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Carbon Sequestration Dynamics in the Coastal Mangrove Plantations in Bangladesh

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BANGLADESH

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COURSE TITLE # THESIS WORK

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19/09/18

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Dedicated to…

My Beloved Family

…who were, are and always will be
with me whoever I be & whatever I consist,
learn and create

Abstract

This study unfolds information about dynamic partitioning of organic carbon (C) in the soil vegetation system in coastal mangrove plantations in Bangladesh. 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 performance of *S. apetala* for the development of monospecific stands in the coastal areas. This study was conducted to quantify the C sequestration in the soil-vegetation system of the mangrove plantations in Bangladesh and to build a simple C sequestration model to predict C sequestration in mangrove plantations in next few decades. The relationships of soil C concentration and soil carbon stocks to stand age were analyzed. The variation of C stocks in the soil vegetation system at different age of stands. Our results suggest that soil C concentration and carbon stocks increases with increasing stand age. 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, *S. apetala* plantations can be more productive if a suitable initial spacing and an intermediate thinning are followed.

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I, **Atikur Rahman**, with passionate gratitude, proclaiming heartiest joy for my fulfilment of this research by the grace of almighty Allah. The journey was a tough one to reach the goal line, where every step needed a help, and that's why this research is confessing the gratitude of all the people helped, in between the research completion time period.

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....

Atikur Rahman

APPROVAL

This is to certify that, Atikur Rahman, Student ID: MS-150503 has prepared this thesis entitled "**Carbon Sequestration Dynamics in the Coastal Mangrove Plantations in Bangladesh**" 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 Master's 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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Abbreviations and Acronyms

C = Carbon

N = Nitrogen

CO_2 = Carbon Dioxide

SOC = Soil Organic Carbon

BD = Bulk Density

AGB = Above Ground Biomass

AGC = Above ground Carbon

BGB = Below Ground Biomass

BGC = Below Ground Carbon

DBH = Diameter at Breast Height

GHG = Green House Gas

ODD = Overview, Design concepts, Details

ZOI = Zone of Influence

FON = Field of Neighbourhood

POM = Pattern Oriented Modelling

REDD+ = Reducing Emissions from Deforestation and forest Degradation

IPCC = Intergovernmental Panel on Climate Change

UNESCO = The United Nations Educational, Scientific and Cultural Organization

UNITS

cm	Centimeter	**Mg**	Megagram
ha	Hectare	**mm**	Milimeter
Kg	Kilogram	**ppm**	Parts Per Million
m	Meter	**pg**	Picogram
m^2	Square Meter		

CHAPTER ONE: INTRODUCTION

1.1 Background of the Study

The World today is facing major challenges caused by atmospheric CO_2 causing global warming. Anthropogenic carbon dioxide (CO_2) emissions into the atmosphere have increased significantly over the last 20 years (Boden *et al.* 2009, Sommer and Bossio 2014) and could reach between 478 and 1099 p.p.m. by 2100 (Stocker *et al.* 2013a). This increase is attributable to fossil fuel combustion and land use change, including deforestation and burning of forests or degradation of soils and loss of soil organic carbon (SOC). Global warming is mostly due to man-made emissions of greenhouse gases (mainly CO_2) (Stocker *et al.* 2013b). The average global temperature will increase by 2-4^{0}C by the year 2050 (IPCC 2013) and as a result most of the polar ice melting to raise the sea level by 5 m causing serious loss of life and property specially in the developing countries (Detwiler and Hall 1988, Rahman *et al.* 2015). Bangladesh is among the most vulnerable countries affected by global warming. Ways and mechanisms are needed to reduce greenhouse gases emissions or e.g. by capture or sequestration of C in aboveground biomass or soils.

Forests play an important role in mitigating global climate change through sequestering atmospheric carbon (Adame *et al.* 2013) and mangroves are amongst the most efficient in carbon sequestration (Rahman *et al.* 2015). Mangroves are particularly efficient sinks, sequestering four times carbon per unit area compared with terrestrial forests in the tropics (Khan *et al.* 2007, Donato *et al.* 2011). However, deforestation of mangroves, which was very widespread in the last few decades may render them significant sources of atmospheric carbon (Donato *et al.* 2011) and policy makers are looking at new ways to save mangroves through different mitigation approaches such as 'Reducing emissions from deforestation and forest degradation (REDD+)'. So, in order to participate in UNFCCC's mitigation programs (e.g., REDD+) and thereby generate economic benefit for the country, it is imperative to make a baseline assessment of the carbon storage (Adame *et al.* 2013) in the coastal mangrove plantations.

Mangrove reforestation and afforestation (collectively referred to as forestation) programs in coastal area have been initiated in many countries over the past few decades (Field 1999, Ellison 2000). The earliest forestation efforts were essentially silviculture-oriented, while more recent projects have included ecological objectives, such as shoreline stabilization and environmental remediation (Ellison 2000, Lunstrum and Chen 2014). With increasing concerns related to climate change, carbon sequestration is also beginning to be considered among conservation and forestation goals (Murray *et al.* 2011). To predict whether and at what rate C accumulates in the soil of mangrove plantations, simulation modeling have been proven to be more efficient tools (Köhler and Huth 2004, Phillips *et al.* 2004).

Modeling provides a unique approach for projecting forest ecosystem carbon dynamics. Forest ecosystem models have a tight coupling between physical and biological processes such as photosynthesis, growth, mortality, and decomposition while simulating aboveground carbon dynamics. They also include biogeochemical processes while simulating belowground carbon dynamics (Lu and Cheng 2009). Several forest ecosystem models were developed to predict forests carbon stocks, including the Boreal Forests Carbon Dynamics Model (Nalder and Wein 2006), the Carbon Budget Model of the Canadian Forest Sector (Kurz *et al.* 2009, Huang *et al.* 2017), the Individual based Spatially Explicit Simulation Model of Forest Ecosystem (Chertov *et al.* 2009), the Individual based forest ecosystem model LINKAGES (Post and Pastor 1996) and the Terrestrial Ecosystem Model (Zhuang *et al.* 2002). These models offer valuable insights into the effects of climate change and disturbances on future potential changes in carbon dynamics (Huang *et al.* 2017).

The ratio of aboveground to belowground biomass (top/root, *T/R*) is a standard to judge the biomass-allocation pattern to the underground part of a forest. Mangroves show relatively high amount of root biomass than other forms of forests (Saintilan 1997, Komiyama et al. 2000). Therefore, mangroves play a significant role in carbon sequestration not only in aboveground but also in belowground. In mangrove forests, a large proportion from half to over 90% of total ecosystem Carbon (C) is found in soil organic matter as opposed to biomass (Alongi *et al.* 2003, Khan *et al.* 2007, Lunstrum and Chen 2014). Mangroves constitute efficient sinks of C, Nitrogen (N) and essential nutrients, which ensures high rates of plant growth (Alongi 1996, Alongi *et al.* 2001).

Although terrestrial forests are widely recognized with the quantification of C pools, a few studies exist that have focused on organic carbon stocks and dynamics in the sediments of natural mangroves (Alongi *et al.* 2003, Khan *et al.* 2007, Rahman *et al.* 2015), the C sequestration pattern in mangrove plantations is little known. Therefore, the present study aims to quantify the C sequestration, as well as to evaluate the C in the soil-vegetation system of the mangrove plantations.

1.2 Objectives of the Study

The objectives of the study are given below:

- To estimate the above- and belowground carbon stock in study area;
- To quantify the carbon sequestration in the soil-vegetation system of the coastal mangrove plantations;
- To build a simple C sequestration model to predict C sequestration in next few decades.

