Carbon stock assessment and sequestration potential of mangroves in the South West Coast of India

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Certificate

This is to certify that the thesis "**Carbon stock assessment and sequestration potential of mangroves in the South West Coast of India**" is an authentic record of research work carried out by Mrs. Rani Varghese (Reg. No. 4296) under my supervision and guidance in the Department of Marine Biology, Microbiology and Biochemistry, Cochin University of Science and Technology, in partial fulfilment of the requirements for the Degree of Doctor of Philosophy under the faculty of Environmental Studies. There is no plagiarism in the thesis and that the work has not been submitted for the award of any degree/diploma of the same Institution where the work was carried out, or to any other Institution.

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Declaration

I hereby declare that the thesis entitled *"Carbon stock assessment and sequestration potential of mangroves in the South West Coast of India"* is an authentic record of research work carried out by me under the supervision and guidance of Dr. S. Bijoy Nandan, Professor, Department of Marine Biology, Microbiology and Biochemistry, Cochin University of Science and Technology, in partial fulfilment of the requirements for the Degree of Doctor of Philosophy under the faculty of Environmental Studies and that no part of this has been presented before for the award of any other degree, diploma or associateship in any university.

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Rani Varghese

This Thesis is a Devotion to the Almighty

A Tribute to my Guide

Dedication to my Family and Friends…

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Rani Varghese

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List of Abbreviations

AGB	-	Above Ground Biomass
BGB	-	Below Ground Biomass
NPP	-	Net Primary Productivity
DIC	-	Dissolved Inorganic Carbon
DOC	-	Dissolved Organic Carbon
POC	-	Particulate Organic Carbon
POM	-	Particulate Organic Matter
TIC	-	Total Inorganic Carbon
TOC	-	Total Organic Carbon
TC	-	Total Carbon
SOC	-	Soil Organic Carbon
SIC	-	Soil Inorganic Carbon
OC	-	Organic Carbon
TN	-	Total Nitrogen
DN	-	Dissolved Nitrogen
ppm	-	parts per million
IPCC	-	Intergovernmental Panel on Climate Change
CH_4	-	Methane
GHG	-	Green House Gases
REDD+	-	Reducing Emissions from Deforestation and forest Degradation
SGD	-	Submarine Ground water Discharge
Mg C ha− 1 y− 1	-	Mega Carbon per hectare per year
t C ha-1yr-1	-	ton Carbon per hectare per year
Pg	-	picogram
Tg	-	terra gram
g DWm^{-2} y^{-1})	-	gram Dry Weight per metre square per year
mg dw $(gww)^{-1}$ day^{-1}	-	milligram dry weight per gram wet weight per day

g C (gww) $^{-1}$ day $^{-1}$)	-	gram Carbon per gram wet weight per day
CO_{2e}	-	Carbon dioxide equivalent
ha^{-1}	-	per hectare
m^2ha^{-1}	-	metre square per hectare
DBH	-	Diameter at Breast Height
IVI	-	Importance Value Index
%	-	percentage
g kg^{-1}	-	gram per kilogram
mg g^{-1}	-	milligram per gram
^oC	-	degree celcius
et al.	-	et alli, and others
v6	-	Version 6
spp	-	species
Fig	-	Figure
DO	-	Dissolved oxygen
km	-	kilometer
HCl	-	Hydrochloric acid
H_2SO_4	-	Sulphuric acid
SO_2	-	Sulphur dioxide
C/N	-	Carbon to Nitrogen
D/F	-	Dry weight to fresh weight
hr	-	hour
ppt	-	parts per thousand
m	-	metre
cm	-	centimeter
π	-	Pi
Dia	-	diameter
‰	-	per mille
PRE,PRM	-	Premonsoon
MON	-	Monsoon
POM	-	Post-monsoon

Chapter 1

GENERAL INTRODUCTION

The ecosystem that deserves prime attention, which deeply entwined with the human race, is extremely productive, and forms the ecotone between land and open water, is the wetland ecosystem. Wetlands are the spring of life that blanket the earth with its lush greenery. Among wetland ecosystems, mangrove ecosystem is the most precious environment on earth, forming a green wall along the coastal area. Mangrove ecosystems, distributed along the tropical and subtropical tidal areas, at approximately 30°N and 30°S latitude, with structurally and functionally unique plants, and complex biogeochemical processes, are the most biologically rich coastal ecosystem in the world. Mangroves are a part of human life and help in sustainable livelihood management of coastal communities (Bijoy Nandan, 2014). The mangrove forest is an association of halophytic trees, shrubs and other plants growing in brackish to saline tidal waters of tropical and subtropical coastlines (Mitsch and Gosselink, 2015). Mangrove plants (true mangroves and mangrove associates) together with abiotic factors form the mangrove ecosystem. The word 'mangrove' is used for denoting vegetation type and also its habitat

which is also named mangal, swamp, tidal forest or wetland in which it exists (Tomlinson, 1986; Saenger, 2002; Duke et al., 2007; Spalding et al., 2010). The true mangrove plants are having many adaptations including salt regulation (salt exclusion, salt excretion, salt accumulation), respiring pneumatophores, prop and stilt roots, viviparous seedlings for thriving its harsh environments like high salinity, anoxic conditions and muddy substratum.

1.1 Global and regional background on mangrove distribution

The earliest report on mangroves is dated back to 3580-3536 B. C. in ancient writing of Egyptian king Assa who mentioned about the mangroves in the Red Sea. Later, descriptions of *Rhizophora* trees in the Red Sea and the Persian Gulf by Nearchus (325 B.C), followed by the quote of Theophrastus (305 B.C.), Pliny (A.D.77), Arrian (A.D.136) and Aboul-Abbas-on-Nebaty (1230) about mangroves (Macnae, 1968; Chapman, 1976; Wafar,1987). Bibliography on mangrove research by Rollet (1981) described 14 references before the 1600s, whereas the seventeenth century included a little more research with records of 25 references during this period. Subsequently, the interest in mangrove research gradually increased and reported 48 references in the eighteenth century, and 427 in the nineteenth century. The peak time of mangrove research was in the 20^{th} century having 4500 mangrove references between 1900 and 1975, and from 1978 to 2001 approximately 4466 were reported. The ardent research on this hot topic is continuing.

Globally mangroves extend in 123 countries with 73 true mangrove species (Spalding et al., 2010) and cover an area of 83495 km^2 (Hamilton *and* Casey, 2016). There was a substantial mangrove loss between the twentieth and twenty-first century, and it ranged from 140,000 to 170,000 km^2 by different estimates (Mitsch and Gosselink, 2015) during the twentieth century.

Spalding et al. (2010) reported 152,361 km^2 for 1997-2000 period; Giri et al. (2011) reported 137,760 km^2 from 118 countries and territories of the world for the year 2000 and Twilley and Day 2013 reported 170000 km^2. The history of global mangrove area mapping started in the year 1980 by Food and Agriculture Organization (FAO) and reported 15.6 million ha. Later Saenger et al., 1983; Bunt et al.,1992; Twilley et al.,1992; Spalding et al.,1997; Aizpuru et al., 2000 and FAO,2007 mapped global mangroves. Duke et al. (2007) documented that mangrove degradation is increasing rapidly, and within 100 years, the world's mangrove forests will be considered to be "functionally disappeared". The mangrove area and species lost was studied by Polidoro et al. (2010) and revealed that mangrove degradation is the highest in developing countries and the reasons given for this are coastal development, aquaculture, timber, and fuel production. On a global scale, mangrove forest area change was first mapped by Hamilton and Casey (2016) for the period 2000-2012, and this was the latest global mangrove area estimate (83495 km^2). Recently Thomas et al. (2017) described the change in mangrove cover for the period 1996-2010 and reported 12-38% mangrove loss. However, Hamilton *and* Casey (2016) reported that though global mangrove deforestation continues, the rate of loss reduced between 0.16% and 0.39% per year during 2000-2012 period showing a stable condition in many countries. Significant mangrove loss reported from Southeast Asia from 0.2 to 0.7 % between 2000 and 2012 (Hamilton *and* Casey, 2016). So, most studies have established that the major reason for anthropogenic mangrove loss was due to the conversion of mangrove to aquaculture/agriculture farms.

On considering the global mangrove species diversity, it shows an uneven distribution globally, with maximum species richness and mangrove area in equatorial regions (0^o-10^o latitudes). The highest species composition

exists in the Indo-West Pacific region with 36 species of mangroves reported from the area (Mitsch and Gosselink,2015). Another interesting factor is that till date, there exists an ambiguity or confusion regarding true mangrove species and associated plants and different authors have listed different number as true mangroves based on several adaptations. Globally Chapman, 1976 recorded 90 species of mangroves, Saenger et al., 1983 found 83 species, while in 1986, UNDP/UNESCO mentioned 65 species. Tomlinson, 1986 classified mangroves into three groups (major mangrove species, minor mangrove species, and mangrove associates). He also identified 34 major mangroves, 20 minor species giving a total of 54 species. Recently, 73 true mangrove species were identified by Spalding et al. (2010). However, Duke (2011) documented more hybrid species and listed 77 mangrove species.

India is covered with mangrove vegetation along the East and West coast and in the island territories extending from 7°N-23°N, 69°E-89.5°E and covers an area of 4921 km^2 (Forest Survey of India, 2017). Indian mangroves contribute 3.3% of global mangroves. Mainly three types of mangroves (Deltaic, Backwater-Estuarine type, Neritic Islets) are seen in India. The East coast of India, geographically smooth and gradual slope is characterised by alluvial soil with a high load of nutrients, and continuous supply of freshwater by major rivers form deltaic coast supports lush growth of mangroves. This region also includes the portion of the largest mangrove forest of the world, the Sundarbans. However, the west coast of India has a steep and vertical slope and does not favour much mangrove colonisation. Furthermore, the absence of nutrient-rich alluvial soil makes it comparatively less friendly to mangrove settlement and Backwater-Estuarine type mangroves only inhabit this region. However, the neritic islets, tidal estuaries, small rivers and lagoons support rich insular mangrove flora in Andaman and Nicobar islands (BijoyNandan et

al.,2015; Kathiresan, 2010; Gopal and Krishnamurthy, 1993). Mangrove diversity is high in Sundarbans in West Bengal with a mangrove extent (42.96%) in the country, followed by Gujarat (23.2%) and Andaman and Nicobar islands (12.5%) (State of Forest Report, 2017). The latest survey revealed that there is a total increase in the mangrove area of 181 km^2 as compared to the year 2015.

Indian mangroves were described way back in 1678 in an ancient book '*Hortus Indicus Malabaricus*' of Van Rheede (1678-1703). He described the mangroves of Malabar Coast. The scientific studies on ecology and reports of mangroves in the Indian subcontinent were recorded from the works of Gamble (1915-35); Cornwell (1937); Qureshi (1957). According to Waheed Khan (1957), the mangrove area in India was 6388 km^2. Later Sidhu (1963) and Blasco (1975) studied the mangrove area and reported 6819 and 3565 km^2 of mangroves in India. However, FAO, 1980 reported 9100 km^2 of mangrove extent in India. Forest Survey of India (FSI) initiated mangrove mapping from 1982. The mangroves were mapped by remote sensing technique since 1987 by FSI and estimated an area of 4046 km^2 during that period, and after that regular two-year update was done by the FSI. Another study in the same year (Jagtap et al., 1987) reported an area of 4200 km^2. Kathiresan (2000) reported that there was a significant loss (22400 ha) of mangroves in Andaman and Nicobar Islands during 1987 and 1997. The remote sensing data during the period 1993-1997 recorded a substantial increase in mangrove cover in West Bengal (31.13%); 25.4% in Bay Islands and 12.83% in Orissa and a decline in mangrove cover in other states: 76.7% in Tamil Nadu; and 20.21% in Andhra Pradesh. A substantial, large area under mangroves (6700 km^2) was reported by Aizpuru et al. (2000) compared to 1987 estimates. Regular assessment of mangrove distribution was carried out by FSI during 2003, 2009, 2011, 2013,

2015 and the latest report published in 2017 with an area of 4921 km^2 under mangrove cover.

In India, the definite number of species of true mangroves that inhabited different states not entirely known due to confusion in mangrove taxonomy, scattered data, and insufficient field studies. However, about 56% of the world's mangrove species occur in India (Kathiresan, 2010) including one endemic species to India, *Rhizophora x annamalayana* Kathiresan, a natural hybrid from two species of Rhizophora (*R.apiculata and R. mucronata*), seen in Pichavaram of Tamil Nadu (Kathiresan, 1995 and 1999). The number of mangrove speciesin India varies in different studies. Blasco et al., 1975 reported 50-60 mangrove species in India. Untawale, 1987 reported about 55 mangrove species; however, in the same year, Naskar and GuhaBakshi reported 35 true mangrove species. Recent estimates by Ragavan et al., 2016 identified 46 true mangrove species belonging to 14 families and 22 genera, including 42 species and four natural hybrids. Forty mangrove species exist in East coast, 27 species in the West coast and 38 species in Andaman and Nicobar Islands.

The state of Kerala with 44 rivers and ten coastal districts with a coastal line of 590 km was formerly very rich in mangrove habitats. The mangroves in Kerala are under high threat due to massive scale deforestation and multiparametric anthropogenic activities (Bijoy Nandan et al.,2015). Eighteen true mangrove species have been identified from the Kerala coast where Kollam district is having highest mangrove diversity and the Thiruvananthapuram district with the least (Bijoy Nandan et al., 2015). Recent studies by Sreelekshmi et al. (2018) revealed that *Sonneratia alba*, *Avicennia alba* and *Ceriops tagal* are rare to Kerala and *Bruguiera parviflora* is extinct to the state.

