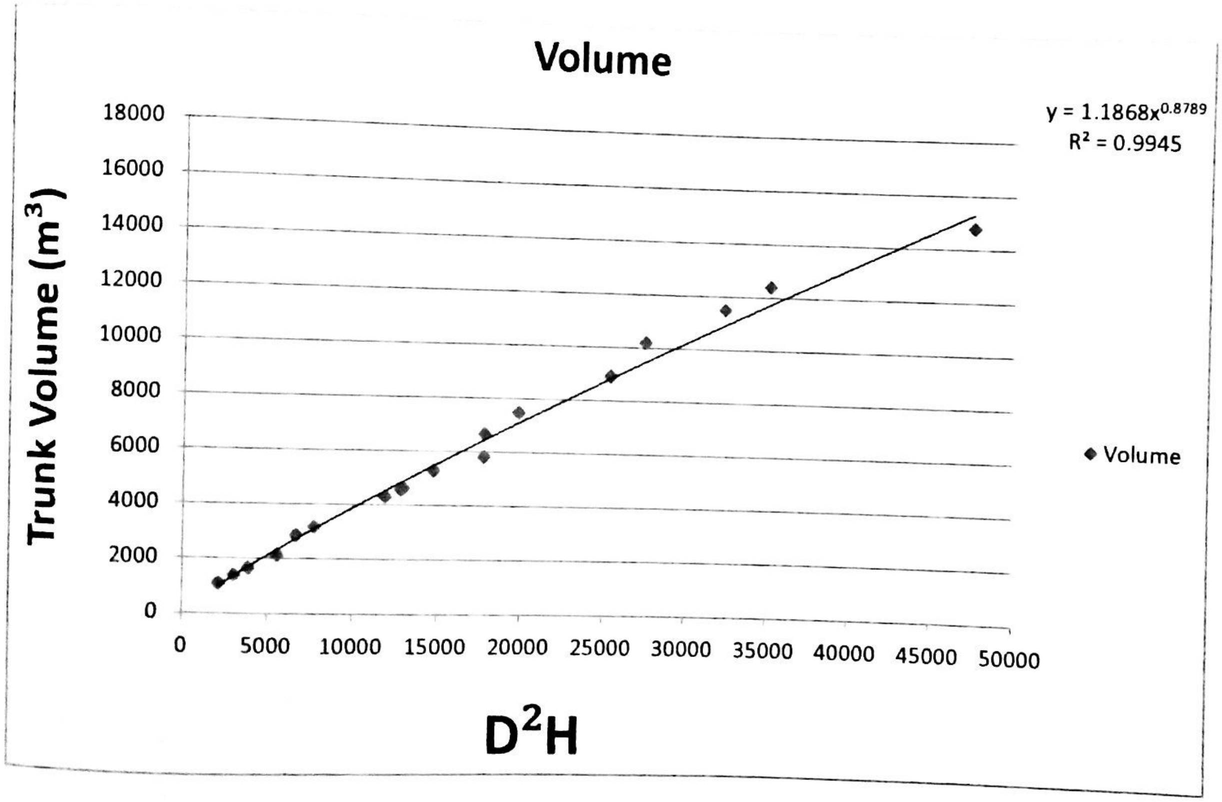

Figure 4.1: Allometric relationship of trunk volume (m^3) in relation to tree diameter and height in *Sonneratia apetala* using field data ($y = 1.1868x^{0.8789}$, $R^2 = 0.9945$)

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.