CHAPTER TWO: LITERATURE REVIEW

2.1 Carbon Sequestration

Carbon sequestration refers to the capture and long-term storage of carbon in forests and soils so that the build-up of CO_2 (one of the principles greenhouse gases) in the atmosphere will reduce or slow. The (UNFCCC 1992) defines carbon sequestration as the process of removing carbon from the atmosphere and depositing it in a reservoir. According to the U.S. Geological Survey (USGS 2008), The term "carbon sequestration" is used to describe both natural and deliberate processes by which CO_2 is either removed from the atmosphere or diverted from emission sources and stored in the ocean, terrestrial environments (vegetation, soil and sediments), and geologic formations. At present, carbon sequestration 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).

2.2 Types of Carbon Sequestration

According to (Metz *et al.* 2005), CO_2 sequestration can be done by the following three ways

I. **Terrestrial sequestration or vegetative sequestration:** Terrestrial sequestration is the natural intake of CO_2 by plants, which incorporate in their wood, leaves, and roots and also bind it to the underlying soil so much of this CO_2 is not released into the atmosphere until the plant is destroyed (by decay or burning) or the soil is tilled and exposed to the atmosphere. This can be enhanced by increasing the growth of land plants through planting trees, mitigating deforestation or adjusting forest management practices. It is the easiest and most immediate option for carbon sequestration at the present time.

II. **Geologic sequestration:** Geosequestration is burying the CO_2 deep within the earth. It can be done by the mechanical capture of CO_2 from an emission source (e.g., a power plant, fossil fuel burning etc.) and the captured CO_2 is injected and sealed into deep rock units. The most suitable sites are deep geological formations, such as depleted oil and natural gas fields or deep natural reservoirs filled with saline water (saline aquifers).

III. **Oceanic sequestration:** Oceanic sequestration is dumping the CO_2 into the depths of the ocean. This uptake is not a result of deliberate sequestration but occurs naturally through chemical reactions between seawater and CO_2 in the atmosphere. While absorbing atmospheric CO_2, these reactions cause the oceans to become more acidic. Many marine organisms and ecosystems depend on the formation of carbonate skeletons and sediments that are vulnerable to dissolution in acidic waters (USGS 2008).

2.3 Carbon Sequestration in Mangrove Forest

Mangrove can trap not only fine sediment and organic matter but also coarse sediment driven by storm waves to form special mangrove sediment. Thus, the rate of sedimentation in mangrove is high. Besides, the litter productivity is also high in Mangroves, which provides more carbon sequestrated in sediments of mangrove, high below ground carbon sequestration. This indicates positive action in mangrove conservation and rehabilitation would contribute immensely to sequestrate CO_2 (Tateda *et al*. 2005).

Components like NPK, organic carbon export etc. per ha, were estimated in different studies. The global storage of carbon in mangrove biomass is estimated at 4.03 Pg C. The average rate of wood production is 12.08 Mg ha^{-1} $year^{-1}$, which equivalent to a global estimation of 0.16 Pg C $year^{-1}$ stored in mangrove biomass. The net ecosystem production in mangroves is about 0.18 Pg C $year^{-1}$ (Eong 1993). Mangroves are important carbon sinks and sequester approximately 25.5 million tons of carbon every year (IUCN 2009). They also provide more than 10% of essential dissolved organic that is supplied to the global ocean from land (IUCN 2009, Laffoley and Grimsditch 2009). Disturbed mangrove soils release greater than an additional 11 million metric tons of carbon annually.

2.4 Climate Change and its Effects

According to (UNFCCC 1992), "Climate change" means a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods. The main characteristics of climate change are increasing in average global temperature (global warming) (UNFCCC 2007). This increase in atmospheric CO_2 from about 280 to more than 380 parts per million (ppm) over the last 250 years (USGS 2008) and it has been predicted that atmospheric CO_2 will range between 467-555 ppm by the year 2050 and average global temperature will increase by 2-42°C, will causing measurable global warming (IPCC 2007, Anderson and Bows 2011, Stocker *et al.* 2013b).

Coasts are very likely to be exposed to increasing risks, including coastal erosion, due to climate change and sea-level rise. Many millions more people are projected to experience severe flooding every year due to sea-level rise by the 2080s. The numbers affected will be largest in the mega-deltas of Asia and Africa, while small islands are especially vulnerable. Regional changes in the distribution and production of particular fish species are expected due to continued warming, with adverse effects projected for aquaculture and fisheries (UNFCCC 1992).

A 4°C rise could be potentially devastating leading to inundation of coastal areas, increased intensity of tropical cyclones; unprecedented heat waves exacerbated water scarcity; increasing risks for food production potentially leading to higher malnutrition rates; and irreversible loss of biodiversity (Hemani 2015). In the Indian coast past observations on the mean sea level indicates a long-term rising trend of about 1.0 mm year^{-1} on an annual mean basis (Unnikrishnan *et al.* 2006, Raha *et al.* 2012).

More than four-fifth (83.9%) of the poor households of the Sundarbans community reported that rainfall has reduced significantly due to climate change. More than two-fifth (43.1%) poor households have experienced inundation of their household due to flood and more than half (56.0%) reported about the flood at the surroundings of their household. More than one fourth (27.0%) experienced the increasing trend of temperature or feeling hotter than before. Climate change will have wide-ranging effects on the environment, and on socio-economic and related sectors, including water resources, agriculture and food security, human health, terrestrial ecosystems and biodiversity and coastal zones (UNFCCC 2007).

2.5 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 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, Barishal 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 2009). 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).

2.5.1 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.

2.5.2 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 chosen for the better performance in monospecific stands.

2.5.3 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*.

2.6 Species Information

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).

2.7 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 (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. There are also a few static trophic models estimating matter and energy flow in mangrove ecosystems (Wolff 2006). Currently there are only three spatially explicit individual based simulation models (IBMs) describing Neotropical mangrove forests: FORMAN, KIWI, and MANGRO (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 THREE: MATERIALS AND METHOD

3.1 Description of the Study Site

The Forest Department in 1960 to commence a programme of planting mangroves outside the protective coastal embankments in order to provide greater protection for inhabited coastal areas (Drigo et al. 1987). From 1960-61 to 2002-03, a total of 150,000 ha of mangrove plantation has been established through different development projects using mainly Keora (*Sonneratia apetala* Buch.-Ham.), Baen (*Avicennia officinalis* L.) and few other mangrove species. 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 $dS{\cdot}m^{-1}$ 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).

3.2 EXPERIMENTAL DESIGN:

3.2.1 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.