The existence of mangroves was evident in Kerala from the *Hortus Indicus Malabaricus* by Van Rheede (1678-1703). He recorded eight true mangrove species in Malabar Coast. Consequently, Drury, 1864 had identified a few more plants, like *Eriops candolleanus* and *Bruguiera eriopetala* from Kollam region. The mangroves of the Malabar Coast was again studied by several authors (Beddome, 1866; Hooker, 1872; Bourdillon, 1908; Rama Rao, 1914 and Gamble, 1915-35). Gamble (1902) described the use of wood of the important mangrove species of the Malabar Coast, while Govinda Menon, 1930 reported the medical uses of mangroves. Many references are reported on the description of mangroves in Kerala by Thomas, 1962; District Gazetteer of Ernakulam, 1965; District Gazetteer of Cannanore, 1972; Rao and Sastri, 1974; Blasco, 1975; Kurien, 1980 and Ramachandran et al., 1986. Ramachandran and Mohanan, 1987 recorded the mangrove area in Kerala and reported the large scale destruction of mangroves for the construction of the Cochin Port.

Kerala had a large patch of mangroves extending up to 700 km^2 along its coast during the 1975-1987 period (Blasco, 1975; Ramachandran et al., 1986). However, the mangrove spread of the state declined sharply to 161.1 km^2 (Basha, 1992), then to 109.5 km^2 (Kurien et al.,1994) primarily due to the destruction of the habitat for developmental and aquaculture conversion activities. Contradictory to previous estimates, Mohanan et al. (1997) reported the mangrove area in Kerala as 420 km^2. Forest survey of India also documented the mangrove area in Kerala since 1987, and the latest report showed 9 km^2 (FSI, 2017) mangrove formation exist in Kerala. Although the mangrove extent is declining due to various anthropogenic activities, the studies on the extent of mangroves have been underestimated due to lack of extensive field surveys. The severe depletion of mangrove areas in Kerala is

mainly because almost 90 % of the area is under private property (Basha, 1991), that inhibited conservation strategies for the state. Thus, the studies on mangrove habitats of Kerala was restricted only on the extent of mangroves in the state, some limited floristic and faunal biodiversity studies and also on the abiotic factors of the ecosystem. Detailed study on mangrove ecosystem dynamics and it's stock assessment are scanty for Kerala mangroves.

1.2 Classification of mangroves

Mangrove habitats are classified according to various hydrogeomorphic settings (Lugo and Snedaker, 1974). The primary productivity and bio-geochemical cycling varied significantly depending upon these mangrove types. The classification include: 1) Fringe mangroves: found along protected shorelines, sloping beaches, islands along lagoons with elevations higher than the mean high tide and mostly inundated during high tide. 2) Riverine forest: most productive forests along with river and creek drainage areas, which are inundated by most high tides and flooded during rainy seasons and therefore subjected to varying levels of salt concentrations. The freshwater runoff with high nutrients from upland areas and nutrient inputs from the estuarine environment makes these forest the most productive one. 3) Overwash forest: small islands and peninsulas, which are completely overwashed during all high tides. 4) Basin forest: this type exists in inland areas along drainage depressions and inundated by a few high tides during the dry seasons (also depending on the distance from the coast) and more high tides during rainy seasons. It occurs behind fringe mangroves. Low redox potential prevails in these forests due to stagnant condition and less flushing by tides. 5) Dwarf forest: seen in topographic flats above mean high water levels; small trees and may be stunted or dwarf-like; additionally, the environment lacks external nutrient sources. 6) Hammock

forest: similar to the basin forest type, but here, the ground is slightly elevated (5-10 cm) above the surrounding area.

1.3 Ecosystem services offered by the mangroves

Mangroves provide numerous services directly or indirectly for ecosystem structuring and the well being of human beings (Fig.1.1). The ecosystem services include flood control, groundwater refill, shoreline stabilization *and* storm protection, sediment and nutrient retention and export, water purification, nutrient cycling, energy flux, food web structuring, hydrology, biodiversity, carbon sequestration and climate change mitigation and adaptation. It also provides many cultural, recreation and tourism and socio-economic services. Mangroves help in the protection of other marine ecosystems like coral reefs and seagrass beds by filtering the sediments. These coastal habitats help in nutrient retention, and through filtration of sediments and pollutants, it helps in water quality improvement. Mangroves act as a soldier, protecting the coast from various calamities and stabilising the coast. The Tsunami event in 2004 highlighted the importance of these marshy ecosystems in India and around the globe (Kathiresan and Rajendran, 2005). The role of mangroves in weakening the effects of Tsunami was studied before 2004 by Harada et al. (2002). The unique intricate root system of mangroves help in weakening of strong waves and mangrove plants with aerial roots act as a barrier against strong winds and storms. This mechanism also helps in flood control. The capacity of mangroves in weakening of waves depends on various factors like water depth, wave height, wave period, mangrove species, its root and trunk diameter and density of mangroves (Mazda et al., 1997).

The high productivity of mangroves from the litterfall forms a basis of the detrital food chain in the mangrove ecosystem. The complex structure of

the mangrove plant and harsh environment with less predation makes it a right place as refuges, migration sites and nurseries. Mangroves protect many threatened and endangered species like Royal Bengal tigers, Olive Ridley turtle, white breasted sea eagle, the tree climbing fish, the proboscis monkey and the dugong (Mangrove Action Project, MAP, 1990; Subramanian et al., 1990). In 2002, Macintosh *and* Ashton reviewed mangrove biodiversity in detail. In India, 3066 faunal species was recorded by Kathiresan and Qasim (2005). State wise distribution of faunal species in mangrove habitats was enlisted by Devroy and Sivaperuman (2012). Besides its role in strengthening the biodiversity,mangroves also provide a lot of natural products and value-added products and thereby helps in sustainable livelihood management. It is traditionally used for firewood, medicine, food, charcoal, construction materials, tannin, pulp and paper, capture fishery, culture fishery, crocodile farming, sea-weed culture, wax and honey: honeybees prefer *Excoecaria, Avicennia* and *Aegiceras* species for nectar collection.

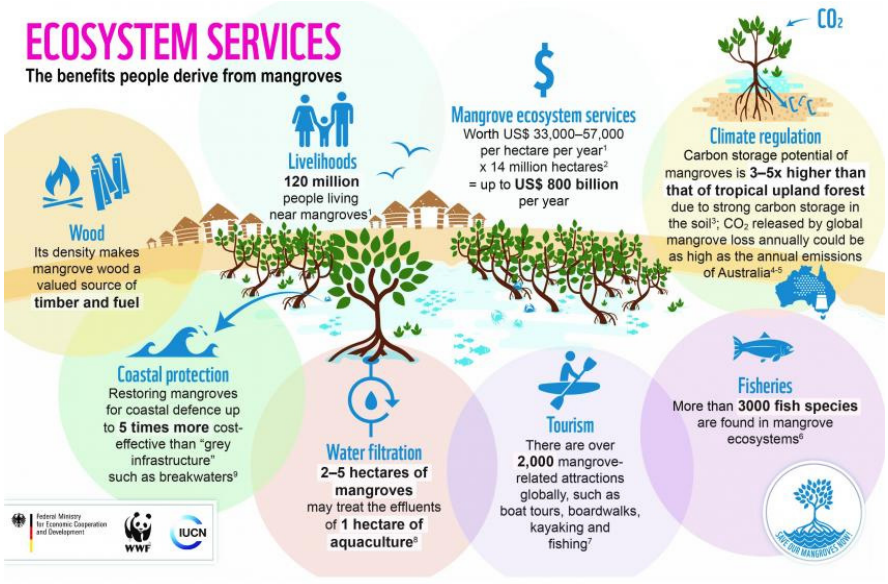

Figure 1.1 Schematic representation of ecosystem services by the mangrove habitats (Source: https://www.iucn.org)

1.3.1 Nutrient cycling

Among the different ecosystem services rendered by the mangrove habitats, nutrient cycling is crucial even though it is benefited by the human being indirectly. Mangroves are not only known as the sink of sediments or nutrients but also a source of nutrients to the adjacent coastal water bodies and even net exporters of organic or inorganic matter to the ocean through biological and physical processes within the forest ecosystem. The biogeochemical cycling of major nutrients: nitrogen, phosphorus, sulfur and carbon is very complicated and depending upon various biological and geographical factors, the pathway of cycling also changes in each mangrove ecosystem (Robertson,1986; Dittmar and Lara, 2001a).The nutrients in mangrove ecosystem majorly come from litterfall and recycling of this nutrients include reabsorption or retranslocation of nutrients before leaf fall (Ryan and Bormann, 1982; Vitousek, 1982), and the immobilization of nutrients in leaf litter during decomposition (Brinson, 1977). The fate of nutrients from litterfall may be through recycling and retaining mechanism majorly with the help of crabs and microbial community and may undergo mineralization and decomposition or may export as particulate organic matter (POM) or dissolved organic and inorganic matter. Herbivorous sesarmid crabs, fiddler crabs and burrowing crabs significantly influence nutrient cycling within mangrove forests by their burrowing and grazing activities (Smith et al., 1991).

The nitrogen (N) cycle within mangrove forests is controlled primarily by microbial activities rather than chemical processes (Alongi et al., 1992). Depending on the N pools present in the mangrove habitat, different transformations take place during nitrogen cycling. Biotic processes include nitrogen fixation, nitrification, denitrification and ammonification. Abiotic

processes are mainly though sediment-water column exchange. The nitrogen fixation rate in mangrove sediments was low and studied by many researchers; Zuberer and Silver (1978); Hicks and Silvester (1985); Boto and Robertson (1990). A global overview of nitrogen dynamics in mangroves was studied by Reis et al., 2017, and he documented the nitrogen cycling and its rates based on different works.

Marine ecosystems such as mangroves trap significant quantities of phosphorus and act as a sink of this essential nutrient which has a vital role in global biogeochemical cycles. Organic phosphorus concentration is very high in mangrove sediments compared to inorganic phosphorus. However, the former is not readily biologically available as it is bound to humic compounds, while inorganic phosphorus is readily available to plants (Boto,1988; Alongi, et al., 1992). In mangrove forests, phosphorus may be limiting productivity. However, the studies on the role of mangroves in phosphorus cycling are limited. The phosphorus cycle is comparatively simple as there is no gaseous phase. However, the microbial pathway is very complex and very difficult to study and measure. The major phosphorus pools in mangrove ecosystems are above and belowground biomass and sediment. The phosphorus input is from atmospheric dry and wet deposition, litterfall and through mineralisation from the soil. Anthropogenic sources like sewage, agriculture and aquaculture also contribute to phosphorus input in mangroves. The major mechanisms involved in the removal of phosphorus are mangrove plant assimilation, uptake by macro-feeder, microbial uptake, tidal exchange and soil immobilisation. In India, many researchers studied different stages of phosphorus cycling (Sheeba et al., 1996; Prasad et al., 2006; Gupta et al., 2006; Kumar et al., 2013; Ramanathan et al., 2008 and Mishra et al., 2008). Singh et al. (2015) reviewed major works on phosphorus cycling in India.

Sulfur cycling is very crucial in the mangrove ecosystem as it is very much related to the benthic community. The sulfur cycle includes four main mechanisms: 1. reduction of sulfate to hydrogen sulfide by microbes and its conversion to sulfide minerals by reaction with iron. 2. Organic sulfur formation or immobilisation. 3. Oxidation 4. Reduction (Sabine and Jorgensen, 1999; Behera et al., 2014). The sulfate reduction in mangroves depends on the availability of organic matter and controlled by bioturbation, oxidation of roots and tides (Kristensen et al., 1995; Alongi et al.,1998; Holmer et al.,1999). Bioturbation is carried out by the benthic communities, especially burrowing by crabs; which helps in oxidation of the sediment, resulting in aerated pore water condition in the mangroves and thereby helps in sulfate reduction. The tidal inundation also helps in aerating the sediment and increasing pore water oxidation. The presence of mangrove roots helps in sulfur cycling by vertical translocation of organic matter (Holmer and Neilsen, 1997; Holmer and Laursen, 2002) and the cycling is also related to reactive iron pools (Thamdrup, 2000). The role of microbes in sulfur cycling is very much essential. Behera et al. (2014) reviewed the works on sulfur-oxidizing bacteria.

1.3.2 Carbon cycling in mangrove habitats

The carbon cycling in mangrove ecosystem is unique due to its complex biogeochemical process which leads to carbon sequestration in its biomass, sediment pool and also through its export to the ocean; thereby playing a significant role in global carbon budgets (Fig.1.2). Mangrove plants efficiently capture atmospheric carbon dioxide (CO_2) during photosynthesis and store a major portion of this fixed carbon in its biomass. The biomass pool included both Above ground biomass (AGB) and Below ground biomass (BGB) of the plant. The stored carbon from the biomass reaches into the mangrove ecosystem through litterfall. The litterfall is again processed majorly by

foraging of mangrove crabs and other organisms and helps in retaining the mangrove primary productivity within the ecosystem. The litter processing and removal of these benthic organisms facilitate the microbial decomposition or mineralisation of this mangrove-derived organic matter and helps in long term burial of organic carbon in the sediment pool, or a portion of the organic component may export to adjacent water bodies. Another mechanism is mineralisation of this organic carbon where it may either be exported as dissolved inorganic carbon (DIC) to the ocean or may act as a long term sink of carbon or it may be emitted to the atmosphere as CO_2 efflux (Alongi et al., 1998; Bouillon et al., 2008 a; Maher et al., 2018). The different carbon pools in the mangrove ecosystem, carbon flux and burial mechanism are described in detail.