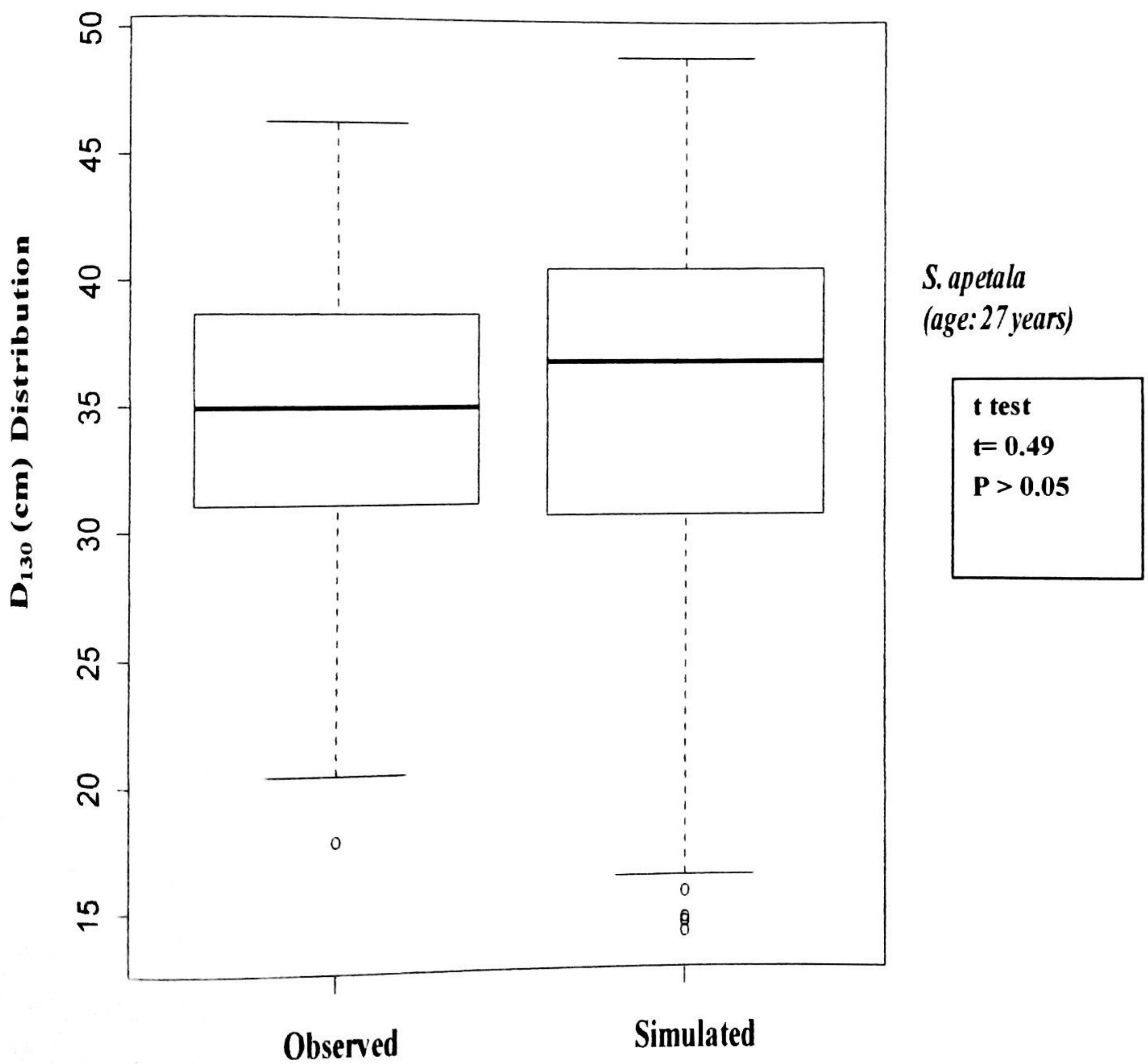

Figure 4.2: Box plot of observed and simulated distribution of tree diameter (D_{130}) in *Sonneratia apetala* stands

The highest harvested above-ground biomass as well as basal area at 60-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 60 years of stand age.

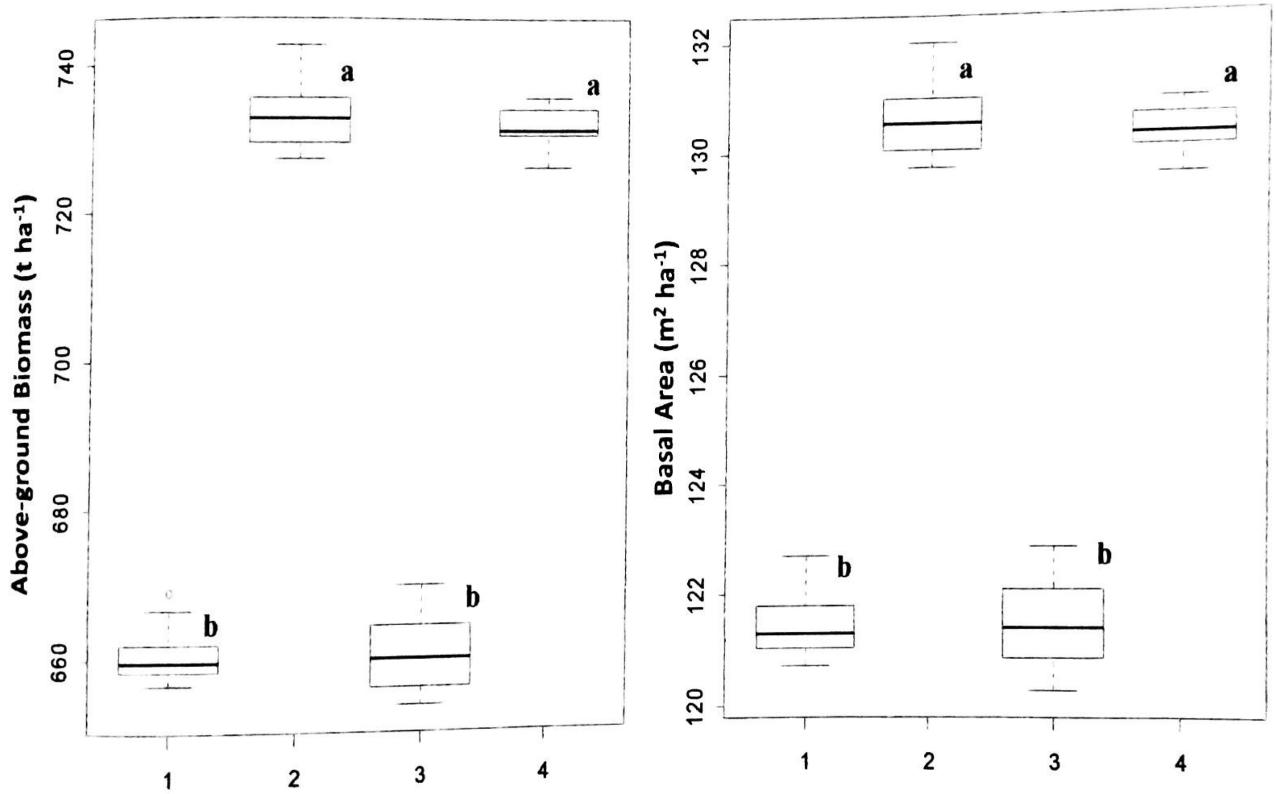

Figure 4.3: Above-ground biomass and basal area in *Sonneratia apetala* over 60 year's rotation period.