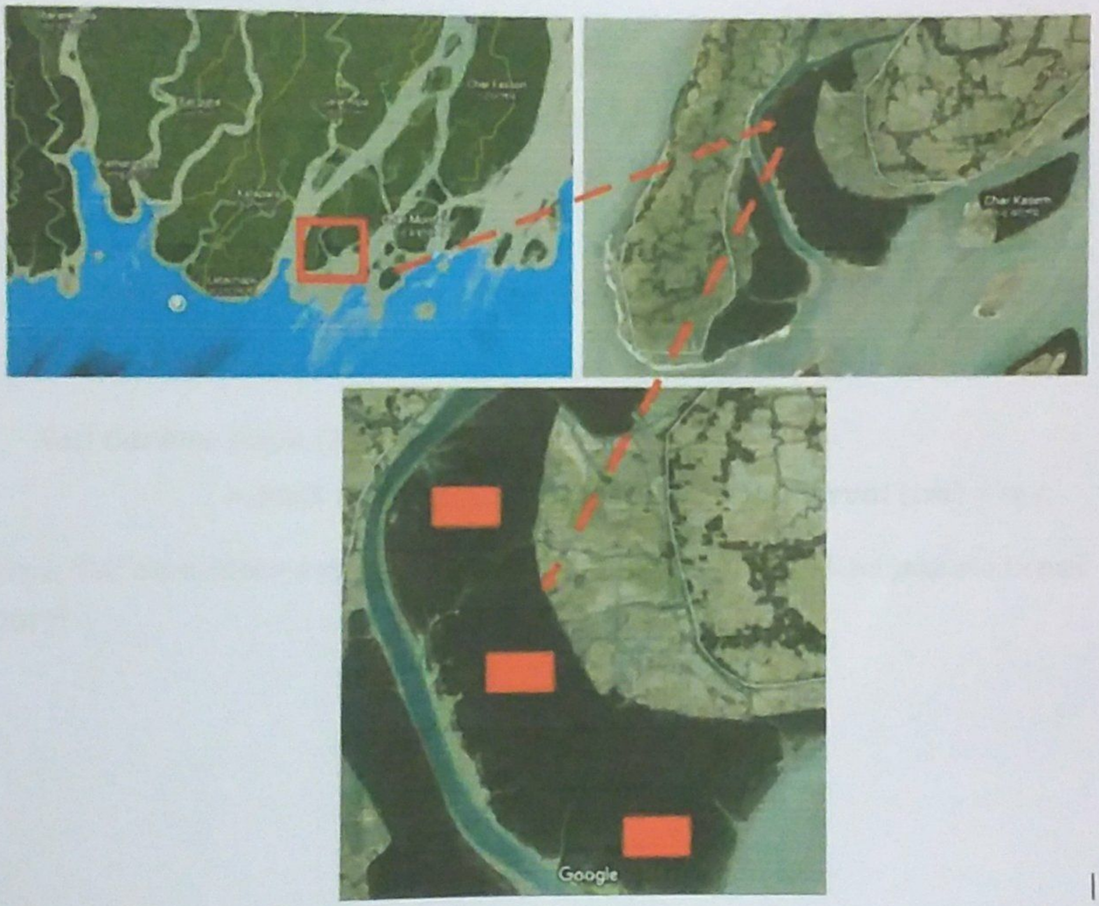

Figure 3.1: Map of the study site (Madarbunia, Rangabali, Patuakhali) and Location of sample plots (in Red colours) (Source: Google Map and Google Earth).

3.2.2 Soil Sampling and Carbon Estimation

Three soil samples (5 cm length) were collected at the point of 0–15, 30-50 and 50–100 cm depth intervals from each of the sample plots for determining soil bulk density and organic carbon concentration. Soil core of 1 m length was pulled out near the sample plot centre by using a one meter long open face peat auger. Soil samples were sealed with vinyl tapes immediately after collection and were also placed in closed plastic bags. Soil samples were air-dried in the field, oven-dried to constant mass at 60°C for determining bulk density and to stop microbial decomposition of organic matter and then sent to Soil Science Laboratory, Khulna University, Khulna for carbon analysis. Soil sample were oven dried at 105°C before homogenizing and carbon concentration was determined by following "Titrimetric Analysis" method.

Soils are spatially very heterogeneous, so soil sampling will be done in wide range of regions and soil profile will be taken to a depth of 100 cm (Khan *et al.* 2007). The Bulk Density (BD) was obtained by the ratio of dry mass per volume of wet sample (known from corer's manual) (Ha *et al.* 2018).

$$\boldsymbol{Bulk\ Density\ (BD\ in\ g\ cm^{-3}) = Dry\ mass\ (g) \div Wet\ Sample\ Volume\ (cm^{3})}$$

The soil carbon mass per sampled depth interval was calculated using the equation-

$$\begin{aligned}&\boldsymbol{Soil\ Carbon\ Stock\ (Mg\ ha^{-1})}\\ &\qquad = \boldsymbol{Bulk\ density\ (g\ cm^{-3}) \times Soil\ depth\ interval\ (cm) \times \%\ C}\end{aligned}$$

Here, %C is the carbon concentration expressed as a whole number (Kauffman and Donato 2012).

3.2.3 Biomass and Carbon Computation

Actually tree biomass includes above ground biomass including shoots, branch, twigs etc. and the below ground biomass includes roots biomass. Aboveground Biomass (AGB) and carbon of live trees, poles, saplings and dead ones (having stem, branch and twigs) is estimated by the following general equation for mangrove tree species (Chave *et al.* 2005).

$$\mathbf{AGB = 0.0509 \times \rho \times D^2H}$$

Where AGB = aboveground biomass, ρ = wood density, D = Diameter (cm), H = Height (m). The wood density data were obtained from destructive samples supplemented with local literatures, World Agroforestry Database (Carsan *et al.* 2012) and the Global Wood Density Database (Chave *et al.* 2009, Zanne *et al.* 2009).

Belowground biomass of trees will be computed by using the following general allometric equation for mangroves (Komiyama *et al.* 2005)

$$\mathbf{BGB = 0.199 \times \rho^{0.899} \times D^{2.22}}$$

Where BGB= Belowground Biomass, ρ= Wood density and D= Diameter (cm).

Conversion of dry biomass of trees, understory, and downed wood to carbon mass was done by multiplying 0.5 as forest biomass contains half carbon by mass (Gifford 2000). Soil C stock was determined as the product of soil carbon concentration, bulk density, and depth intervals (Donato *et al.* 2011).

The total carbon density per plot will be calculated by adding each of the carbon pool as below:

$$\mathbf{Total\ C = C_{tree\ AG} + C_{tree\ BG} + C_{Soil}}$$

Annual C input in the stand will be estimated using the growth rate of Trees. The growth will be estimated using plantation age in relation to tree DBH and Height during inventory.

3.3 Simulation Modelling for Predicting Long Term C Sequestration

Modeling provides a unique approach for projecting forest ecosystem carbon dynamics and several forest ecosystem models were developed to predict boreal forests carbon stocks. Among them, the KiWi model (Berger and Hildenbrandt 2000) was used for simulation experiments to understand how species-dependent growth rate and shade tolerance lead to the observed patterns in horizontal and vertical forest structure in the coastal mangrove plantations. Field data on available mangrove species was used for the purpose of parameterization of the KiWi model. The model output was validated by comparing with observed patterns. The purpose of modelling is to investigate the mangrove forest dynamics affected by intra-specific competition in order to predict long term carbon sequestration.

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 Mooij 2005). These models integrate different hierarchical levels of ecological processes, and they can be directly and relatively simply parameterized. The KiWi model was developed in order to analyse 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 neotropical mangrove forest dynamics affected by environmental settings (pore water salinity and nutrient availability), natural disturbances (lighting and hurricane destruction) and tree cutting (Khan *et al.* 2012), 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 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.

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).