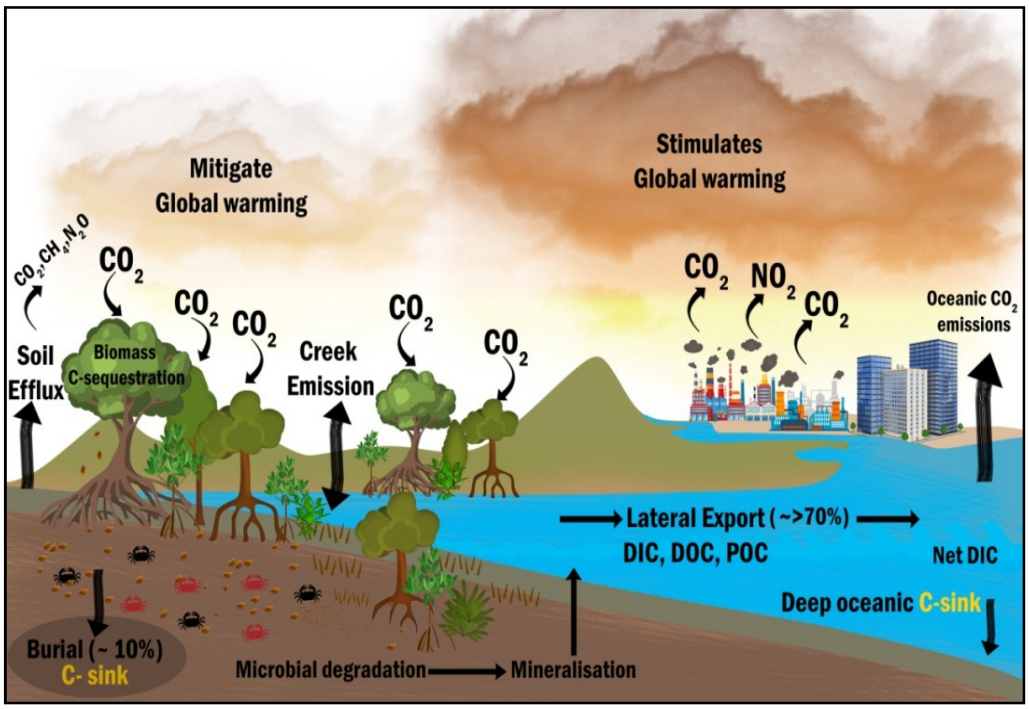

Figure 1.2 Schematic representation of carbon pathway in mangrove ecosystems

I. Carbon Pools

a. Biomass

Mangrove plants sequester carbon during photosynthesis and store it as biomass known as its primary productivity, and this net primary productivity may be estimated in terms of biomass and respiration or in terms of litterfall. Carbon is initially stored in living biomass as above-ground biomass and belowground biomass. As dead biomass like dead wood and leaf litter; the carbon reaches to the ecosystem. The carbon fixed by the plant is converted to biomass and when deforestation or disturbance for these plants occurrs, it leads to the emission of large amount of stored carbon to the atmosphere, and it is calculated that mangroves contributes 10 % of total carbon emissions from deforestation (Donato et al., 2011).

Mangroves exhibit high above-ground biomass, below-ground to above-ground biomass ratios (Komiyama et al., 2008; Lovelock, 2008), productivity (Putz*and* Chan, 1986; Matsui, 1998; Alongi et al., 2004), and high rates of carbon sequestration (Mcleod et al., 2011; Alongi, 2012; Breithaupt et al., 2012). Many regional and global studies focused on biomass studies and carbon sequestration through biomass increment estimates. For the last 20 years, some major global reviews done by Twilley et al., 1992; Saenger and Snedaker, 1993; Chmura et al., 2003; Bouillon et al., 2008b; Komiyama et al., 2008; Kristensen et al., 2008; Adame and Lovelock, 2011; Alongi, 2014; Hutchison et al., 2014 and Estrada and Soares, 2017 and their estimates are listed in Table 1.1. Almost half of the total global mangrove AGB is contributed by South-East Asia (Fig.1.3). According to Hutchison et al., 2014, the global mangrove AGB was 184.8 t ha^{-1}. Most of the biomass studies and primary productivity studies focused on only aboveground biomass and its increment. Only a few studies looked into both AGB and below ground

biomass. However, studies reveal that belowground biomass contributes a significant part (10–55%) of the total mangrove biomass (Twilley et al., 1992; Matsui, 1998; Alongi and Dixon, 2000). Kristensen et al., 2008 combined all the available global data on mangrove litterfall, wood and root production and estimated an approximate total Net primary productivity (NPP) of mangroves as 149 mol C $m^{-2}year^{-1}$. Recent estimates on NPP were based on above ground production only. Alongi, 2009 estimated an average above ground NPP rate of 11.1 Mg C ha^{-1} y^{-1} and recently, Estrada and Soares, 2017 estimated mangroves were having a global average carbon stock of 7 8.0 ± 64.5 t C ha^{-1} and sequestration 2.9 ± 2.2 t C $ha^{-1}yr^{-1}$ as AGB. Since Alongi, 2009 also included litterfall data in his estimation of carbon stock as AGB, and it was having high sequestration value (11.1 Mg C ha^{-1} y^{-1}) compared to Estrada and Soares, 2017. Estrada and Soares, 2017 revealed that carbon stock increases towards the equator and carbon stock variability was controlled by climatic parameters, age and physiographic types.

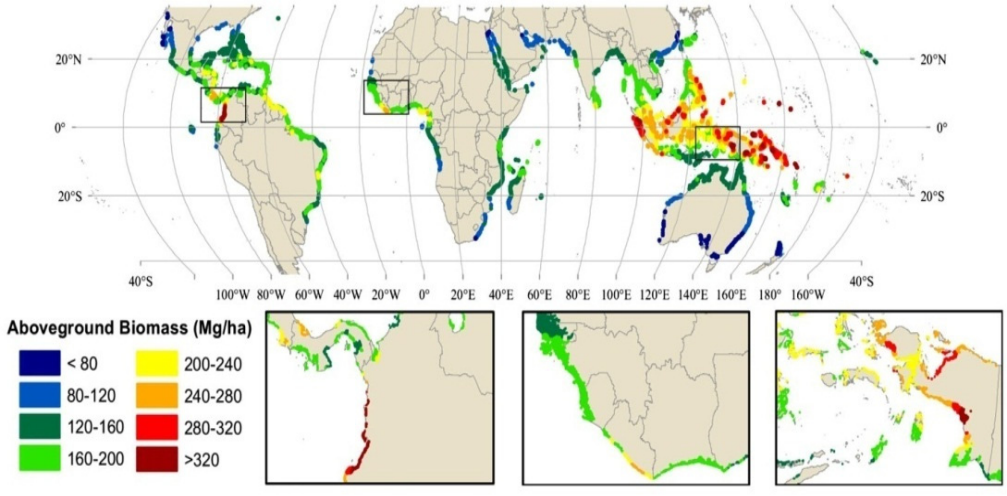

Figure 1.3.Global distribution of mangroves and range of above ground Biomass
(Source: Hutchison et al., 2014)

b. Sediment pool

Microbes decompose the carbon from the litterfall, that is incorporated into the sediment pool by leaching, bioturbation (macrobenthic communities especially crabs) or through burial. Some studies revealed that 90% of mangrove primary productivity is stored in the sediment pool (Donato et al., 2011; Kauffman et al., 2011; Stringer et al., 2015).

Table 1.1 Global studies on Carbon stock assessment as biomass and sequestration potential

Biomass carbon stock (t ha^{-1})			References used(Values)	Reference
Mean	**Max**	**Min**		
80.1 ± 50.5	129.1	28.3	8 (11)	Twilley et al.,1992
62.8 ± 46.9	196.4	3.1	17 (43)	Saenger*and* Snedaker,1993
78.3 ± 51.0	207.0	3.6	23 (54)	Komiyama et al., 2008
74.5 ± 54.6			52 (102)	Hucthison et al., 2014
78.0 ± 64.5	418.5	0.9	69 (316)	Estrada and Soares, 2017
Carbon Sequestration (t C ha^{-1} yr^{-1})				
5.4 ± 2.6	10.9	1.4	7 (9)	Twilley et al.,1992
4.5 ± 2.5	10.9	0.5	15 (31)	Bouillon et al.,2008
2.9 ± 2.6	9.0	0.4	6 (12)	Komiyama et al., 2008
2.9 ± 2.2	9.7	0.4	26 (101)	Estrada and Soares,2017

Therefore soil carbon stock or soil carbon pool assessment is very relevant for the assessment of total ecosystem carbon stock in a mangrove ecosystem. Recent estimates (Atwood et al., 2017) showed that globally mangrove could store ~2.6 Pg C (~9.5 Pg of CO_2e), with a mean soil C stock per unit area of 283 ± 193 Mg C ha^{-1}. Indonesia (831 Tg C), was having the highest soil carbon stock followed by Brazil (236 Tg C), Malaysia (199 Tg C) and Mexico (111 Tg C). Carbon stock studies should always be coupled with

stable isotope study using $\delta^{13}C$ and $\delta^{15}N$ as it revealed the source of organic matter; whether it is mangrove litter origin or marine phytoplankton origin. However, only a few carbon stock studies coupled with stable isotope studies are reported around the globe (Bouillon et al., 2003a; Gonneea et al., 2004; Prasad and Ramanathan, 2009; Tue et al., 2011; Ranjan et al., 2011; Weiss et al., 2016 and Prasad et al., 2017). C/N ratio is also used as a proxy to evaluate the sedimentary organic matter origin. Mangrove sediments usually have C/N ratios above 10, and sometimes may exceed 20 when there is significant input of mangrove litter (Alongi, 2014).

II. Carbon flux

a. Litter fall

The carbon which is fixed in the biomass enters into the ecosystem through litterfall. Thus the movement of carbon in the ecosystem starts with litterfall and takes part in carbon flux. Even though litterfall is considered as one-third of mangrove primary production (Robertson et al., 1992), still it is taken as a reliable proxy of net primary productivity (Twilley et al., 1992; Jennerjahn and Ittekkot, 2002; Alongi, 2014). It may be remineralised by decomposition, buried in the sediment or may be exported to adjacent coastal waters (Pool et al., 1975). The litterfall dynamics and its decomposition studies is a fascinating topic of research during the period of Odum (Odum *and* Heald, 1975). Several environmental and biological characters may control the litterfall rate in a particular mangrove habitat. On a global scale, litter production varied between 1.30 and 20.3 t $ha^{-1}y^{-1}$. Usually, lower latitudinal tropical mangroves exhibited higher litter production than higher latitudinal regions (Saenger and Snedaker, 1993; Komiyama et al., 2008; Bernini and Rezende, 2010). The highest litterfall was reported in Brazilian mangroves, 00°52′S (Mehlig, 2001) and lowest in 26° latitude in USA (Teas, 1979). Alongi

et al. (2005a) reported an exceptionally higher litterfall rate in Australian mangroves (34.4 t ha^{-1} y^{-1}) despite being in higher latitude (21°).

b. Export of Carbon

The organic matter entering into the ecosystem through litterfall may either be retained in the ecosystem or may be exported as particulate organic matter, thereby acting as a source of organic matter to the surrounding water bodies. Mangrove derived organic carbon has global significance in the coastal zones. Mangrove forests could export ~10% of the global terrestrial particulate and dissolved organic carbon (POC and DOC) to the ocean (Jennerjahn and Ittekkot, 2002; Dittmar et al., 2006). The export may be in the form of particulate organic carbon, dissolved organic carbon or dissolved inorganic carbon (DIC). Understanding of carbon fractionation (TOC [total organic carbon], DOC, POC, TIC [total inorganic carbon], DIC) in mangrove creek water is the basis for export studies. The export mechanism is a very complex biogeochemical process depending on the geographical type and tidal regime. Few works are reported globally on export studies (Twilley et al., 1992; Duarte and Cebrian, 1996; Jennerjahn and Ittekkot, 2002; Dittmar et al., 2006).

The study of the source of organic matter within mangroves and estuary also gives an idea of whether the mangrove habitat exported the materials more or it sequestrated carbon as biomass or in sediment. Therefore carbon fractionation study should always be accompanied by stable isotope study in which stable isotopic ratios, $\delta^{13}C$, and δ^{15} N and elemental composition (C: N) are widely used for indicating the source of organic matter. The C_3 plants, including mangroves, are having a typical $\delta^{13}C$ ratio and δ^{15} N ratio (Kendal, 1997). Mixing models can also be used when there exists confusion regarding the stable isotope range (Bouillon et al., 2003a). The understanding of the

source of carbon and nitrogen will add scientific strength to the carbon dynamics study rather than merely stating the concentration of each carbon fractions.

III. Role of sesarmid crabs

The primary production of mangroves is retained in the ecosystem with the help of herbivorous and burrowing crabs. Crabs are capable of removing 30–90% of the litterfall (Robertson, 1986; Micheli, 1993; Slim et al*.,* 1997; Schories et al*.,* 2003), while the remaining is either exported or degraded by microorganisms. Sesarmid crabs usually possess low assimilation, and therefore, ingested litter subsequently becomes more available as faeces for decomposer or detritus food webs (Thongtham and Kristensen, 2005). The processing of leaf material and its gut passage also facilitate nitrogen-rich, microbial rich faecal pellets which are more palatable for other invertebrates due to the smaller size of the particle fragments (Lee, 1997,1998). It has significantly higher decomposition rates compared to the original material (Lee, 1997; Kristensen and Pilgaard, 2001), resulting in a much quicker turnover of organic carbon. Kristensen *and* Alongi (2006) later studied the role of crabs in nutrient budgeting and its feeding ecology; Nordhaus*and* Wolf (2007) and Chen *and* Ye (2008). The burrowing activity of crabs also helps in changing the biogeochemistry of the ecosystem. The bioturbingmechanism by the crabs helps in aerating the sediment and also facilitate pore water entry into the ecosystem.