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 60 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

4.1.3. Spacing Dependent Experiment for (Without thinning Without Recruitment)

The output and parameterization of the model was evaluated based on monitoring data obtained in the field. At first, we have set different spacing (2m×2m to 10m×10m) in the model code and at that time thinning and regeneration were totally omitted. Then we have simulated for 10 times. From the output of the model, we can see that at the earlier age the number of trees is so high but the total aboveground carbon is low. But at the end of the rotation age (60years) the total number of trees is low but the total aboveground carbon is high. At every age, the aboveground carbon is maximum at a certain stage and then it starts to reduce which create a bell shaped curve showing in the figure 4.4.

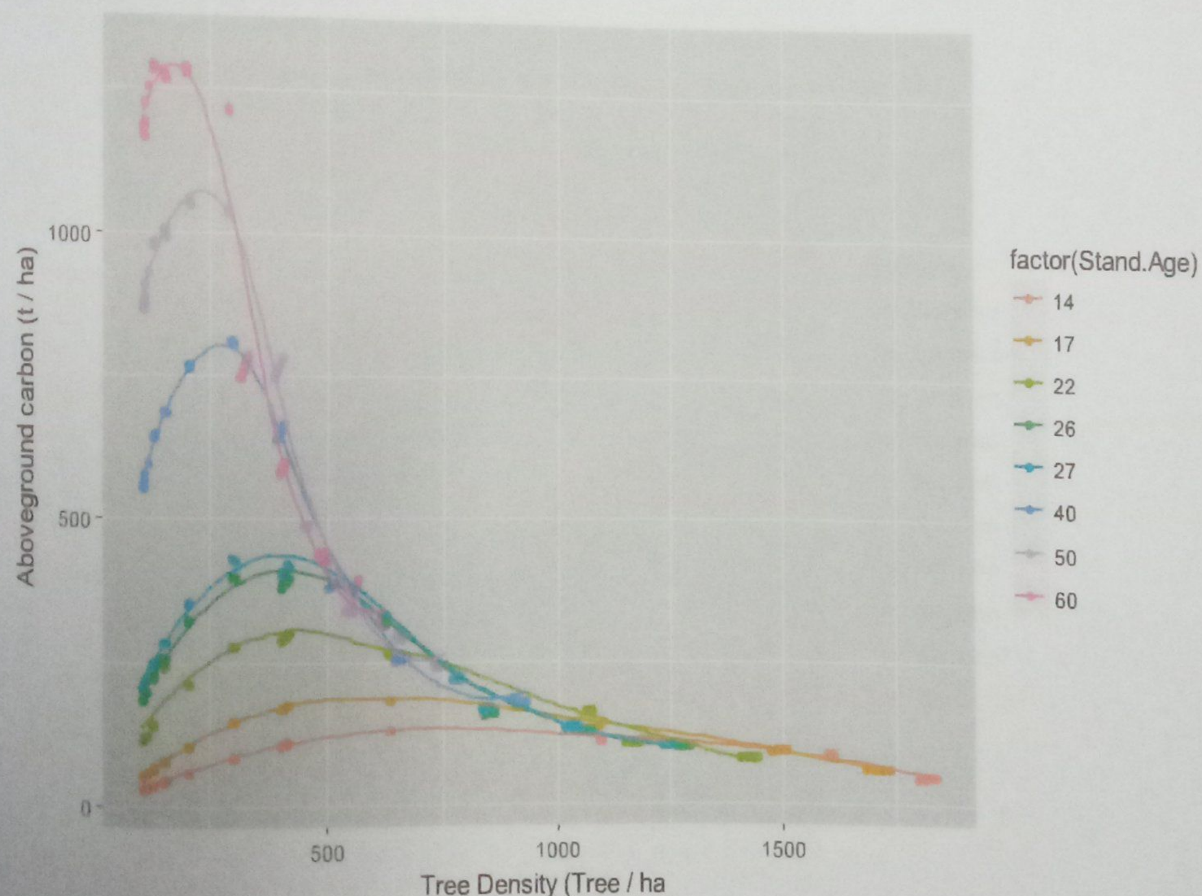

Figure 4.4: Tree density (Trees/ha) and aboveground carbon at different ages

When we observe at the different spacing (2m×2m, 2.5m×2.5m, 3m×3m, 4m×4m, 5m×5m, 6m×6m, 7m×7m, 8m×8m, 9m×9m, 10m×10m) in the figure 4.5, the tree density is highest at the 2m×2m spacing but the aboveground carbon is lowest at the 2m×2m spacing. Then the tree density decreases and aboveground carbon increases chronological way up to 6m×6m spacing but aboveground carbon is higher at 7m×7m spacing than 8m×8m spacing. Tree density is lowest at the spacing 10m×10m and the maximum aboveground carbon is at 9m×9m spacing. The aboveground carbon is almost same in 8m×8m and 9m×9m spacing although the tree density is difference. The most interesting thing is that from the spacing 6m×6m, the tree density becomes fixed at every spacing but the aboveground carbon increases at every age.