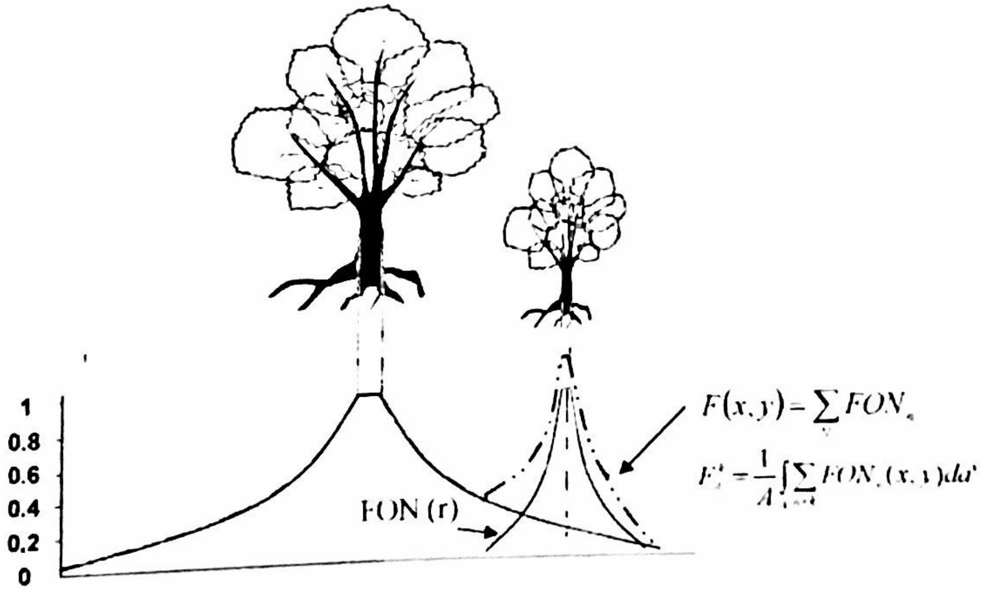

Figure 3.2: The Field of Neighborhood describes the competition strength that an individual exerts on its neighbors or on its environment. F(x, y) indicates the competition strength of all established trees at the location (x, y). FA records the competition that an individual encounters from its neighbors.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

3.4.2 Description of KiWi Model

The model will follow the ODD (**Overview, Design concepts, Details**) protocol for describing individual- and agent-based models (Grimm and Railsback 2005, Grimm *et al.* 2006, Grimm *et al.* 2010).

3.4.2.1 Overview

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.

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.

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): **establishment of new trees, growth of trees,** and **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.

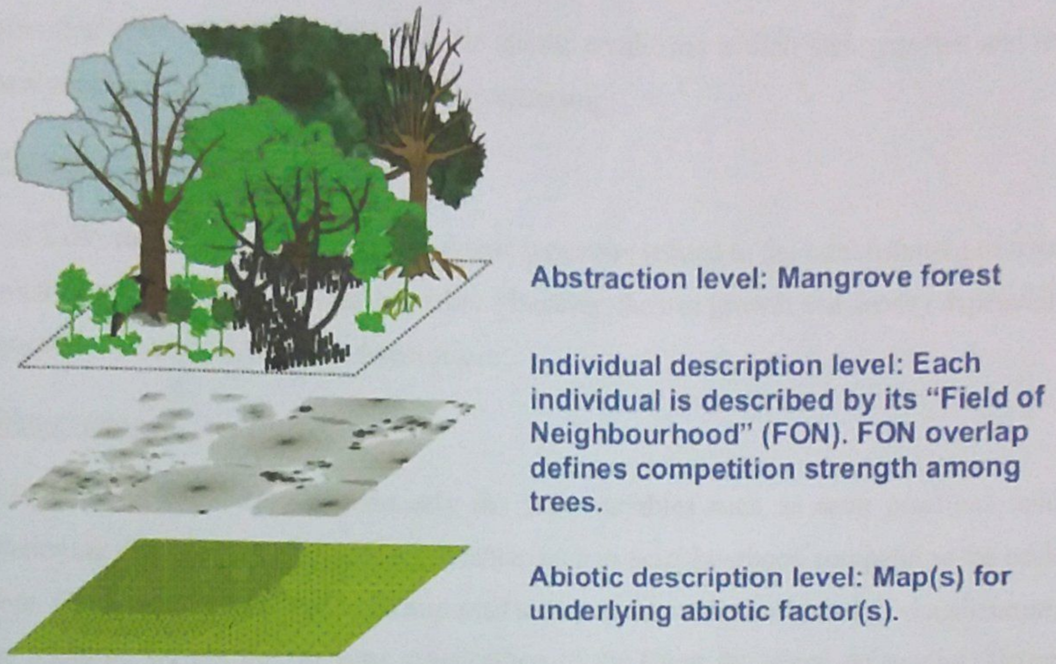

Figure 3.3: Scheme of KiWi Model

3.4.2.2 Design concepts

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.

Interactions

Trees compete with one another for spatially distributed resources. This competition is phenomenological 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".

Sensing

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

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.

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

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.

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 Sub models

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 $(r) = e^{-c\,(r - (D130/2))}$.

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.

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.

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.

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 phenomenological. 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.

CHAPTER FOUR: RESULT

4.1 Model Parameters

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 and Railsback 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 (Berger and Hildenbrandt 2000).

4.2 Model Validation

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 26 years as revealed by the median values in the box plot (**Fig 4.1**). There was no significant difference in the mean diameter between observed and simulated trees at 26 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.

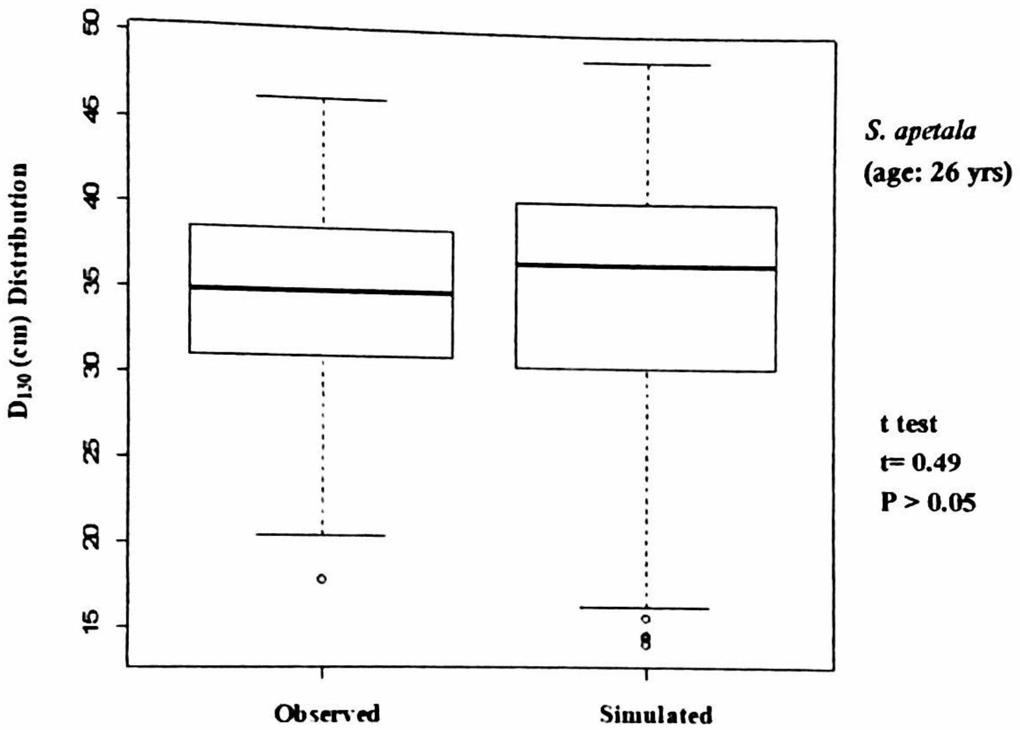

Figure 4.1: Box plot of observed and simulated distribution of tree diameter (D_{130}) in *Sonneratia apetala* stands

4.3 Forest Structure and Biomass

Forest structure parameters are shown in **Table 4.2**. Tree density in the forest varied significantly: the 12-year-old *S. apetala* forest had more number of trees than the number of trees of the 26-year-old *S. apetala* forest. Tree sizes of the different forest sites differed substantially in different forest ages, with an average diameter of 14.51 cm for 12-year-old *S. apetala* and 34.58 cm 26-year-old *S. apetala*. Although the forests in different sites were planted with the same initial density, the 26-year-old *S. apetala* had much higher above and below ground biomass relative to the 12-year-old *S. apetala* at all sampling times.