IV. Carbon burial

Mangrove habitats can store huge amounts of organic carbon for a long period in its sediment known as organic carbon burial or carbon sequestration in sediment pool (Matsui, 1998; Fujimoto et al., 1999). The storing was

observed several meters of depth (Twilley et al., 1992; Lallier- Verges et al., 1998). It accounted for ~10% of mangrove productivity (Duarte and Cebrian, 1996). The percentage of carbon burial will vary according to each mangrove habitat, and it depends on several environmental conditions like age, mangrove species and faunal diversity and sedimentation rate (Kristensen et al., 2008). Alongi et al. (2004) found out that burial rate increases from 16% to 27 % for a 5-year-old forest to 85-year-old mangrove stand. The sedimentation rate again depends on topography, tidal inundation and also size, shape, and zonation of mangroves (Mazda et al., 1997). When tides enter the forest, it will create turbulence around the trees and keep flocs suspended. When the tide returns from mangroves, particle settling occurs. Many researchers worked on this carbon burial part on a global scale, like Twilley et al.,1992; Jennerjahn and Ittekkot, 2002; Chmura et al., 2003; Duarte et al., 2005; Bouillon et al., 2008; Alongi, 2009; Mcleod et al., 2011 and Breithaupt et al., 2012. Recent studies are based on radioisotope analysis using ^{210}Pb activity and ^{137}Cs activity, which gives historical evidence of stored carbon in a vertical profile of mangrove sediment. Globally mangroves buried 163 g OC $m^{-2}yr^{-1}$ with 26.1 Tg OC in the sediment (Breithaupt et al., 2012). However, there is a significant gap which requires future studies on explaining the control mechanisms for a wide range of burial rates in mangrove habitats.

1.3.3 Carbon sequestration

Globally carbon dioxide concentration in earth's atmosphere is increasing in such an extent that it threatens the world with global warming and climate change related issues. Most recently, it has reached 414.28 ppm on 2 June 2019, with a monthly average of 413.52 ppm for April 2019. The Fig.1.4 depicts the recent change in CO_2 concentration (https://www.esrl.noaa.gov/gmd/ccgg/trends/global.html) from 2015 onwards. Further increase in

concentration could increase global warming up to 1.5^{o}C that can create severe global climatic problems and sea level rise. Even though we could minimise the expected 2^{o}C global warming (IPCC, 2018), we are still suffering the impacts of just 1^{o}C increase in temperature. Therefore, carbon storing or carbon removal is of prime concern of the globe. Plants can efficiently capture this atmospheric CO_2 and store it as organic compounds as above and belowground biomass through photosynthesis. That is why we talk about forest conservation and importance of tropical rain forests. However, in addition to biomass, the storing of carbon in the sediment pool for long periods is another add on service by mangrove ecosystems. The carbon cycling in mangrove ecosystem through a complex biogeochemical process leads to long term carbon sequestration in different carbon pools. Carbon sequestration is a term used for long term carbon storage and is defined as "*Carbon sequestration implies the transfer of atmospheric CO_2 into other long-lived global pools including oceanic, pedologic, biotic and geological strata to reduce the net rate of increase in atmospheric CO_2*"(Lal, 2008).

Even though mangrove forests contribute only 0.5% of the global coastal area (Alongi, 2014), its service in carbon sequestration is very high compared to tropical rain forests (Donato et al., 2011). Mangrove plants have higher photosynthetic carbon fixation capacity than terrestrial forests (Christensen, 1978). Every year, the mangroves, salt marshes and seagrasses which are considered as earth's 'blue carbon sinks', capture and store between 235- 450 trillion tons of carbon (Nellemann et al., 2009). However, these global treasures are facing rapid degradation, having lost 35% of the global area (3.8 x 10^{14} g of carbon stored as mangrove biomass) with a current rate of 0.7-3% yr^{-1} (Pendelton et al., 2012). Kerala mangroves are also under similar threat from various anthropogenic and coastal developmental activities

(Bijoy Nandan et al., 2015). Declining area of these unique carbon pools will ultimately have a severe impact on climate change. In the last 20 years, some reviews have been published addressing the storage and flux of carbon or organic matter in mangrove ecosystems (Twilley et al., 1992; Saenger and Snedaker 1993; Chmura et al., 2003; Bouillon et al., 2008; Komiyama et al., 2008; Kristensen et al., 2008; Adame and Lovelock, 2011; Alongi, 2014 and Hutchison et al., 2014).

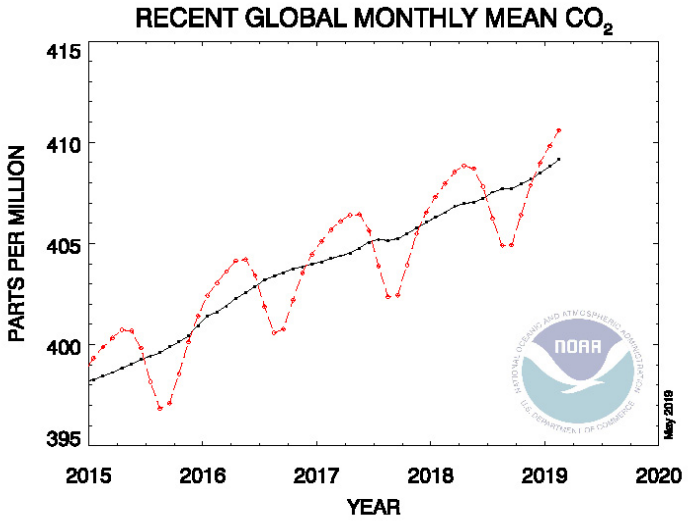

Figure 1.4 Temporal change in the atmospheric Carbon dioxide concentration

(Source: https://www.esrl.noaa.gov/gmd/ccgg/trends/global.html The red line denoted the monthly mean values and the black line denoted the average seasonal cycle).

1.4 Carbon cycling and sequestration studies in Indian scenario

Studies on carbon sequestration potential of agroforestry are numerous in the Indian context. However, mangrove ecosystems have not been studied in depth, and only limited studies exist in literature. Kalyan Chakrabarti, 1987; Choudhuri, 1991; Mitra et al., 2011 and Joshi et al., 2014 studied Sundarban's

mangroves-biomass productivity and resource utilisation. Sandipan Karmaker, 2006 studied mangrove biomass, net primary production and species distribution using remote sensing data. Kathiresan (2007) studied rehabilitation of destroyed mangrove forests as a carbon and nutrient sink. Ravichandran et al. (2007) studied leaf choice of herbivorous mangrove crabs. Ray et al. (2011) estimated carbon sequestration of Sundarban mangrove forest by considering AGB, BGB, litterfall, CO_2 gas exchange and also reported soil carbon sequestration by using empirical formula. Wafar et al. (1997) also studied litterfall dynamics in Mandovi–Zuari estuaries on the Central-West Coast of India and Ghosh et al. (2013) in Sundarbans mangrove forest. The sensitivity of mangroves to changing climate was reported by Mitra (2013). The stable isotope study for organic matter source in mangroves/estuary was done by Sarma et al. (2014). Raha et al. (2013) studied carbon stock assessment in mangrove above ground biomass. The mangrove biomass carbon stock was studied by Bhomia et al. (2016a) in Bhitarkanika mangroves, Sahu et al.,2016 in Mahanadi deltaic mangroves and Suresh et al., 2017 assessed biomass carbon stock for all over Indian mangroves.

An important and significant study on the export of mangrove-derived carbon in Sundarban mangroves were studied by Ray and Shahraki (2016). Only a few studies are reported from Kerala on mangrove carbon budgeting. Nameer et al.,1992 studied floristics, zonation and above ground biomass production in the mangroves of Puduvyppu, Kerala. Vidyasagaran, 2011 estimated above ground biomass of Kannur mangroves, Vinod et al., 2018 studied about carbon stock assessment in Kadalundi mangroves and Bindu et al., 2018 used remote sensing data (used wood density data from the database and biomass calculation using allometric equations) for the calculation of carbon stock as AGB in Kunhimangalam, Kannur mangroves. Thus from the

perusal of literature, it is evident that carbon sequestration or in-depth carbon cycling pathways are not seriously studied for any Indian mangrove habitat. The studies reported as carbon sequestration do not account the real sediment carbon burial assessment and is merely based on carbon stock assessment. Thus a critical carbon stock assessment together with sequestration potential study is needed for the Indian mangroves.

1.5 Significance of the study

Mangroves are the global treasures on the earth which fight against global warming and climate change problems. However due to ignorance of this vital fact, the global mangroves are declining very fast, and about 38% of the mangroves are lost (Thomas et al., 2017) globally with the highest loss in developing countries. This mangrove loss will trigger the emission of precious carbon stored in these habitats as green house gases like CO_2 and CH_4. Therefore, accounting of carbon sequestration potential of each mangrove habitat is a prerequisite for the conservation and developing management strategies; also for policy making and receiving the benefits of REDD+ schemes for the practices for reducing carbon emission in developing countries.

With this background, even though several studies have globally documented on the carbon stocks, it's flux, carbon partitioning in the mangroves, including carbon sequestration potential through burial, knowledge from Cochin or Kerala mangroves are least explored. In this context, the present research will hypothetically test whether the Cochin mangroves are potent in storing carbon in its biomass and sediment comparing to the global mangroves; is there any change in biomass stock depending on the mangrove species and also check the reasons (biological pump or geochemical pump) for

change in soil carbon stock in different mangrove habitats. This PhD thesis has made pioneering effort to document the carbon sequestration potential of mangrove habitats through the carbon stock assessment, its variants (organic and inorganic carbon) contributing to above ground biomass (AGB from plant) and belowground biomass (BGB); the significant part of which gets transformed to primary production as leaf litter; the part involving biological consumption and transfer of carbon by sesarmid crabs, and also on the historical source and sequestration path and efficiency of the carbon in Cochin mangroves. The conceptual diagram of the study is depicted in Fig. 1.5.

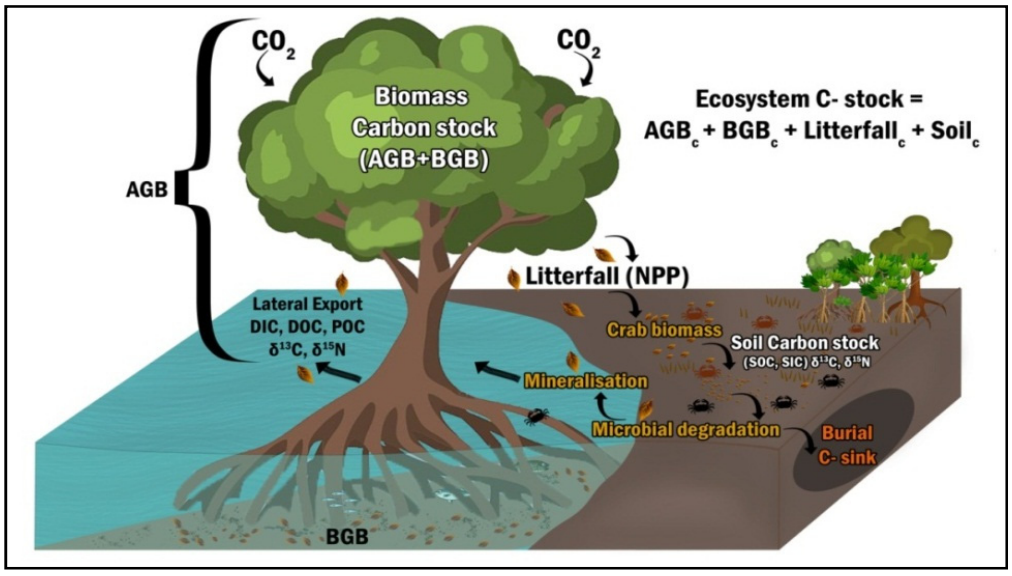

Figure 1.5 Carbon flux and budgeting in a mangrove habitat- A conceptual framework of the study

Therefore, the study will provide the carbon derivative pathway, it's sequestration pattern, with signature of CO_2 equivalent- an indicator of climate change from the mangrove habitat. The outcome of the study can also be employed as tool for the sustainability of other mangrove habitats in India. The study will also include climate adaptability measures for long term

management of coastal habitats. In this context, the following objectives are outlined for the study.

1.6 Objectives

- To assess the phytosociology and community structure of mangrove plants.
- Estimate the mangrove biomass at species and spatial scale.
- Assess carbon stock from different carbon pools.
- Study the role of mangrove crabs in carbon structuring.
- Estimate the carbon sequestration potential and impact on climate change.

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Chapter 2

PHYTOSOCIOLOGY AND COMMUNITY STRUCTURE OF MANGROVES

2.1 Introduction

Mangroves are the inimitable vegetation, living at the convergence of land and sea, and forming the third most productive ecosystem in the world as compared to rain forests and coral reefs, and other wetland ecosystems. Mangroves have characteristics that make them structurally and functionally unique. Characteristics such as zonation show difference in patterns depending on regions and locations. Another characteristic of mangroves is forest structure or phytosociology, which is one of the ways to evaluate the development or maturity of a forest ecosystem. Understanding the structural attributes of the mangrove plant is essential for productivity studies and carbon stock assessment studies. Structural attributes include diversity, density, frequency, basal area and height and diameter at breast height (DBH). From these data, several structural indices were computed, which can be used for

conservation practices. The structural parameters like DBH and height are used for biomass estimation studies that are further useful in carbon stock assessment and productivity studies. The structural characters like tree density and basal area are widely used to assess mangrove community structure into young/growing or mature forests (Satyanarayana et al. 2002; Satyanarayana, 2005). The wood and aboveground roots of mangrove forests have a significant influence on the hydrodynamics and sediment transport within forests (Quartel et al., 2007). The structural attributes like density, stem and root diameter and shore slope are important in controlling the wave energy and wind energy and help to reduce the flooding, storms and Tsunami like natural disasters in the coastal zones (Massel et al., 1999, Alongi, 2008).