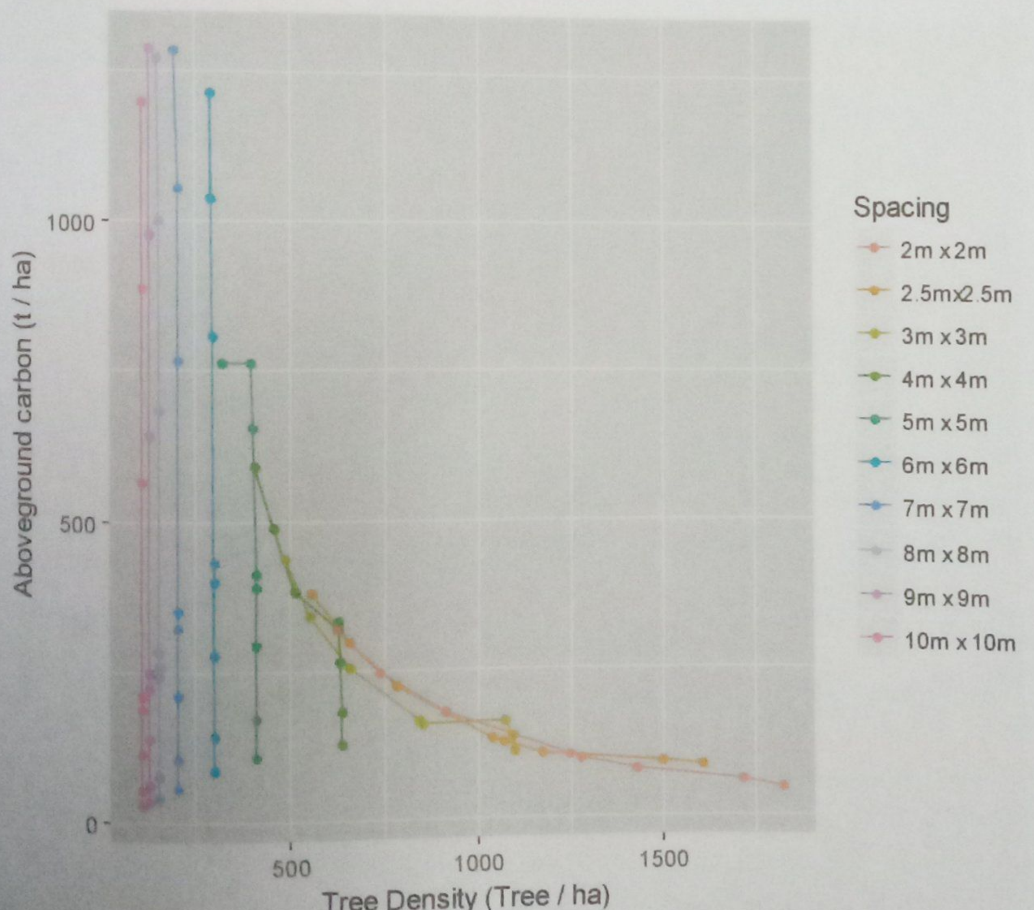

Figure 4.5: Tree density (Tree/ha) and aboveground carbon at different ages due to spacing variation

The initial aboveground carbon is almost same at every stages and it increases up to the rotation age. From the Figure 4.6, the aboveground carbon of (2m×2m, 2.5m×2.5m, 7m×7m, 8m×8m, 9m×9m, 10m×10m) spacing increases continuously but others show difference. In 3m×3m spacing, the aboveground carbon decreases at 26 years and 27 years and after that it becomes increasing linearly up to 60 years. In 4m×4m spacing, the aboveground carbon decreases at 40 years and after that it becomes increasing linearly up to 60 years. In 5m×5m spacing, the aboveground carbon increases up to 50 years and after that the aboveground carbon becomes fixed. In 4m×4m spacing, the aboveground carbon increases up to 40 years and after that it becomes decreasing up to 60 years. 9m×9m spacing produces the maximum amount of aboveground carbon after the rotation age which is shown in Figure 4.6.