Table 4.2_Environmental parameter averages for each stand years

Site	Bulk Density (gcm^{-3})	Forest Structure					
		DBH (cm)	Height (m)	Density ($m^2 ha^{-1}$)	Basal Area ($m^2 ha^{-1}$)	Above Ground Biomass ($ton\ ha^{-1}$)	Below Ground Biomass ($ton\ ha^{-1}$)
S. apetala (12 yrs)	0.84	14.51	10.95	1040	18.24	81.05	50.04
S. apetala (17 yrs)	0.79	21.09	12.78	980	34.81	171.91	99.69
S. apetala (22 yrs)	0.78	25.58	14.83	900	50.48	275.15	150.97
S. apetala (26 yrs)	0.89	34.58	17.79	850	79.74	516.07	249.46

4.4 Soil Carbon Pool

In the field work, we have taken the soil sample at the different soil depth of *Sonneratia apetala* trees from the sampling plot for calculating the soil carbon (**C**) concentration. After calculation, tested many regression equations for estimating the relationship between soil C concentration and forest age. From different regression analysis, chosen the best fitted according to the best R^2 value. In the repeated measured data set, soil C concentration increased with forest age in the *Sonneratia apetala* forest. Forest age and soil C concentration were significantly related in the mangrove plantation forests (**$R^2 = 0.9673$**).

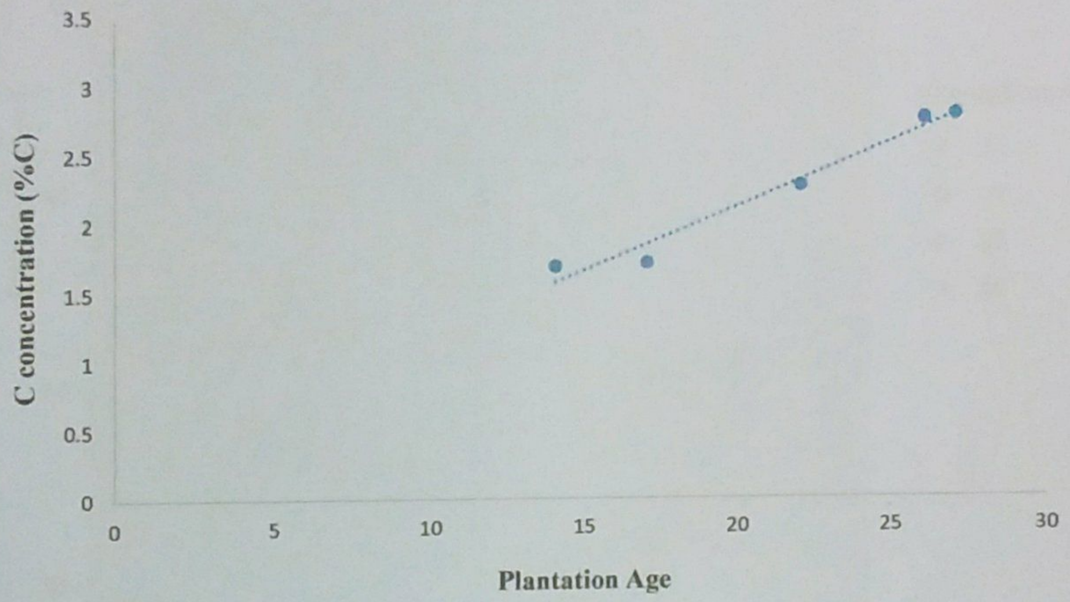

Figure 4.2 Relationship between soil carbon concentration and forest age. Lines shown are linear best fits for *S. apetala* (**$y = 0.0958x + 0.2774$; $R^2 = 0.9673$**)

Soil organic carbon varied from 0.25% to 1.52% and showed an increasing trend with increasing stand age (**Fig. 4.3**). The carbon concentration is maximum in the top soil and gradually decrease with soil depth (**Fig. 4.3, Fig. 4.4**). The average carbon concentration in 22 and 26 year old stands was significantly ($P<0.05$) different from 17 and 12 year old stands of *Sonneratia apetala* (**Fig. 4.5).**

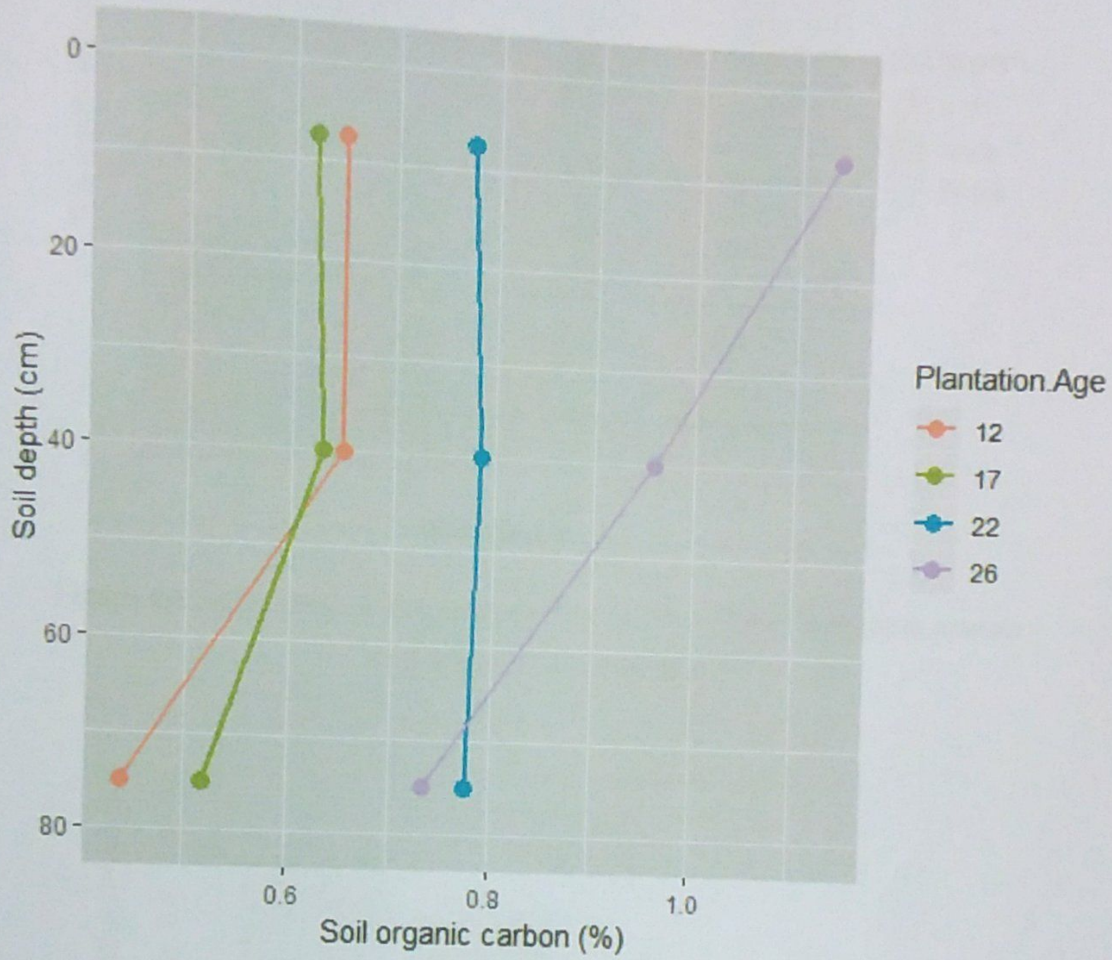

Figure 4.3 Mean soil organic carbon at different soil depths in *Sonneratia apetala* plantations of different stand ages.