Mangrove plants varies regionally and locally in their structural attributes as it is influenced by regional environmental factors including stressors, e.g. hurricane, storm, drought or frost, topography, sediment characters, changes in sea level, freshwater input/rainfall, temperature/evapotranspiration, light and tide fluctuations (Smith, 1992; Kauffman and Cole, 2010). The biotic factors that control phytosociology of mangroves include propagule size, predation and availability of propagules, weight and viability, herbivory, human interference and interspecific competition. The understanding of the drivers of vegetation structure is essential for conservation and management purposes (Berger et al., 2008, Komiyama et al., 2008, Krauss et al., 2008, Triest, 2008, Bosire et al., 2008 and Glaser and da Silva Oliveira, 2004).

2.2 Literature Review

The methods of studying mangrove structure were described in detail by Cintron and Novelli, 1984. In 1992, Duke classified mangroves based on their structure and tidal regime and the categories were “plants preferring low-

tide level; low to mid-tide level; mid-tide level and mid to high-tide level". Later Pellegrini et al., 2009 classified mangroves into different maturity classes based on structural aspects. The studies which describe only on structural characteristics of mangroves were merely accounted in the global level. Most of the structural studies were done as part of biomass estimation (Clough et al., 1997; Komiyama et al., 2005; Soares and Schaefer-Novelli, 2005; Chen et al., 2012; Sitoe et al., 2014; Tang et al., 2018). Structural aspects of mangrove forests together with zonation pattern in different parts of the globe were studied by Pool et al.,1977 in Florida, Puerto Rico, Mexico, and Costa Rica mangroves; Snedaker, 1982 described structure and zonation pattern of mangroves; Smith, 1992; Amarasinghe and Balasubramaniam, 1992 in Srilankan mangroves; Saenger and Siddiqi, 1993 in Bangladesh mangroves; Schaeffer-Novelli and Cintron, 1994; Matthijs et al., 1999; Ellison et al., 2000; Dahdouh-Guebas et al., 2002 in Srilankan mangroves and Satyanarayana et al., 2002 in Coringa mangroves, India. Fickert and Gruninger, 2010 reported the floristics, zonation pattern together with structural aspects of Caribbean mangrove forest. Maia and Coutinho, 2012 reported the structural characteristics of mangroves in and around Brazilian estuaries. They measured DBH, basal area, density, frequency and tree height of the mangroves together with sediment characters and checked the difference in structural parameters of mangroves with edaphic characters.

Many structural studies were focused on the influence of environmental characters on mangrove structure (Cintrón et al., 1978; McKee, 1993; Koch, 1997; Fromard et al., 1998; McKee and McGinnis, 2002; Feller et al., 2002; Satyanarayana et al., 2010). Ashton and MacIntosh (2002) reported the influence of salinity, tidal inundation, and soil characters whereas Satyanarayana (2005) found out that the inundation frequency with respect to

landward, mid-forest or seaward sites could play a key role in structuring mangrove distribution. The influence of salinity, the concentration of available phosphorus, Eh and sulfide concentration on mangrove structure and its biomass was studied by Lovelock et al., 2005. Calegario et al., 2015 also studied on structural aspects of two Brazilian mangroves in Rio de Janeiro based on salinity gradient.

In India, primary research on mangrove ecosystem was based on structural aspects (Naskar and Mandal, 1999; Mandal and Naskar, 2008). In Sundarbans, major studies were done by Mukherjee and Mukherjee, 1970; Matilal et al., 1986; Chaudhuri and Chakrabarti, 1989 and Saha and Choudhury, 1995. While the structural aspects and the influence of environmental characters were studied by Joshi and Ghose, 2003; Joshi and Ghose., 2014. They reported that *Acanthus ilicifolius* was intolerant to pH and salinity gradient and therefore showed a wide distribution and also reported the complexity index of mangroves was maximum in low saline regions. Manna et al. (2012) did another interesting study on the influence of mangrove community establishment and its association with other plants in an abandoned brick kiln, lower Bengal. They assessed the community establishment of a mangrove plant *Sonneratia caseolaris* together with several mangrove associates based on structural characters. Some studies carried out along major mangroves of India were: Pichavaram and Muthupet (Muniyandi,1986; Kathiresan et al., 1994; Kathiresan et al., 2016), Andaman and Nicobar Islands (Dagar,1987; Singh et al., 1990; Mall et al., 1991; Singh and Odaki, 2004; Ragavan et al., 2015; Kiruba-Sankar et al., 2017). Kathiresan et al. (1994) documented the structural aspects of mangroves and its relation to prawn seeds in Pichavaram mangroves, and the density of mangroves in Pichavaram was documented in Kathiresan et al. (2016). Structural characteristics of mangroves

of Andaman and Nicobar Islands was studied by Ragavan et al. (2015) and described in detail on the diversity of mangroves in that region; it's density, Importance Value Index (IVI). They reported that Andaman and Nicobar Islands was most diverse among other mangrove habitats of the country and *Rhizophora* spp. contributed the major vegetative part among the mangrove plants of Andaman and Nicobar Islands. In Odisha, the major works on mangroves were done by Upadhyay and Mishra (2008, 2010 and 2014) and in Andhra Pradesh (Azariah et al., 1992; Venkanna and Narasimha Rao,1993; Satyanarayana et al., 2002, Satyanarayana et al., 2009). Satyanarayana et al. (2009) used the structural characters like density and basal area in order to understand the zonation pattern of mangroves using multivariate methods. In Gujarat, the major reported works were r and Sawale and Thivakaran (2013). In Kerala, Nameer et al. (1992) studied mangrove structural characteristics in terms of the biomass of Puduvyppu mangroves, Cochin. Later, Suresh Kumar and Mohan Kumar (1997) worked on mangrove floristics, structure, biomass and its relation to soil characters of the same study area. The phytosociology of Kannur mangroves was studied by Vidyasagaran et al. (2011), Kadalundi mangroves by Rahees et al. (2014) and Kollam mangroves by Vijayan et al. (2015). The structural aspects of mangroves for entire Kerala was studied by George et al. (2018) and Sreelekshmi et al. (2018). Only 13 true mangrove species were reported by George et al. (2018) compared to 18 true mangrove species as described in Sreelekshmi et al. (2018). The former study focused mainly on structural aspects in detail while the latter discussed mainly on zonation pattern of mangroves based on the density of mangroves.

However, the specific structural aspects of mangroves in and around Cochin region, in relation to the environmental features are not well documented. Thus this chapter elaborates the structural aspects of mangroves

which would serve as a tool for understanding the carbon structure in the system.

2.3 Materials and Methods

2.3.1 Study Area and Sampling design

Kerala, with ten coastal districts, is located on the South-West coast of Peninsular India, is blessed with 44 rivers originating from the Western Ghats and emptying into the Arabian Sea (Lakshadweep Sea) and having 590 km long stretch of coastal shoreline. Kerala has a humid equatorial tropical climate with three distinct seasons: pre-monsoon (February- May), southwest monsoon (June- September), northeast monsoon/ post-monsoon (October- January). The tropical climate and valuable coastal habitat help in the growth of mangrove plants along the beautiful estuaries, lagoons and backwaters of Kerala. The mangrove habitats selected for the study is located in central Kerala, in and around the district of Ernakulam. The study area is bordering the Cochin estuary, that is a positive tropical tidal estuary (76^{o} 9'25" E- 76^{o}24'28" E and 9^{o} 47'31" N - 10^{o}12'N) has also encompassed the renowned Cochin port city. It supports the luxurious patch of mangroves along this estuary and in the Islets. However, the construction of Cochin shipyard followed by intense and large scale constructional activities, reclamation and aquaculture farming has resulted in massive destruction of mangroves in this area; however, the significant patch can only be observed in Puthuvypin region, Vypin Island. Therefore, scientific study and documentation of the existing degrading mangroves is very much needed for the Cochin mangroves. Based on the need, the floristic and structural character of mangroves were carried out along eight mangrove habitats in and around Cochin estuary (Fig.2.1, Fig.2.2 Plate 2.1a-h). Eight study stations were selected from the mangrove habitats extending for approximately 30 km from Aroor in the South to Malippuram,Vypin Island in

the north along the Cochin coastal and estuarine zone, hereafter referred as Cochin mangroves for regular monthly/ seasonal and short term sampling. The samples collected from 2013-2015 and 2017 period for various phyto sociological and carbon stock/ sequestration studies have outlined in Fig. 2.3. Global Positioning System (Magellan ® Triton 200/300) was used for the selection of each station with the help of information collected from the local administration.

Station 1: Aroor located at 9^{o} 52' 1.42" N, 76^{o}18'54.97" E in the southern part of Cochin and the northern tip of Alappuzha district. Several seafood processing industries are present near to this mangrove habitat. The station is greatly influenced by fresh water compared to other stations and topographically can be considered as a semi-closed mangrove habitat. This site has dense and old mangrove trees and exhibits abundant crab foraging and burrowing activities. *Avicennia officinalis* and *Rhizophora* spp dominated the station. Moreover, the fringing zone was inhabited by the lush growth of *Acanthus ilicifolius*. Human settlements are also prevalent in between the mangrove patches of the study area. The depth of the station is shallow, < 0.5 m that usually dries up during the low tide period.

Station 2: Malippuram mangrove habitat (10^{o}1'11.24" N, 76^{o} 12'53.53"E) is situated at Vypin Island, the northern part of Cochin city on the shore of Arabian Sea. This area was affected by the 2004 Tsunami event, and a portion of this mangrove area was converted to aquaculture farm in the 1980's, that is governed by Matsyafed, Govt. of Kerala. The first three quadrats for the present study is located inside this aquaculture farm. The major culture in this farm is Indian Grey Mullet (*Mugil cephalus*, " Thirutha") and other species cultured in this farm include milkfish, tilapia, pearl spot, mud crab and tiger prawn. Now it is converted to an ecotourism centre and is a major tourist spot

in Cochin. Young *E.agallocha* and *Avicennia officinalis* dominate the mangrove island in this aqua-tourism centre,and the average depth of this station is 1 m and crab burrowing, and foraging activities are very less in this station.

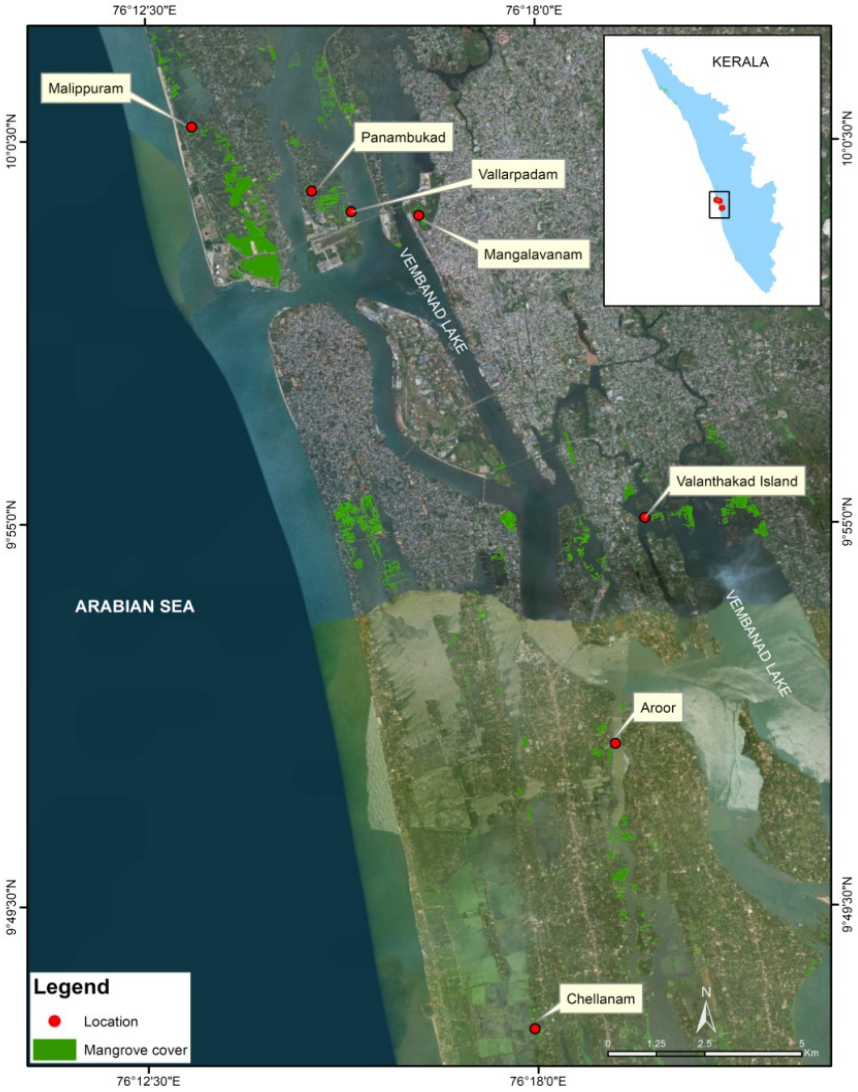


Figure 2.1 Location map of mangrove stations from Cochin for phytosociological analysis during 2013-2014 period (processed Landsat LISS-III No.2018 satellite image from https://www.usgs.gov/)