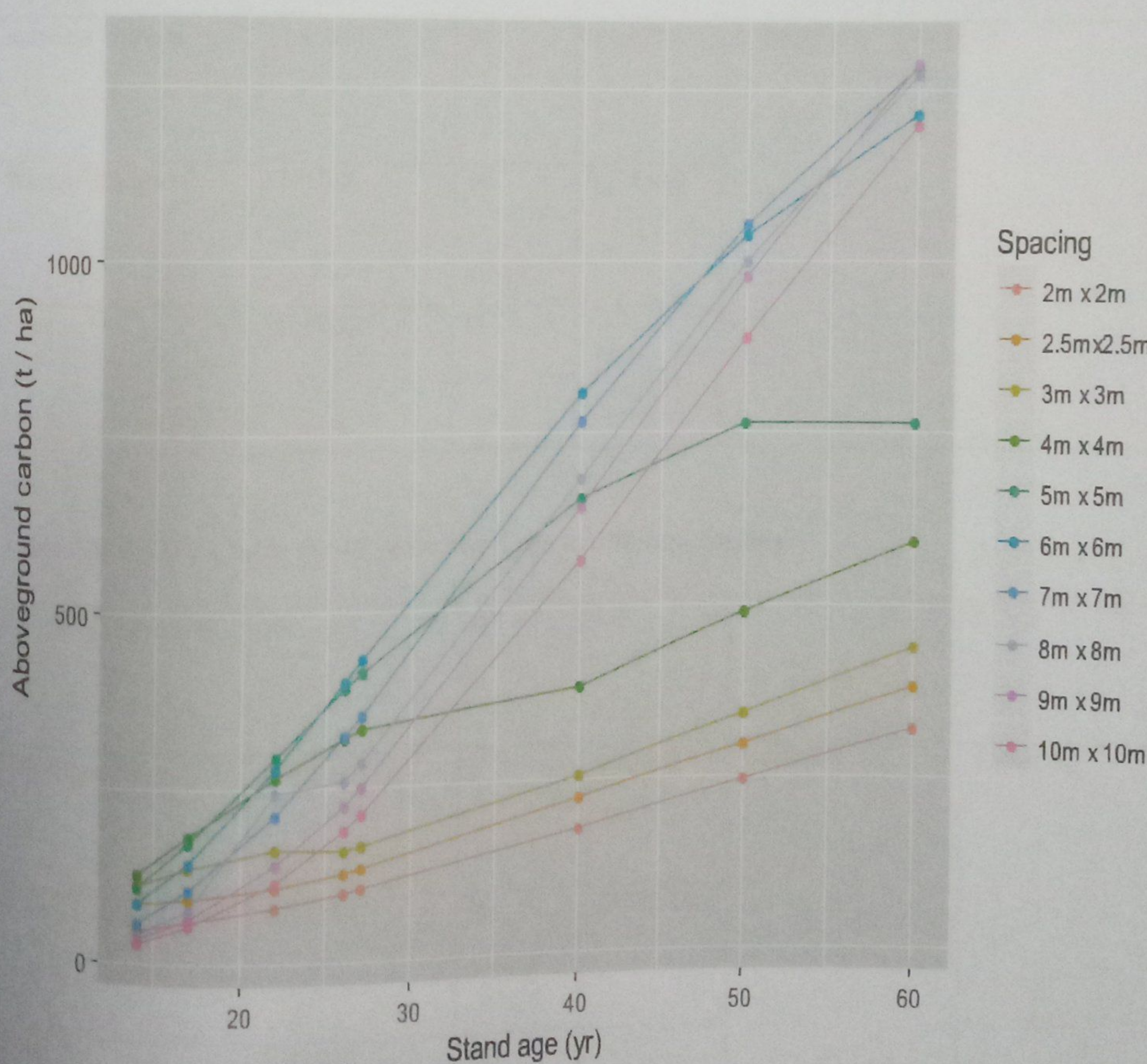

Figure 4.6: Stand age (yr) and aboveground carbon (t/ha) due to spacing variation

4.1.3..1. ANOVA for Testing Variation among Differences Ages

The observed frequency distributions of diameter (D_{130}) in the *Sonneratia apetala* stands showed no remarkable differences to that in the simulated results in different space at stand ages of (14,17,22,26,27,40,50,60) years separately as revealed by the median values. There was no significant difference in the mean diameter between different space at (14,17,22,26,27,40,50,60) years old ($P > 0.05$) as tested with one factor ANOVA test.

Table 4.3: ANOVA table for 27 years stand age in different spacing

Source of Variation	*SS*	*df*	*MS*	*F*	*F crit*
Between Groups	37.46511	9	4.16279	0.00032158	1.985595
Within Groups	1165044	90	12944.94		
Total	1165082	99			

Table 4.4: ANOVA table for 40 years stand age in different spacing

Source of Variation	*SS*	*df*	*MS*	*F*	*F crit*
Between Groups	4180.37	9	464.4855	0.008398	1.985595
Within Groups	4977705	90	55307.84		
Total	4981886	99			

Table 4.5: ANOVA table for 60 years stand age in different spacing

Source of Variation	*SS*	*df*	*MS*	*F*	*F crit*
Between Groups	1515.693	9	168.4103	0.000981	1.985595
Within Groups	15443478	90	171594.2		
Total	15444993	99			

The observed frequency distributions of diameter (D_{130}) in the *Sonneratia apetala* stands showed remarkable differences to that in the simulated results in different spaces at different stand ages of together as revealed by the median values. There was significant difference in the mean diameter between different space at different ages together ($P < 0.05$) as tested with one factor ANOVA test.

Table 4.5: ANOVA table for different stand ages in different spacing

Source of Variation	*SS*	*df*	*MS*	*F*	*F crit*
Between Groups	18519562	29	638605.6	7.987663	1.509627
Within Groups	21586227	270	79948.99		
Total	40105789	299			

4.1.4. Effect of Thinning Operation in Carbon Stocks

The output and parameterization of the model was evaluated based on monitoring data obtained in the field. At first, we have set different radius (0.5m to 4.5) in the model code and at that time regeneration were totally offed. Then we have simulated for 10 times. From the output of the model, we can see that at the earlier age, the number of trees is so high but the total aboveground carbon is low. But at the end of the rotation age (60years) the total number of trees is low but the total aboveground carbon is high. The aboveground carbon is found maximum when the number of trees is approximately 200/ha. At the age 14 years, the aboveground carbon is same in all stage but at the age of 17 years, the aboveground carbon is decreasing continuously which are shown in figure 4.7. At every other age, the aboveground carbon is maximum at a certain stage and then it starts to reduce which create a bell shaped curve showing in the figure 4.5