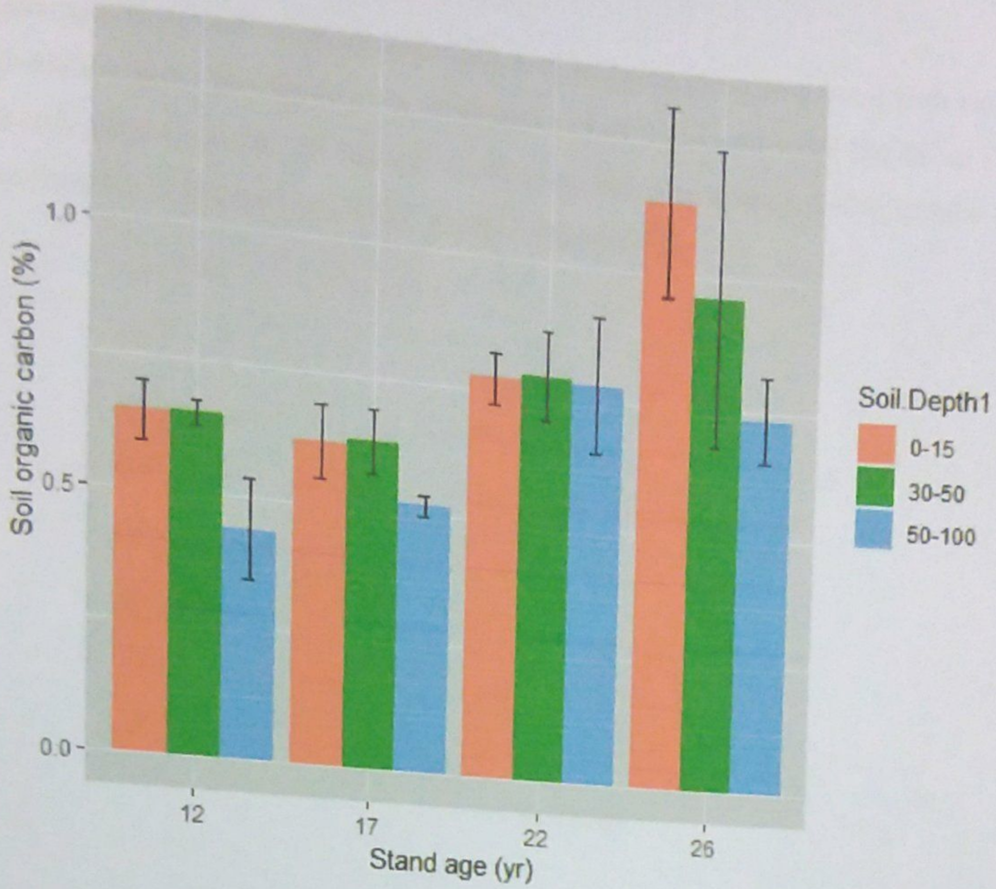

Figure 4.4 Soil organic carbon concentration (mean ± SE) in *Sonneratia apetala* plantations of different ages.

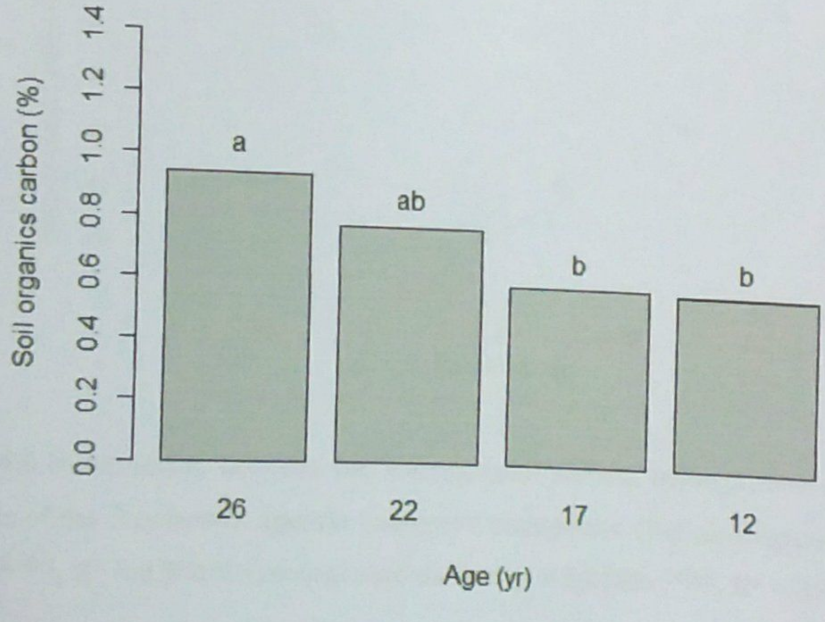

Figure 4.5 Mean soil organic carbon in *Sonneratia apetala* plantations of different ages. Same letters on bars represent no significant difference as tested with Tukey HSD test ($P<0.05$).

The average above and below ground carbon showing an increasing trend with increasing the plantation ages. The average above ground carbon was found 38.09 Mg ha^{-1} at 12 years old which grew up to 242.56 Mg ha^{-1} at 26 years old. The average below ground carbon varied from 23.52 Mg ha^{-1} to 117.24 Mg ha-^{1} respectively.