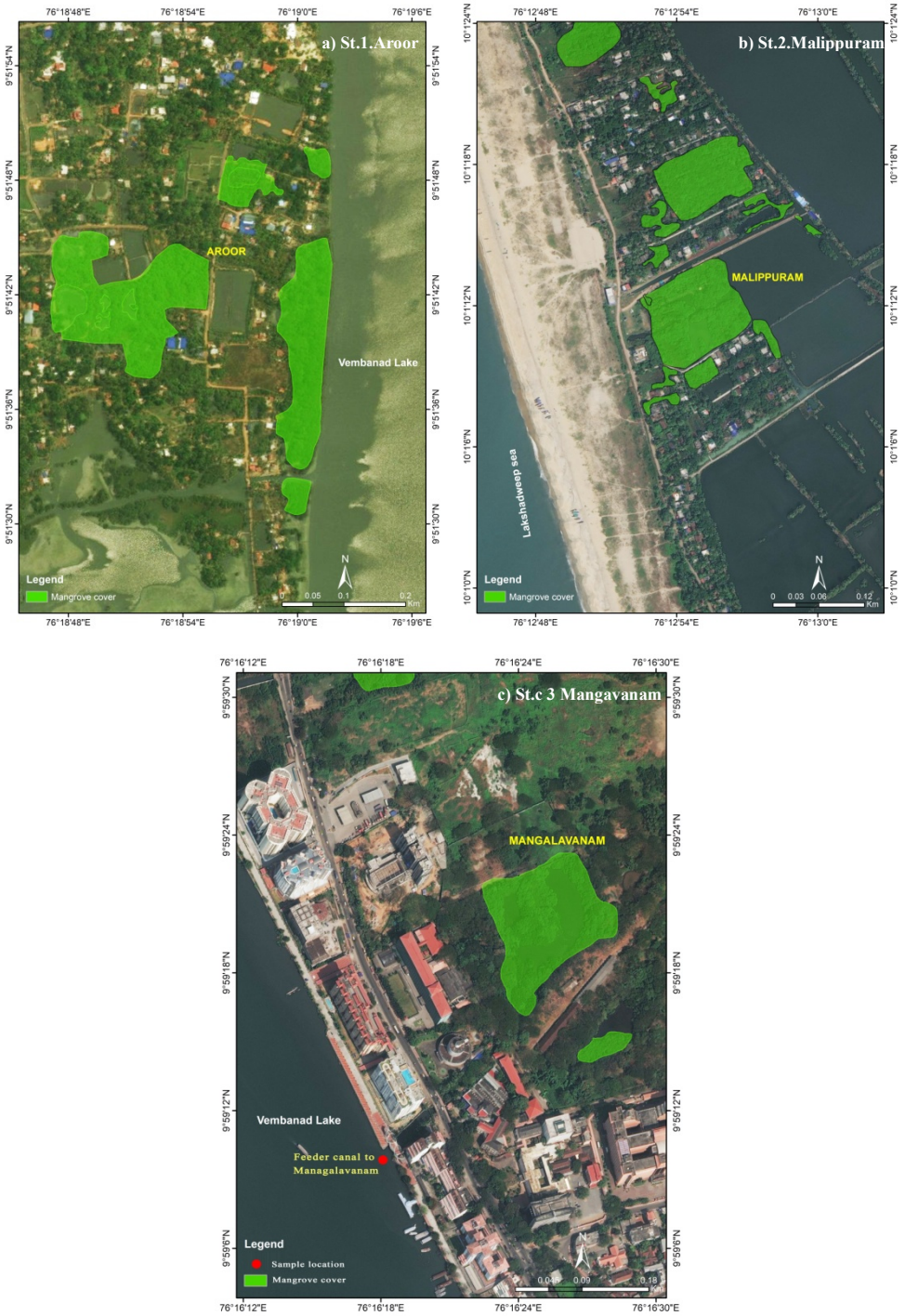


Figure 2.2 a-c Location map of mangrove stations from Cochin selected for carbon assessment studies during 2013-2017 period

a) Station 1. Aroor

b) Station 2. Malippuram, Vypin Island

c) Station 3. Mangalavanam Bird Sanctuary

d) Station 4. Chellanam

e) Station 5. Valanthakad

f) Station 6. Panambukad

g) Station 7. Vallarpadam

h) Station 8. Puthuvypin

Plate 2.1 a-h Photographs of sampling stations for phytosociology analysis of Cochin mangroves

Station: 3 Mangalavanam Bird Sanctuary, (9^o 59' 23.83"N, 76^o 16' 26.74 E) is a semi-closed wetland dominated by mangrove forest, connected to the estuary with a feeder canal and is considered as the "green lung of Kochi city". This station is closer to the Barmouth of Cochin estuary that receives more marine nutrient loads during high tide. The mangrove trees are very old, inhabiting the shallow (<0.5 m) habitat which is almost in dry condition except at high tide flooding period. It was declared as a protected area on 31st August 2004. Mangalavanam is famous for the congregation of breeding birds, migratory birds and the presence of mangroves.

Station: 4 Chellanam (9^o 47'43.8 N, 76^o 17' 57.11 E) is situated north-western border of Cochin on the shore of Arabian Sea. However, the mangrove station is more distant from the shore than St.2. It is a popular area for coastal fishery. The mangrove area is inhabited by human settlements and less affected by anthropogenic activities. The mangrove habitat is deeper than other stations

(0.5-1 m), and dominant mangrove species are *Avicennia officinalis* and *Excoecaria agallocha.*

Station: 5 Valanthakad (9^{o} 55'4.22 N, 76^{o} 19'31.87 E) is an open mangrove with a lot of fresh water inflow and high saline intrusion during the pre-monsoon period. It is situated on the eastern side of Vembanad backwater supported by indigenous clam and other fishery activities. The mangrove habitats surrounding this island make it an excellent nursery for prawns, crabs and fishes. The station is inhabited by rare mangrove species like *R.apiculata* and *K.candel*. The depth of this region is 0.75-1 m and is continuously inundated, except in few places where it is completely drained out only during low tide period.

Station: 6 Panambukad (9° 59' 46.53" N, 76° 15' 24.084" E) is the northern part of Vallarpadam Island in the Cochin estuary. The study area has luxurious growth of mangroves dominated by *R.mucronata*. Most areas directly connected to the estuary and depth is around 1-1.5 m. Since major mangrove area in this station is under private property and mainly destroyed for house construction, it is in degrading phase.

Station:7 Vallarpadam (9° 59' 28.644" N, 76^{o} 15'E) is near to Barmouth of Cochin estuary that receives marine influence from the Arabian sea with an average depth of 1-1.5 m. Major mangrove area in this station was lost due to developmental activities as part of Vallarpadam International Container Terminal construction. Currently, only a small patch of mangroves exists near to the Vembanad bridge. Several aquaculture ponds exist in between the mangrove patch controlled by Marine Products Export Development Authority (MPEDA) and private stakeholders.

Station: 8 Puthuvypin (9° 59' 12.912" N and 76° 13' 47.064" E of Vypin Island) is situated near to LNG Terminal and is the most industrially polluted site under high pressure of deforestation. This station is the only site with highest mangrove area in Ernakulam district. The area once harboured 500 ha of mangroves which are now reduced to 250 ha of which only 50 ha is under Government. The reduction in mangrove cover indicates its rapid illegal encroachments. Very old and tall mangrove trees with luxuriant growth can be observed in this station with *A. officinalis* as the dominant species, and very rare species (to central Kerala) such as *A. marina* and *S. alba* are encountered in this station. It is directly connected to the Arabian Sea and having a depth ranging from 0- 2 m.

The overall study of this thesis was conducted on a regular basis from different mangrove habitats of the Cochin region as per the sampling schedule described below. The mangrove phytosociology was conducted in 2013-2014 period at eight mangroves habitats of Cochin mangroves. From these eight mangrove habitats, three mangrove habitat was selected (St.1 to St.3, Fig.2.1b-d) for detailed assessment of carbon stock studies in biomass and soil pool. The accessibility for regular monthly sampling, age of mangrove habitat and crab density were considered for the selection of these three stations for detailed assessment. The structural parameters like height and wood density were measured additionally in these three stations for biomass assessment. Abiotic parameters for a period of three years (2013-2015) was also analysed on a monthly basis from three stations. The litterfall dynamics and productivity was measured in three stations for a period of one year (2013-2014). The sediment carbon stock in the three mangrove stations was done for three years (2013-2014). The carbon flux through intertidal water inside the mangrove habitats was assessed in three stations during 2014-2015 period. The carbon source

characterisation and the analysis of export of mangrove-derived carbon to the estuary was done using stable isotope analysis in three mangrove habitats and five stations in the Cochin estuary in 2017. The carbon sequestration through burial was estimated in three mangrove habitats during 2017. The schematic representation of the sampling schedule is shown in Figure 2.2

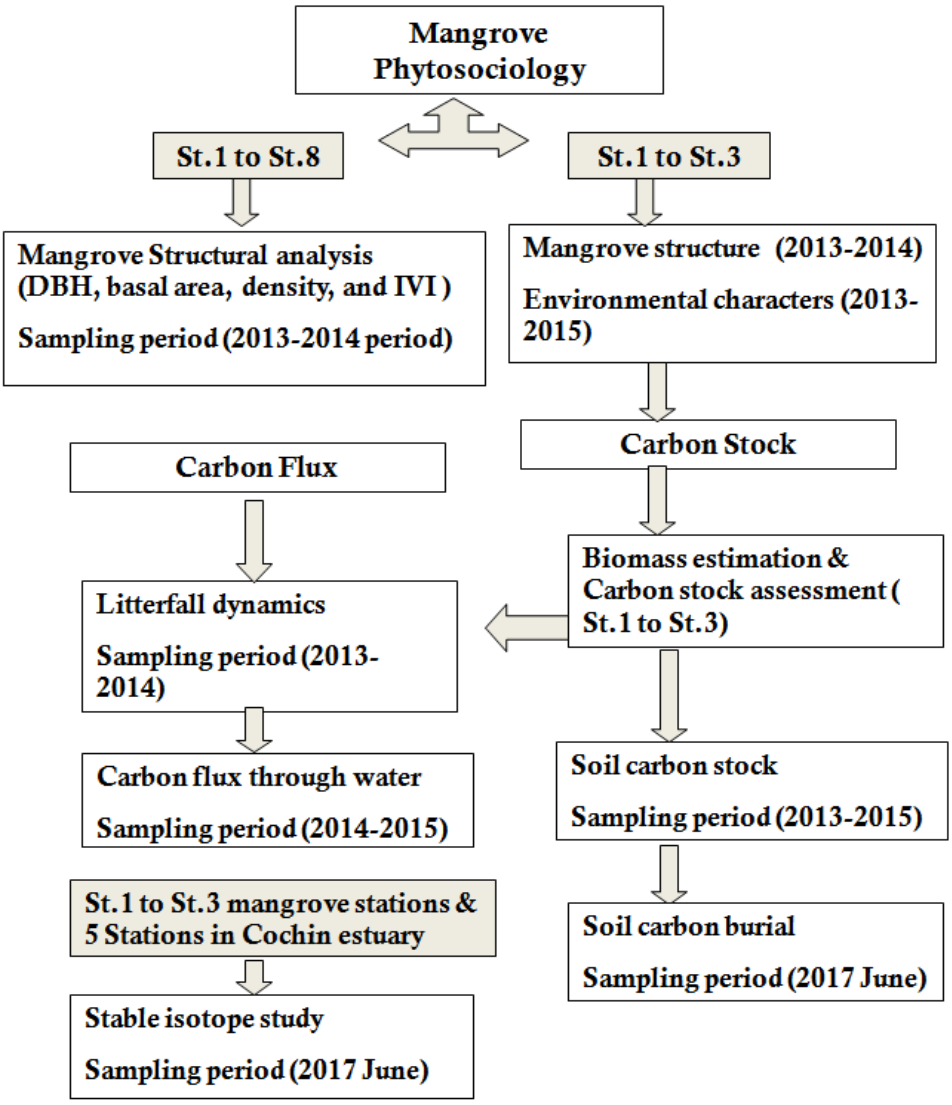


Figure 2.3 Schematic representation on sampling schedules and study stations outlined under the thesis

2.3.2 Community structure and Phytosociology

The structural analysis was done during 2013-2014 period for which fixed area plot measurement was used for the characterization of the plant structures of mangroves based on the methodology proposed by Cintro´n and Schaffer-Novelli (1984). In each site, five transects were laid perpendicular to the shoreline, and in each transect, one quadrat was laid with a total of 5 quadrats in each station. The size of the quadrat was fixed at 5 x 5 m (25 m^2). The criteria followed for the selection of areas for the study was, representativeness, importance and accessibility. Since the study area was small, the number and size of the quadrat were minimized. Each species in the quadrat was counted, analysed and the species identification was made as per standard keys by Tomlinson (1986), and the family nomenclature followed Stevens (2001) except Pteridaceae family. International Plant Naming Index (IPNI, 2015) was used for checking the nomenclature of the mangrove plants. The true mangrove plants were checked with the species list of Spalding et al. (2010).