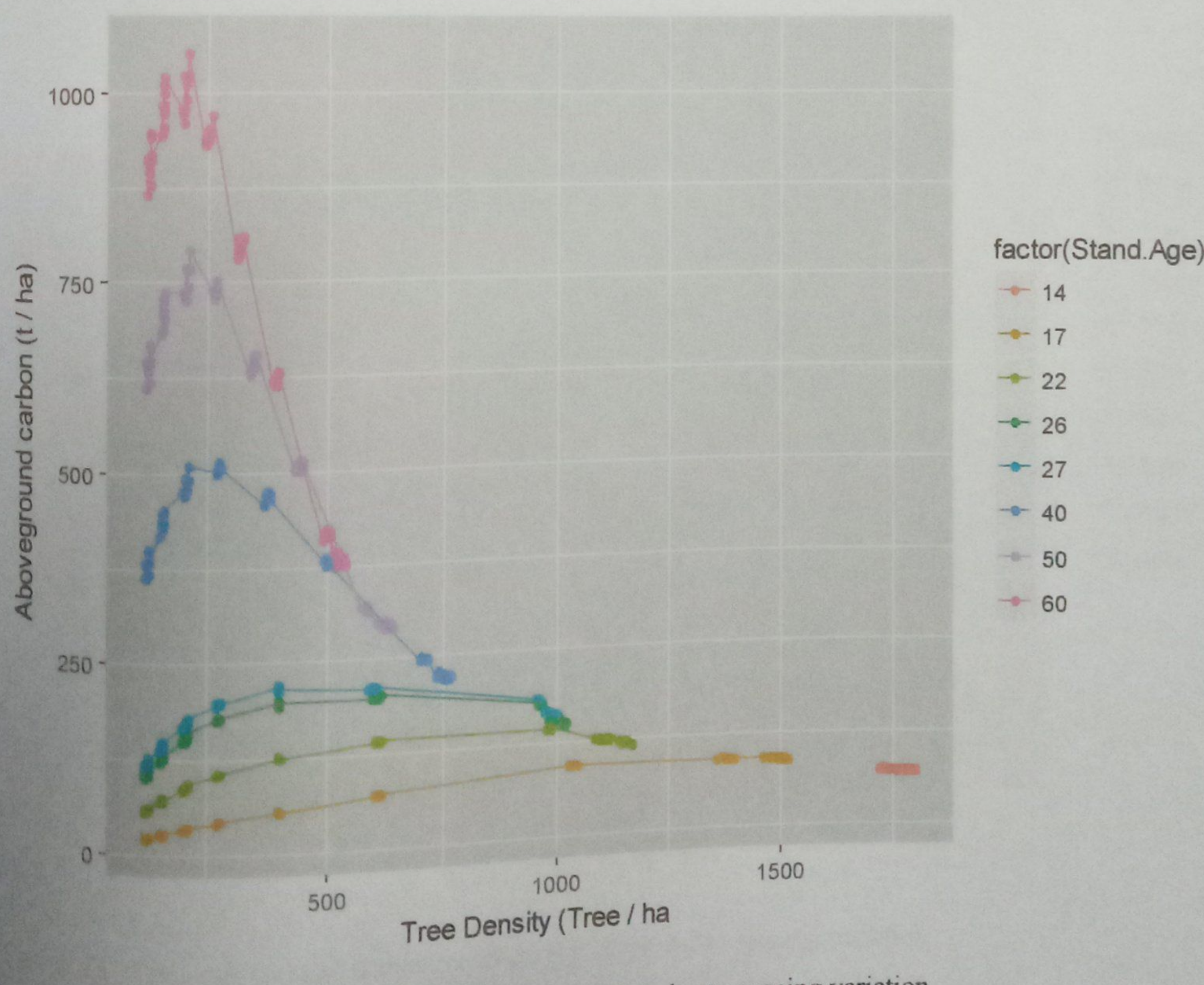

Figure 4.7: Stand age (yr) and aboveground carbon (t/ha) due to spacing variation

When we observe at the different thinning radius (0.5m, 1.0m, 1.5m, 2.0m, 2.5m, 3.0m, 3.5m, 4.0m, 4.5m) in the figure 4.8, the tree density is highest at 0.5m radius but the aboveground carbon is lowest at the 0.5m radius. Then the tree density decreases and aboveground carbon increases chronological way up to 3.0m thinning radius but aboveground carbon is maximum at 3.5m thinning radius. Tree density is lowest at the 4.5m thinning radius and the maximum aboveground carbon is at 3.5m thinning radius. The aboveground carbon is lower in 4.0m and 4.5m than 3.5m thinning radius. The most interesting thing is that from the 3.0m thinning radius, the tree density becomes fixed at every thinning radius but the aboveground carbon increases at every age. On the other hand 2.5 m and 3.0 m thinning radius contain adequate number of trees and also produce above ground carbon as same as 3.5 m thinning radius.