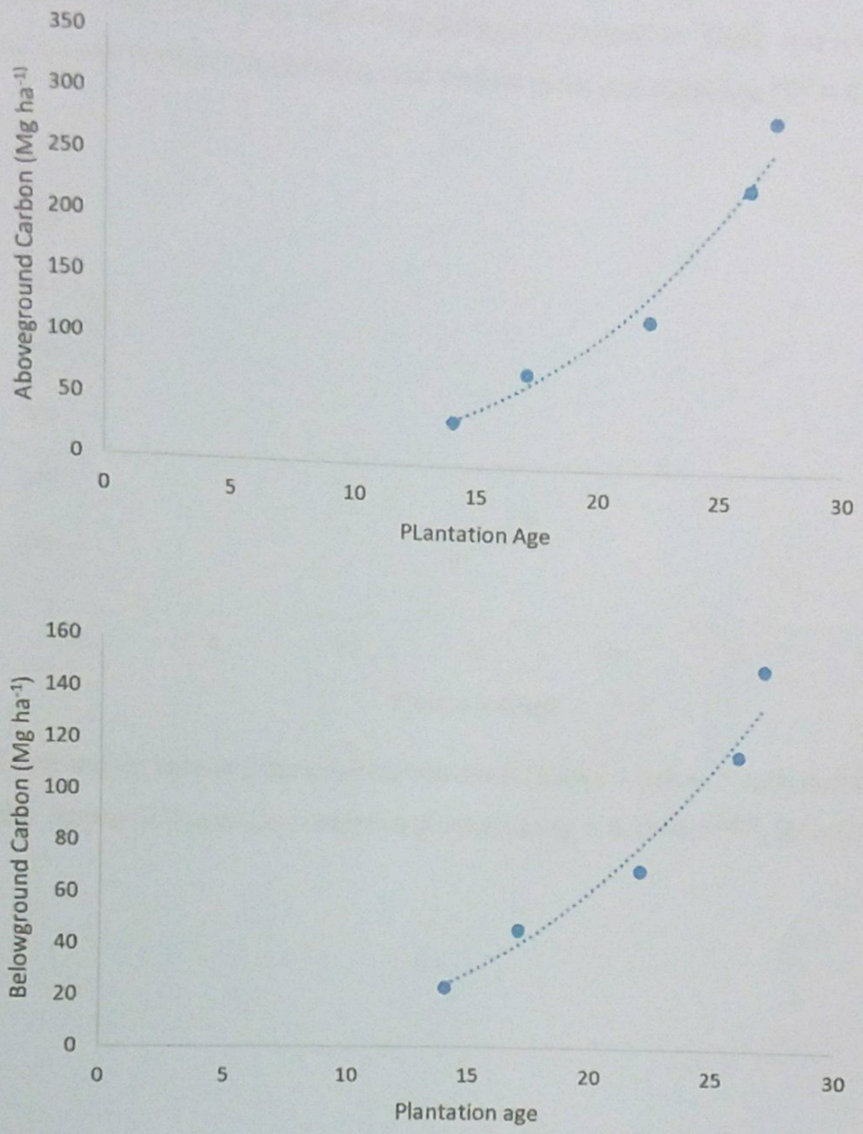

Figure 4.6 Relationship between the aboveground carbon, belowground carbon and the stand age of the *Sonneratia apetala* mangrove plantations. (For aboveground carbon, **$y = 0.0168x^{2.9453}$, $R^2 = 0.9817$;** Belowground carbon, **$y = 0.0255x^{2.6065}$, $R^2 = 0.9777$)**

In this figure represents the relationship between the total carbon stock and the stand age of the *Sonneratia apetala* mangrove plantations. It was observed that total carbon storage increased steadily with stand age. The positive changes in carbon stock with stand ages from young *Sonneratia apetala* to mature planted mangroves support our hypothesis that carbon stock increases over time following mangrove plantation. There was a significant positive and power correlation between total carbon stock and stand age (**$R^2 = 0.94$**).

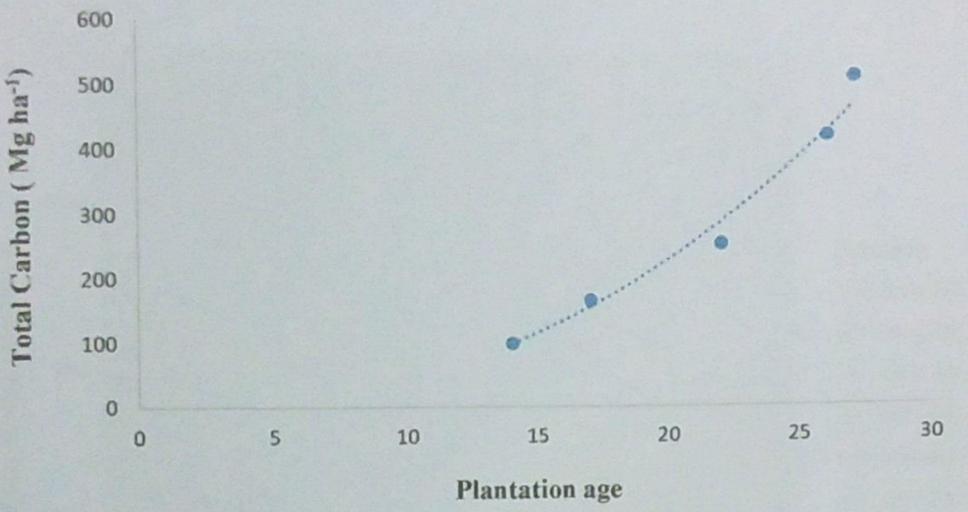

Fig. 4.7 Relationship between the total carbon stock (above + below + soil) and the stand age of the *Sonneratia apetala* mangrove plantations (**$y = 0.1991x^{2.3633}$, $R^2 = 0.9846$**)

4.5 Growth of biomass carbon stocks

In this figure represents the simulated growth of biomass carbon stocks (aboveground + belowground) in *Sonneratia apetala* at different stand ages with different plantation spacing. Simulated results of growth of biomass carbon stocks (aboveground + belowground) in *S. apetal*a using KiWi mangrove growth model suggest that biomass carbon stocks in *S. apetal*a can reach up to 1200 Mg ha^{-1} at 60 the age of years having a plantation spacing of 5 m x 5 m (**Fig. 4.8**).

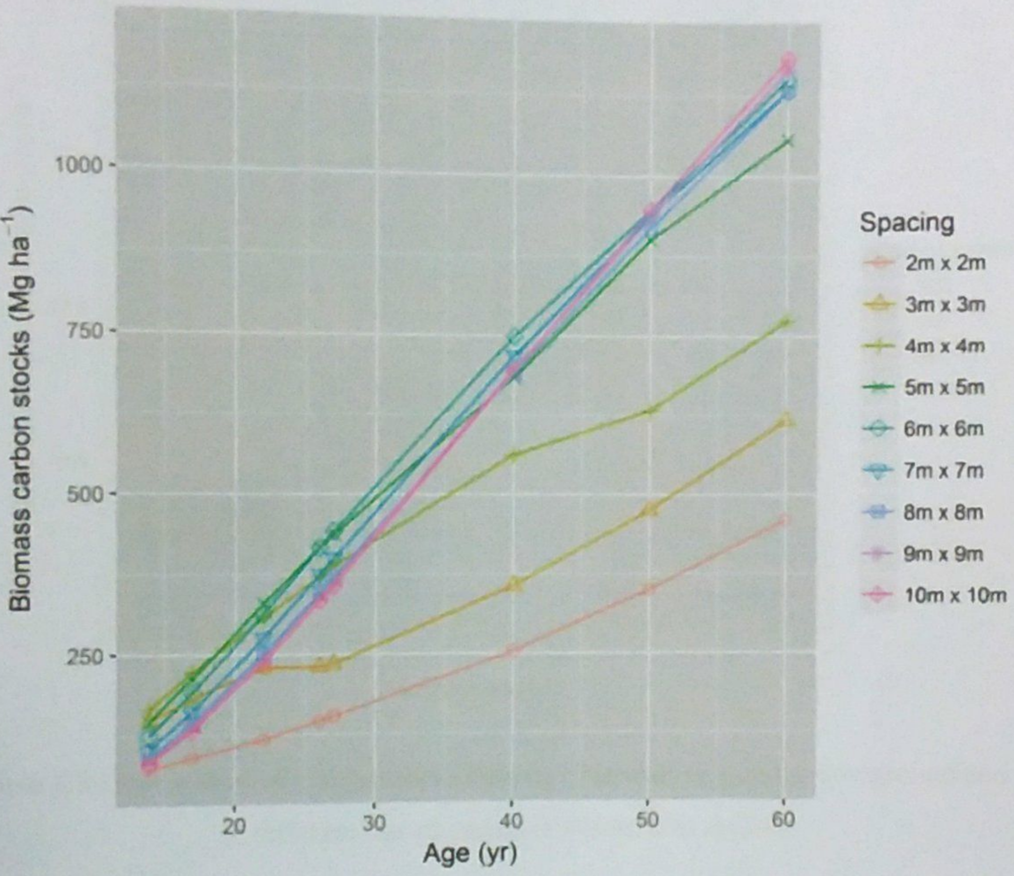

Figure 4.8 Simulated growth of biomass carbon stocks (aboveground + belowground) in *Sonneratia apetala* using simulation experiments with KiWi mangrove growth model. Data points represent mean carbon stocks at particular age and plantation spacing.

4.5 Carbon stocks in the soil-vegetation system

The organic carbon partitioning in the soil-vegetation system along with stand age is illustrated in (**Fig. 4.9**). The distribution of carbon stocks in aboveground, belowground and soil at different age of stands suggests that at young stage (12 yrs) soil carbon is close to biomass carbon. As stand grows older the relative growth in biomass carbon is much faster than soil carbon. At the age of 12 year about 25% carbon is stored in the soil, which becomes about 12% at the age of 26 year.