The structural parameters such as Diameter at Breast Height (DBH) and height were measured by using a steel measuring tape. Based on data obtained from quadrats, the structural parameters like density, relative density, abundance, percentage frequency, relative frequency, basal area, relative basal area, importance value index (IVI), relative IVI, were calculated by using standard formula (Cintro´n and Schaffer-Novelli, 1984). Density was reported as the number of trees within 1 ha plots. Diameter at breast height (DBH) was taken for each site, once during the sampling year. The girth of a tree at breast height was measured using a steel tape (in cm) and was converted into diameter, dividing by π (3.14). Breast height was determined as being

approximately at 1.3 m. The DBH tape had to be placed levelled and stretched firmly against the trunk to ensure accuracy. When abnormalities such as swelling, forks or prop roots prohibited a measurement being taken at 1.3 m, an appropriate height was chosen by following standard rules (English et al., 1997). From DBH, the basal area was calculated. The different equations for the calculation of structural characters are given below:

Density	=	Number of individuals of a species/ha
Abundance	=	Total number of individuals of a species in all quadrats/Total no. of quadrats of occurrence
Basal area	=	$\prod d2/4$, where d = DBH (cm)
Relative density	=	(No. of individuals of a species/ Total no.of individuals of all species) × 100
Percentage frequency	=	(No. of quadrats of occurrence/ Total no. of quadrats studied) × 100
Relative basal area	=	(Basal area of the species/ Basal area of all species) × 100
Importance Value Index (IVI)	=	Relative density + Relative frequency + Relative basal area

The community analysis was done using univariate analysis, such as computing various diversity indices using the software PRIMER v.6 (Clarke and Gorley 2006). The spatial difference in species diversity was compared through this analysis. The various indices used and its calculation were: species richness (Margalef's index, d), species evenness (Pielou's index, J'), species diversity (Shannon index, H') and species dominance (Simpson's index, λ').

a. Species richness - Margalef's index (Margalef, 1968)

$$d = (S-1) / \log_e N$$

Where, d = species richness

S = total number of species

N = total number of individuals

b. Species evenness - Pielou's index (Pielou, 1966)

$$J' = H'/\log_2 S \text{ or } H'/\ln 2 S$$

Where,

J' = evenness

H' = species diversity

S = total number of species

c. Species diversity - Shannon index (Shannon and Weaver, 1963)

$$H' = 3.3219(N\log - \Sigma ni - \log ni)/N$$

Where, H' = the species diversity in bits of information per individual

N = total number of individuals in the collection

ni = the proportion of individuals of each species belonging to the i^{th} species of the total number of individuals (number of individuals of the i^{th} species)

Σ = summation

d. Species dominance - Simpson's index (Simpson, 1949)

$$D = 1/\lambda$$

Where, $\lambda = \Sigma Pi2$

$Pi = ni/N$

Where, ni = number of individuals of i, i2 etc.

N = total number of individuals.

2.3.3 Environmental Parameters

Environmental characters were analysed for a period of 3 years, 2013-2015 in three selected mangrove habitats (St.1, St.2, St.3). Rainfall data was obtained from the India Meteorological Department (IMD) (www.imd.gov.in). The water samples were collected from intertidal water inside the mangrove habitats. The average tidal height in Cochin area ranges from 0.2-1.1 m (www.incois.gov.in). Since the depth of water column is below 0.5 m and sometimes below 0.30 m, the major portion of water may be from ground water source. Subsurface water samples were collected from the sampling stations using pre-cleaned plastic containers (500 mL) and BOD bottles (Grasshoff et al., 1999). The physical parameters such as **water temperature** were measured *in situ*, using a 0-50 °C precision thermometer. **Salinity** was measured in the field using Refractometer (Atago, Japan). It was then cross-checked by salinity determination through chlorinity estimation by modified Mohr-Knudsen method (Grasshoff and Wensk, 1972; Grasshoff et al., 1999). The standard silver nitrate was used for titrating with halides present in the water samples with potassium chromate as an indicator, and the chlorinity estimated through this method was converted into salinity by using an equation by Knudsen, 1959 and was recorded as parts per thousand (ppt). Nephelo–Turbidity meter - Systronics model no: 132 (APHA, 2005) was used for **Turbidity** measurement and expressed in NTU (Nephelometric Turbidity Unit).**Conductivity** and **Total Dissolved Solids** (TDS) were measured by respective probes using water analyser (Systronics model no. 371; accuracy ± 0.01, (APHA, 2005)).

The chemical parameter such as **pH** was measured in a water analyser having a pH meter with a glass electrode and a calomel electrode as reference (Systronics model no.371; accuracy ± 0.01). Modified Winkler method (Strickland and Parsons, 1972) was used to measure **Dissolved oxygen (DO)**. The potential sources of systematic errors and principles of the determination addressed by Grasshoff et al. (1999) have also noted. In this method, oxidation of manganese dioxide takes place with the help of oxygen dissolved in the samples, causing the formation of a tetravalent compound, which on acidification liberates iodine equivalent to the dissolved oxygen present in the sample. The quantity of iodine liberated was determined by titration with sodium thiosulfate. The results were expressed in the unit, milligrams per litre (mg L^{-1}).

Samples for sediment analysis were collected using a PVC core (4.6 cm Dia and 20 cm length) from five quadrats from each station. The sediment characters such as temperature were measured using a digital thermometer (Metravi DTM-902) with an accuracy of 0.01and was expressed in ^{o}C., pH and Eh was measured using pH meter (Systronics make, model no. 371) and Digital Eh meter (Systronics make, No.318 with platinum and reference electrode, Garrels and Christ, 1965) respectively. Eh was expressed in mV units. Soil moisture content was measured by applying the gravimetric method. The soil sample was dried in hot air oven at 105 °C for at least 4-5 hours to remove water, organic matter and unstable salts and dry weight was measured after reaching a constant weight. The difference in wet weight and dry weight of the sediment sample will give moisture content of the soil sample in the percentage unit (Pansu and Gautheyrou, 2006). Sediment particle size was analysed using Pipette method, which includes several step by step analysis. The first step was the removal of inorganic carbon using 2N HCl and second step involved

organic matter removal by adding 30% hydrogen peroxide. The remaining sample will give the total weight of the sediment. The dried total sediment sample was sieved in 0.63μ standard sieve and then separated sand and silt content (Folk, 1968, 1980). Each sediment particle is expressed in percentage unit.

Total Carbon (TC), Total Organic Carbon (TOC), Total Inorganic carbon (TIC) were analysed by TOC analyser HT 1300 solid module (Analytik Jena make). From the air-dried samples, the inorganic carbon was removed by treating the sediment samples with 2N HCl to get soil organic carbon (SOC) and then the same sample was combusted at a temperature above 900°C in the oxygen flow to gain the SOC content. Total Carbon (TC) was measured using the same instrument by direct analysis without acid treatment, and soil inorganic carbon (SIC) was calculated by subtracting TC with SOC, and all these parameters expressed in g kg^{-1}. Total Nitrogen was analysed by automated Kjeldhal distillation method (Kelplus DISTYL EM). The samples to be analysed were digested at 400°C before distillation. Digestion was carried out with Con. H_2SO_4 in the presence of a catalyst which raises the digestion temperature. During digestion, H_2SO_4 is reduced to SO_2, which in turn reduces nitrogen to NH_3 and this ammonia forming ammonium sulfate combines with excess H_2SO_4. The digest was made alkaline and ammonia liberated was distilled off into the boric acid solution. The quantity of ammonia liberated was determined by titration against standard acid (Jackson 1973, AOAC (Association of Analytical Communities, 2000), and the result was expressed in g Kg^{-1}.

2.3.4 Statistical analysis

Statistical analysis were conducted with Statistical Programme for Social Sciences (SPSS) version 16.0. All tests were considered statistically significant

at P level <0.05. The Shapiro–Wilk W-test was used to test data (Residual errors) for normality. Homogeneity of variance was examined with the Levene's test. Homogeneous and approximately normally distributed data were tested for significant differences with the two or three way analysis of variances (ANOVA). Post hoc analyses were performed with the Tukey's HSD test. Data that failed homogeneity and normality tests were transformed (logarithmic, square root or Arcsin transformation). When the transformed data did not meet the specified criteria, non-parametric statistics were applied. Kruskal–Wallis (K–W) ANOVAs by ranks were performed for testing multiple independent groups.

Multivariate analysis such as Principal Component Analysis (PCA) was done using Primer v.6 (Plymouth Routines in Multivariate Ecological Research, Clarke and Gorley, 2006). RDA (Redundancy Analysis) was done using CANOCO v.4.5. RDA demarcated spatial variations in environmental parameters during the sampling periods and also represented how they influenced the mangrove plant community. Analysis of Similarity (ANOSIM), a permutation-based hypothesis testing was used aiming to detect significant spatial variation in the density and basal area of mangroves by using PRIMER v6 program. Plotting of data was done using Origin v.8, Microsoft Excel v.2007, SPSS v.16, PRIMER v. 6.

2.4 Results

2.4.1 Community structure

Floristic diversity study of mangroves revealed 13 species of true mangroves belonging to six families. Rhizophoraceae family contributed the highest number of species which included *Rhizophora apiculata* Bl., *Rhizophora mucronata* Poir., *Kandelia candel* (L.) Druce., *Bruguiera*

cylindrica (L.) Bl., *Bruguiera gymnorrhiza* (L.) Lamk and *Bruguiera sexangula* (L.) Bl.. Acanthaceae was represented by three species, *Avicennia officinalis* L., *Avicennia marina* (Forssk.) Vierh., *Acanthus ilicifolius* L. and Euphorbiaceae family was represented by only one species *Excoecaria agallocha* L., *Sonneratia caseolaris* (L). Engler and *Sonneratia alba* Griff., belongs to Lythraceae family and *Acrostichum aureum* L. is the only member which belongs to Pteridaceae. Among this *Avicennia marina* (Forssk.)Vierh., *B. sexangula* (L.) Bl. and *Sonneratia alba* Griff. were rare in the study area. Shannon index of the eight major mangrove habitats in Cochin ranged between (H' = 2.9 to H' = 1.3). Shannon index, Simpsons index and richness (d) was high in St.1(Aroor) where 11 true mangrove species were identified. Evenness was high at St.4 (Chellanam site) (Fig.2.4).

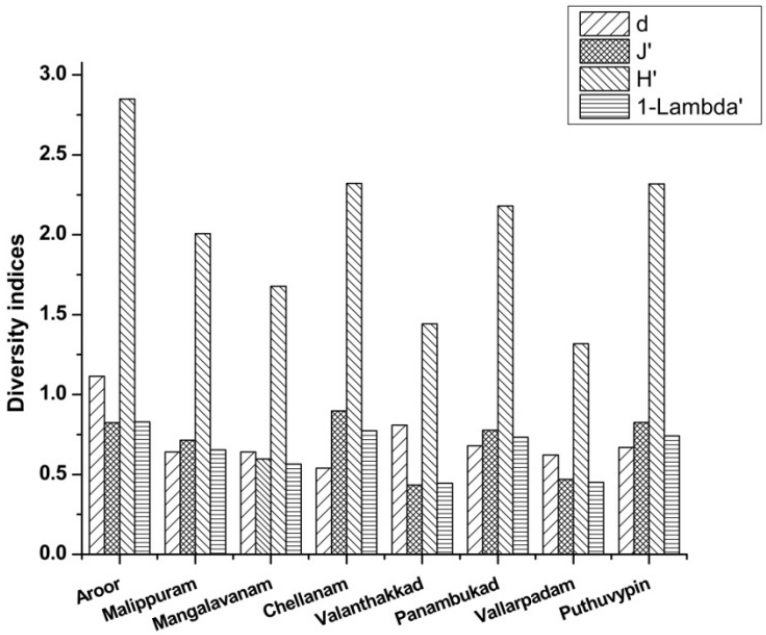


Figure 2.4 Spatial variation in diversity indices of mangrove plants of Cochin during 2013-2014 period

2.4.2 Structural Characters

2.4.2.1 Density

The Cochin mangroves are structurally developed mangrove plants with the highest density for *Acanthus ilicifolius* (9090 ha^{-1}, Fig.2.5). However, the more dense mangrove tree was *E. agallocha* (2440ha^{-1}) followed by *R.mucronata* and *A.officinalis.* Overall, mangrove tree density varied from 11440 trees ha^{-1} in Valanthakad Island to 3840 trees ha^{-1} in Mangalavanam Bird Sanctuary (Fig.2.6). In St.1 *A.officinalis* was the dense mangrove species followed by *Acanthus ilicifolius* and *R. mucronata* and it was the most diverse mangrove habitat in Cochin mangroves with the presence of uncommon species like *B.sexangula* and *R. apiculata*. The frequency of *E. agallocha* species was less in this habitat (20%) compared to other mangrove species. However, St.2 and St.4 were *E.agallocha* dominant stations with density ranging from 400-18400 ha^{-1} in St.2 and 800-13200 ha^{-1} in St.4 with 100% frequency in both stations. In St.2, other dense mangrove species were *B.gymnorrhiza* and *B.cylindrica* that was occupied by only seven species of mangroves. Mangalavanam Bird Sanctuary (St.3) was dominated by *A. ilicifolius*, and the most dense mangrove tree was *A. officinalis.* St.5, Valanthakad Island is the second most diverse (10 species) station among Cochin mangroves, and since it is an open mangrove, waterfront mangroves like *Acanthus ilicifolius* were densely populated in this habitat. However, the most dense mangrove tree was *E.agallocha* followed by fringing mangrove, *R. mucronata,* which was also highly populated in St.6 and 7. The spatial extent of mangroves in Cochin was highest in Puthuvypin, St.8 and rare species of Cochin mangroves like *A. marina* and *S. alba* were also found in this station with *B.cylindrica* as the dense species followed by *A. officinalis*. The variation in mangrove density in different stations of Cochin mangroves was not

statistically significant as the Global R was having low value (R= 0.448, p<.001) while doing ANOSIM. The value of other structural parameters like frequency and abundance are shown in the Appendix.

Figure 2.5 Spatial variation of total mangrove tree density (ha^{-1}) in the Cochin mangroves during 2013-2014 period.