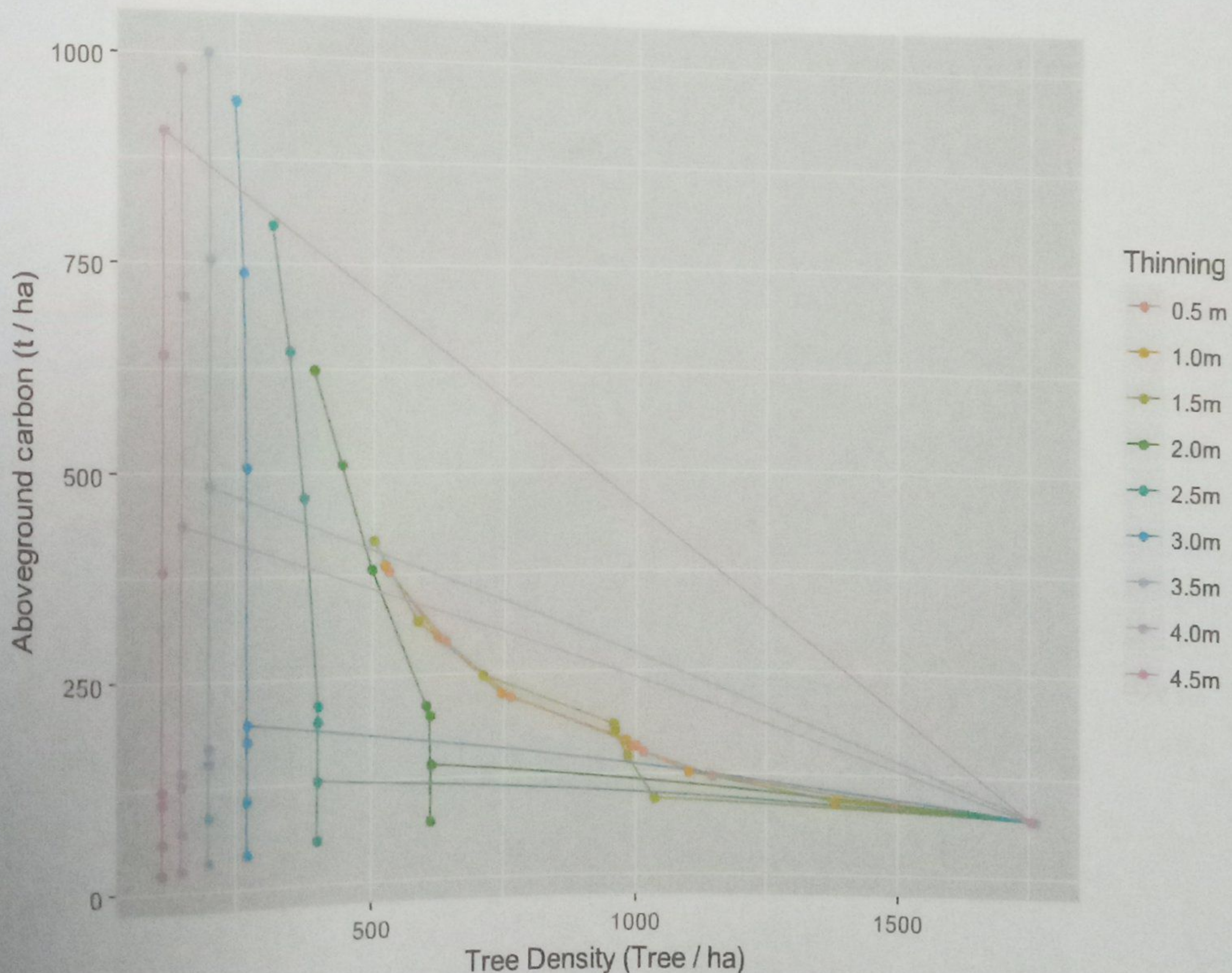

Figure 4.8: Stand age (yr) and aboveground carbon (t/ha) due to spacing variation

The initial aboveground carbon is almost same at every stages and it increases up to the rotation age. From the Figure 4.9, the aboveground carbon of 0.5m, 1.0m, 1.5m thinning radius increases continuously but others show difference. In 2.0m to 4.5m radius thinning, the aboveground carbon decreases after 1st thinning (17 years) and after that the aboveground carbon starts increasing up to 60 years. 3.5m thinning radius produces the maximum amount of aboveground carbon after the rotation age which is shown in Figure 4.9. 4.0m thinning radius produces 2nd highest aboveground carbon. 4.5m thinning radius produces less carbon than 3.5m, 4.0m and 3.0m radius. When the thinning radius is 0.5, the aboveground carbon production is lowest.