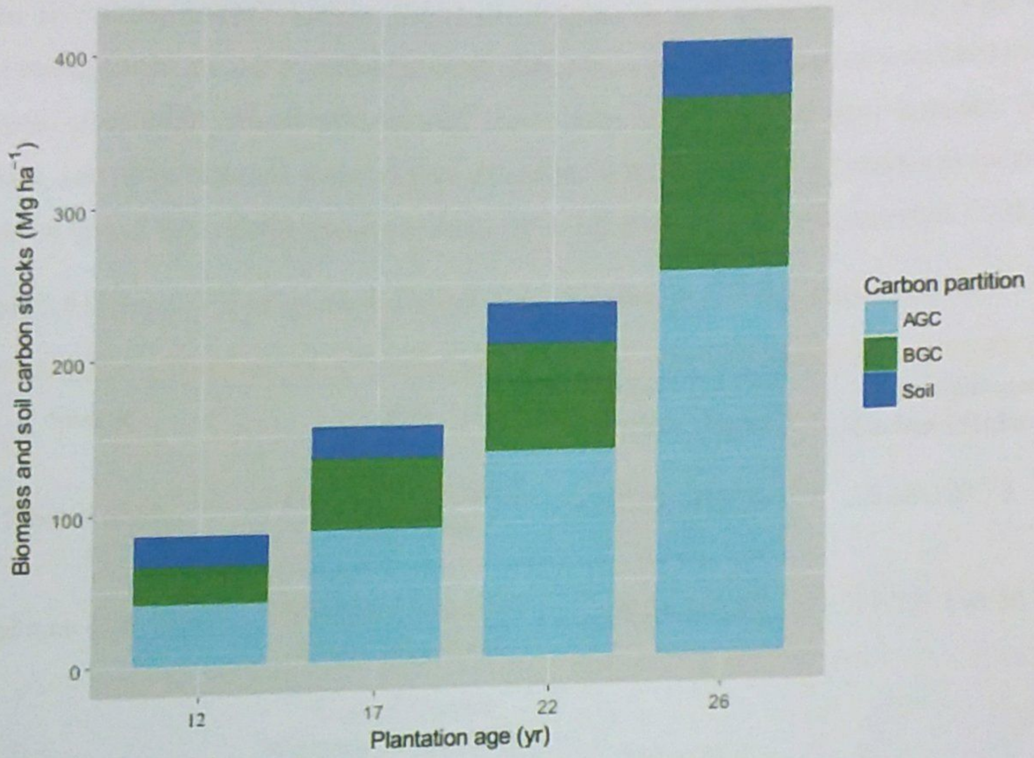

Figure 4.8 Distribution of carbon stocks (Mg ha^{-1}) in aboveground, belowground and soil at different age of stands in *Sonneratia apetala*.

CHAPTER FIVE: DISCUSSION

Our study supports the hypothesis that biomass accumulation at both aboveground and belowground increased with plantation ages (**Table 4.2**). Moreover, the *Sonneratia apetala* plantations accumulated more biomass than many other secondary mangrove forests or plantations (**Table 5.1**). This study indicates that *Sonneratia apetala* plantations can accumulate more biomass in both aboveground and belowground than many other mangrove forests in this region. Moreover, the high biomass accumulation was achieved under few management practices. Initial site preparation and planting probably were the only management measures applied in these plantations. No fertilization has ever been used in these plantations. *Sonneratia apetala* shows high adaptability in poor habitats, fast growth, and large biomass accumulation potentials in this region. This introduced species could be one of the suitable species to restore the degraded coastal area (Ren et al. 2008).

Table 5.1 Comparison of above and below ground carbon in different regions of the world

Source	**Site**	**Above Ground Carbon (Mgha^{-1})**	**Below Ground Carbon (Mgha^{-1})**
Present Study	Rangabali, Potuakhali, Bangladesh	80.12- 215.23	35.68-100.73
Rahman et al. 2015	Sundarban Mangrove Forest, Bangladesh	45.24-152.57	11.72- 196.54
Adame et al. 2013	Tropical Coastal Wetlands in the Karstic Landscape of the Mexican Caribbean	210 ± 33.9	
Adame et al. 2015	South pacific coast of Mexico	8.5-145.6	
Albert et al. 2012	Soloman Island	190.43	

The concentration of organic C in the soil ranged from 0.25% to 1.52%, which is similar to the reported values, such as 0.76-0.11% in a pioneer mangrove (*A. germinans*) forest (Marchand *et al*. 2004), 0.18-0.23% in a *R. apliculata* stand in Thailand (Kristensen *et al*. 2008), 1.58-2.81% in a *B. gymnorrhiza* stand in Okinawa Island (Mfilinge *et al*. 2002), 2.7-6.7% in a mixed mangrove forest in Thailand (Alongi *et al*. 2002). Soil organic carbon content in mangroves depends on various factors, such as forest age, the degree of tidal exchange and sedimentation of suspended matter. In some mangroves, higher ranges of soil organic carbon are reported, such as 6.1% (in *Avicennia*) in a Brazilian mangrove (Lacerda *et al.* 1995), 8.7% in *A. marina* in Australia (Alongi *et al.* 2000, Alongi *et al.* 2002), 6.0-31.7% in *A. officinalis* and *Excoecaria agallocha* (Bouillon *et al.* 2003, Bouillon *et al.* 2008) etc. The low soil carbon concentration in the mangrove plantations in Bangladesh for low stand age and low rate of litter deposition and high rate of litter run-off.

The carbon stocks in the above ground biomass was 1.44 times as large as that in belowground biomass. Soil carbon was 10% - 25% of the vegetation pool depending on stand age (**Fig. 4.8**), indicating that the mangrove stands stores a lower amount of carbon in the soil in comparison to other mangroves such as 48% in a 12 year old *Kandelia obovata* (Khan *et al.* 2007).

Potential ecological issues related to large-scale *Sonneratia apetala* plantations

Widespread mangrove degradation coupled with the increasing awareness of the importance of these coastal forests has spurred many attempts to restore mangroves (Bosire *et al.* 2008). Most of the native mangroves have been deforested by habitat destruction through human encroachment, diversion of fresh water for irrigation and land reclamation and conversion for agriculture, aquaculture and urbanization (Kristensen *et al.* 2008).

The successful introduction of exotic *Sonneratia apetala* may provide an opportunity for mangrove restoration. Our study indicates *Sonneratia apetala* shows high adaptability in poor habitats with fast growth and large C storage capacity in Potuakhali, Bangladesh. Moreover, the C sequestration is accomplished at a low cost. The increasing biomass and C accumulation, especially the development of sediments, will further enhance other ecosystem functions such as nutrient cycling and biodiversity of the plantations (Kristensen *et al.* 2008, Ren *et al.* 2008, Ren *et al.* 2010). We could use *Sonneratia apetala* as a pioneer species to improve habitat quality by accumulating sediments and facilitate the reestablishment of native mangrove species.

CHAPTER SIX: CONCLUSION

Bangladesh is a pioneer country in raising successful plantations with *Sonneratia apetala* along the shoreline and offshore islands. This study unfolds information about dynamic partitioning of organic carbon in the soil vegetation system in coastal mangrove plantations in Bangladesh. This study is based on a combination of field and simulated data to describe the success, importance and performance of *Sonneratia apetala* for the development of monospecific stands in the coastal areas. 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 expansion of *Sonneratia apetala* plantations in the open coastal areas has great potential to sequestrate more C as well as restore the degraded coastal land, although more long-term monitoring and research are still needed to further evaluate biomass and C accumulation of *Sonneratia apetala* plantation over time as well as how the increasing distribution of this monoculture plantation will influence the native mangrove forests.

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