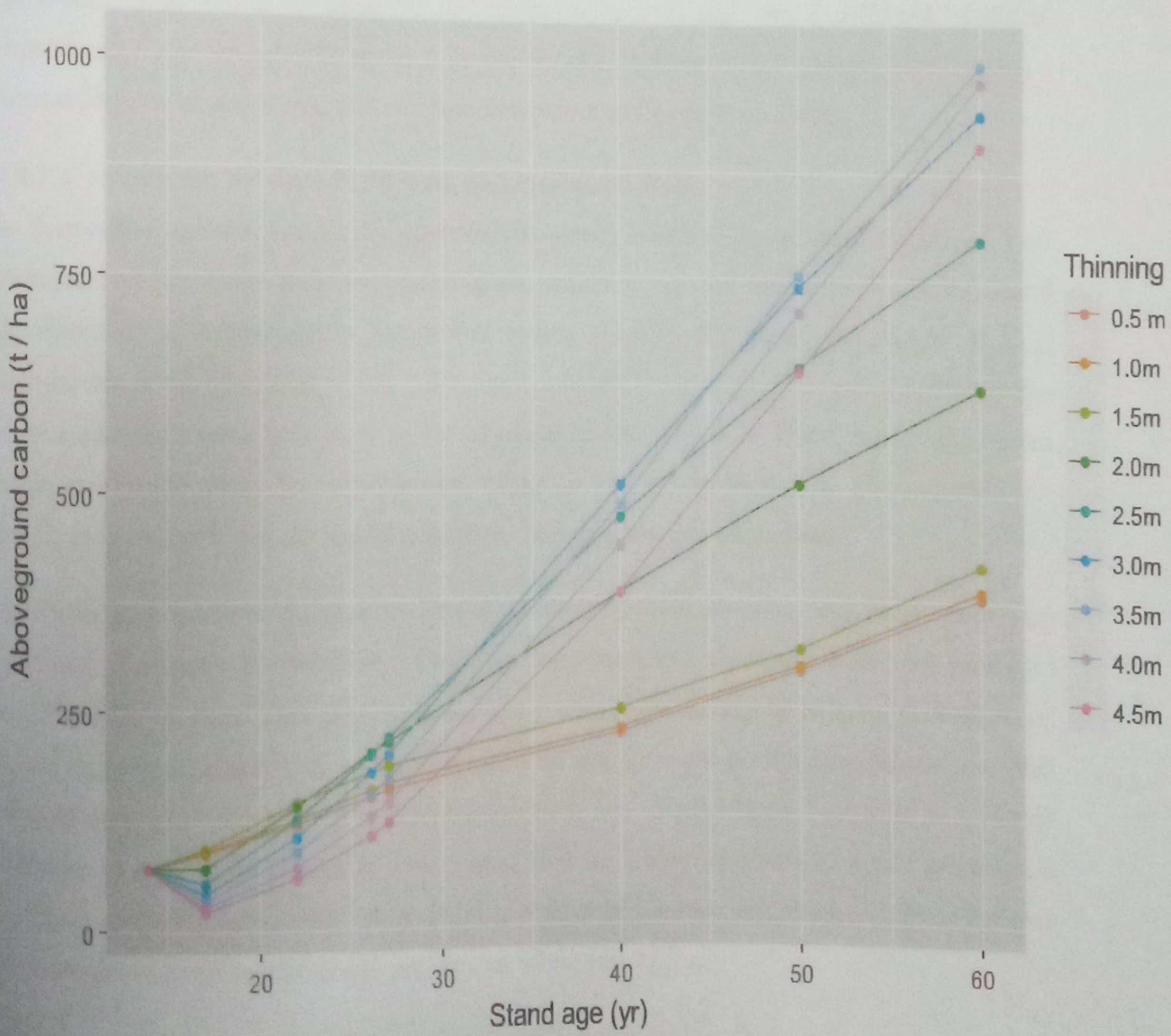

Figure 4.9: Stand age (yr) and aboveground carbon (t/ha) due to thinning radius variation

4.2. Discussion

4.2.1. Analysis of Field Data

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 = 0.9945) was obtained using a combination of tree height and diameter at breast height (D^2H) as the independent variables (Kairo et al. 2009). The strength of the reported allometric relationships of *Sonneratia apetala* (R^2 = 0.9945) 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. 2009).

4.2.2. Comparison between Field Data and Simulated Data

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.

4.2.3. Spacing Dependent Experiment for (Without thinning Without Recruitment)

At the earlier age the number of trees is so high but the total aboveground carbon is low. But at the end of the rotation age (60years) the total number of trees is low but the total aboveground carbon is high. At every age, the aboveground carbon is maximum at a certain stage and then it starts to reduce which create a bell shaped curve showing in the figure 4.4 which supports the ecological logistic growth curve.

When the spacing is low, the aboveground carbon is low. When the spacing is increasing, the aboveground carbon is also increasing because the tree density decreases. The remaining trees get more space, nutrition, light to grow. When tree density is higher, the trees don't get proper space, nutrition to grow. After a certain spacing, the aboveground carbon production starts decreasing. So we should fix the proper spacing to get maximum biomass.

9m×9m spacing produces the maximum amount of aboveground carbon after the rotation age which is shown in Figure 4.6. 9m×9m spacing can be suggested for proper management to obtain maximum benefit. But the number of trees is so low which does not support the coastal plantation's objectives. On the other hand 6m×6m spacing contains adequate number of trees and also produce above ground carbon as same as 3.5 m thinning radius.

From the ANOVA test, we can say that the *Sonneratia apetala* stands show no remarkable differences to that in the simulated results in different space at different certain stand ages such as 27 years, 40 years, 60 years separately. But when we take all the all the stand age at different spacing, the *Sonneratia apetala* stands show no remarkable differences to that in the simulated results.

4.2.4. Effect of Thinning Operation in Carbon Stocks

At the earlier age, the number of trees is so high but the total aboveground carbon is low. But at the end of the rotation age (60years) the total number of trees is low but the total aboveground carbon is high. 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 year stand ages (Fig. 4.3).

When the thinning radius is low, the aboveground carbon is low. When the thinning radius is increasing, the aboveground carbon is also increasing because the tree density decreases. The remaining trees get more space, nutrition, light to grow. When tree density is higher, the trees don't get proper space, nutrition to grow. After a certain thinning radius, the aboveground carbon production starts decreasing. We found that 3.5 m thinning radius produces the maximum amount of aboveground carbon at the rotation age (Figure 4.6). Among the different thinning radius, 3.5 m radius thinning shows maximum aboveground carbon stocks in *Sonneratia apetala*, which is comparable to 1.8 m stick radius thinning practiced in Matang Mangrove, Malaysia for *Rhizophora apiculata*. But in 3.5 m thinning radius, the number of trees is so low which does not support the coastal plantation's objectives. On the other hand 2.5 m and 3.0 m thinning radius contain adequate number of trees and also produce above ground carbon as same as 3.5 m thinning radius.

In our simulation code we used 1 m to 9 m thinning square. The half of these are .5 to 4.5 m as radius. In Matang, it is 1.2 m radius at 15 yrs and 1.8 m radius at 20 yrs. In your case 3.5 m is little bit higher than Matang 1.8. This is for species difference, i.e. keora may require more space to grow to maximum size. But if we think ecologically, 2.5 m or 3.0 m thinning radius is perfect for coastal plantation.

So 2.5m or 3.0m thinning radius can be suggested for proper management to obtain maximum benefit and conserve coastal green belt. This experiment strongly supports that the KiWi model can mimic real dynamic growth pattern.

Chapter 5: CONCLUSION

Bangladesh is a pioneer country in raising successful plantations with *Sonneratia 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 a periodic thinning and spacing offers a higher yield than that with no silvicultural treatment. Simulation experiments, tuned to observed configurations of the study sites, provided a forecast of the stand development to be expected in the future. Although the main objectives of coastal mangrove plantations by Bangladesh forest department is coastal protection, Keora plantations can be more productive if an initial spacing of 5 m x 5 m is followed or a thinning at the age of 15 having a thinning radius of 2.5m-3.0 m is followed.

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