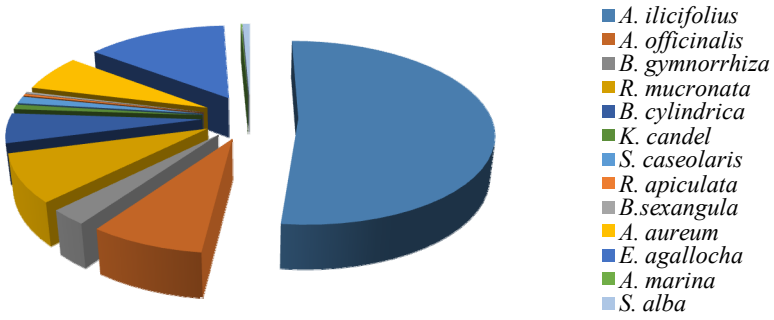


Figure 2.6 Variation in mangrove species density per hectare in the Cochin mangroves during 2013-2014 period

2.4.2.2 Basal area and DBH

The diameter frequency class distribution Vs mangrove density in the eight mangrove habitats of Cochin revealed the maturity of the forest (Figure 2.7 a-h). Since two species, *A. ilicifolius* and *A. aureum* were omitted for DBH frequency class analysis as it is a herb and fern with less than 1 cm in diameter. The data presented in Fig.7a for St. 1, clearly follow an inverse 'j' shaped distribution, characteristic of a balanced uneven-aged forest with the 10 cm DBH class having the maximum density and then declining as the DBH

increases. The mangrove species in different class intervals DBH indicated that 74.3 % of trees occurred in 1–10 cm class followed by 12.16 % of trees in 11–20 cm; 12.16 % of trees in 21–30 cm class and 1.4 % of trees in 31–40 class in St.1. In general, when the forest matures, the density will be less. In St.1, *Sonneratia* and *Avicennia* were having higher DBH and low density. The corresponding average basal area was also high for *S. caseolaris* (39.68± 19.4 m^2 ha^{-1}) and *A. officinalis* (22.42 ±31.5 m^2 ha^{-1}, Table 2. 1).

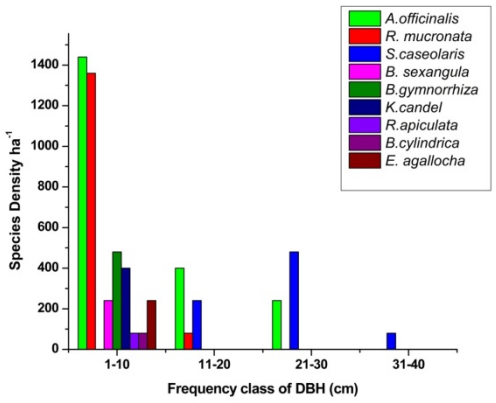
The average basal area was minimum for *B. cylindrica* (0.16 m^2 ha^{-1}). The range of basal area of mangrove trees in St.1 was 0.82 to 78.04 m^2 ha^{-1}. Among the mangrove species of St.2, 81.62 % of trees occurred in 1–10 cm class interval followed by 17.65 % of trees in 11–20 cm; 0.74 % of trees in 21–30 cm class (Fig. 7b). In 31–40 cm class, no species were observed in the plots. This DBH frequency class distribution indicates more number of trees in the young category. The corresponding basal area was high for *E. agallocha* (28.80 m^2 ha^{-1}) and *A. officinalis* (10.35 m^2 ha^{-1}). The basal area of mangrove trees in St.2 ranged from 0.11 m^2 ha^{-1} (*B.gymnorrhiza*) to 55.64 m^2 ha^{-1} (*E. agallocha*). The basal area of mangroves in St.3, Mangalavanam Bird Sanctuary, was very high and reached up to 94.32 m^2 ha^{-1} for *A. officinalis*, which contributes 93.97 % of the total stand basal area. The basal areain St.3 ranged from 0.2 m^2 ha^{-1} (*B.gymnorrhiza*) to 94.32 m^2 ha^{-1} (*A. officinalis*). The species in this station represented 1–10 cm class with 43.75 % (Fig. 7c) and the rest under 11–20 class (31.25 %), 21–30 class (14.58%) and 31–40 class (6.25 %). An additional DBH class was also observed in this station, 41–50 cm class (4.17 %), indicates the maturity of mangroves in the Mangalavanam area. Only two DBH frequency class (1-10, 11-20 cm) were present in St.4. The range of basal area in St.4 was 0.20 m^2 ha^{-1} to 59.34 m^2 ha^{-1} . In St.5, one more DBH frequency class (21-30) was present, and *R. mucronata* was the structurally developed

tree in this station. The basal area of mangrove trees in St.5 ranged from 0.40 m^2 ha^{-1} to 71.75 m^2 ha^{-1}. The density of species was distributed up to 21-30 cm DBH class with *R. mucronata,* and *A. officinalis* were the most structurally developed species in St.6 and 7. The basal area in St. 6 and 7 ranged from 1.20-83.50 m^2 ha^{-1} and 1.2 - 88.65 m^2 ha^{-1} respectively. Puthuvypin, St.8 was the other matured forest among Cochin mangroves. Even though more density is in 1-10 cm DBH class, also had representatives of 31-40 cm DBH class in this site. *S. alba* was the most structurally developed tree. The basal area of mangrove trees in St.8 ranged from 0.2 – 74.2 m^2 ha^{-1}. Basal area of mangrove species varied significantly among the stations in Cochin mangroves (Global R=0.642, p<0.001).

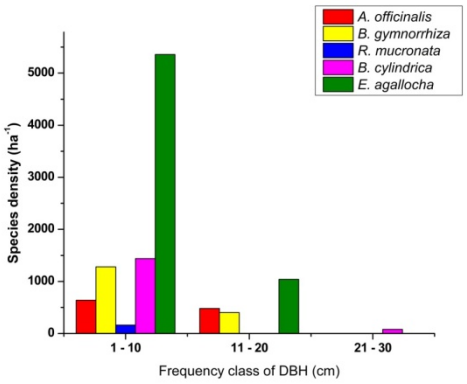
Table 2.1 Basal area (m^2ha^{-1}) of each mangrove tree from Cochin mangroves during 2013-2014 period

Species	St.1	St.2	St.3	St.4	St.5	St.6	St.7	St.8
A.officinalis	22.42 ± 31.5	10.35 ±11.1	94.32 ±41.7	4.01 ±3.8	7.67 ±10.5	17.47 ±15.1	7.30 ±11.4	39.40 ±30.6
B. gymnorrhiza	1.03 ±2.2	6.68 ±12.9	0.30 ±0.6	-	2.33 ±4.9	1.57 ±2.2	-	8.90 ±4.0
R. mucronata	4.10 ±4.4	0.52 ±1.2	5.01 ±9.8	7.50 ±11.3	22.57 ±31.5	31.0 ±31.5	41.12 ±28.8	6.80 ±7.9
B. cylindrica	0.16 ±0.4	5.46 ±11.9	0.42 ±0.9	5.74 ±7.2	-	-	2.63 ±5.9	20.10 ±10.2
K. candel	0.92 ±2.0	-	-	-	1.74 ±1.7	-	-	-
S.caseolaris	39.68 ±19.4	-	-	-	5.03 ±5.7	0.25 ±0.6	0.31 ±0.7	-
R. apiculata	0.31 ±0.7	-	-	-	0.13 ±0.3	-	0.71 ±1.6	-
B. sexangula	0.27 ±0.4	-	0.33 ±0.5	0.00	0.69 ±1.6	-	-	-
E.agallocha	0.82 ±1.8	28.80± 24.2	-	22.03 ±23.9	20.11 ±20.3	6.20 ±7.9	0.24 ±0.5	0.20 ±0.4
A.marina	-	-	-	-	-	-	-	0.10 ±0.1
S. alba	-	-	-	-	-	-	-	25.90 ±37.4

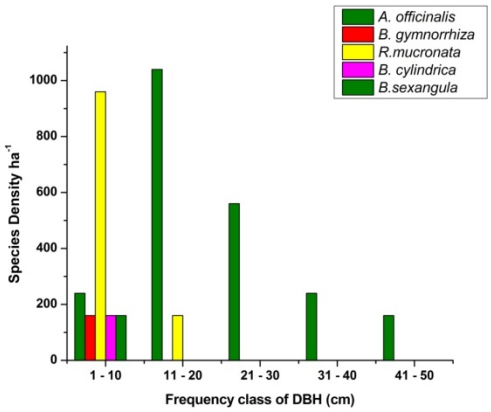
- Absent



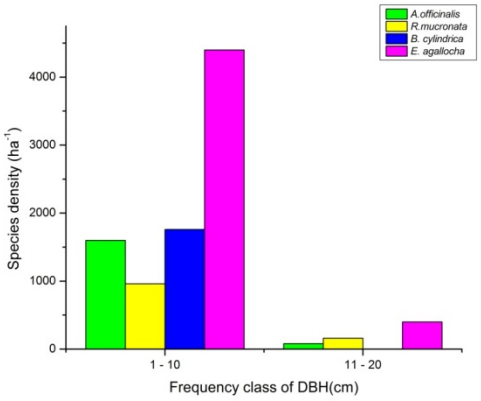
a)St.1



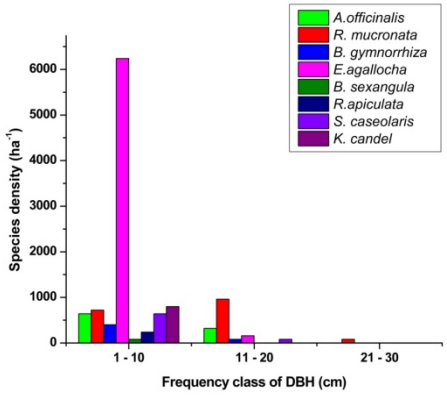
b)St.2



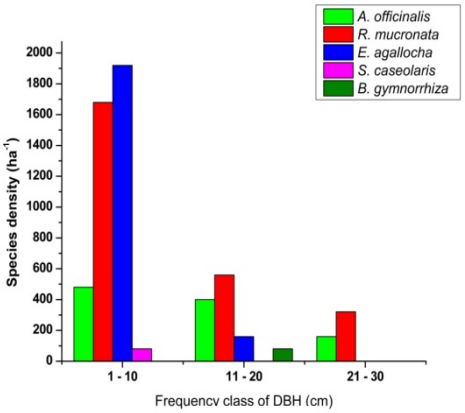
c)St.3



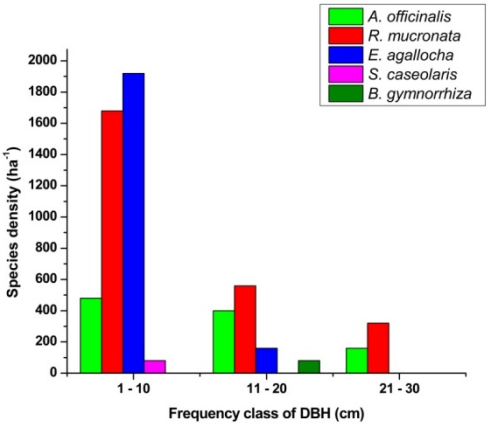
d)St.4



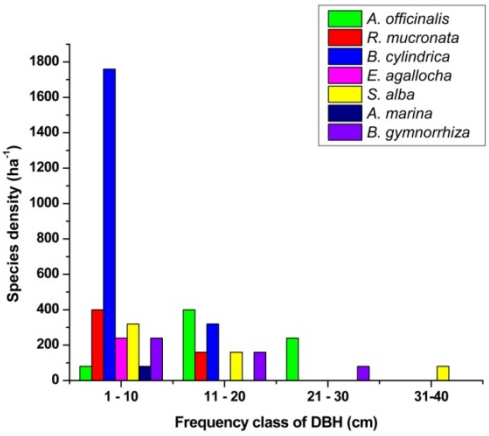
e)St.5



f) St.6



g)St.7



h)St.8

Figure 2.7 (a-h) Density (ha^{-1}) of Mangrove trees in different DBH frequency classes in Cochin mangroves during 2013-2014 period

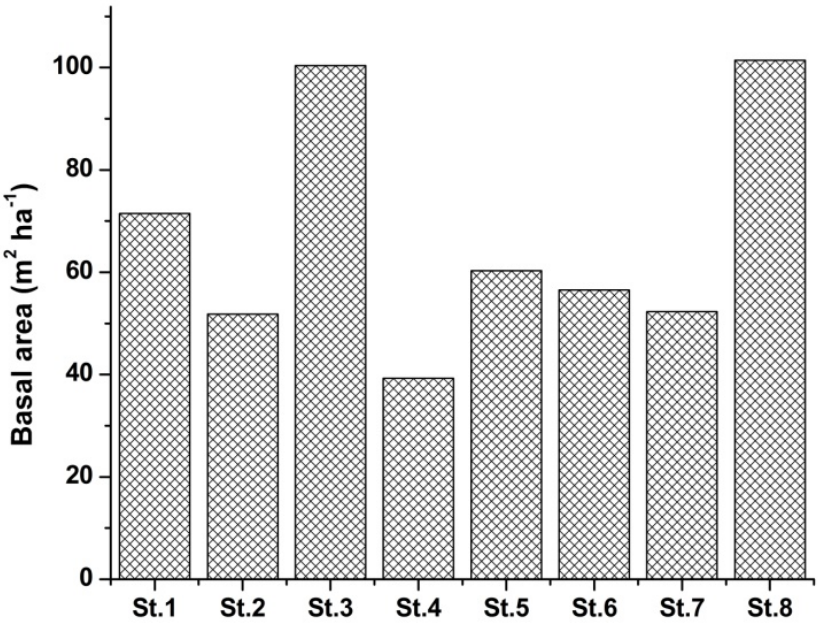


Figure 2.8 Total stand basal area of true mangrove trees in Cochin mangroves during 2013-2014 peiod

Total stand basal area of mangrove trees was exceptionally high in Puthuvypin, St.8 (101.4 m^2 ha^{-1}) and Mangalavanam region, St.3 (100.38 m^2

ha^{-1}) (Fi.g.2.8). The total stand basal area of mangrove trees in other stations were 71.47 m^2 ha^{-1}(St.1); 51.80 m^2 ha^{-1}(St.2); 39.27 m^2 ha^{-1}(St.4); 60.28 m^2 ha^{-1}(St.5); 56.5 m^2 ha^{-1}(St.6) and 52.31 m^2 ha^{-1}(St.7). The average stand basal area of Cochin mangrove tree was 66.97 ± 23.04 m^2 ha^{-1}. The basal area ranges from 0.1- 94.32 m^2 ha^{-1}. *A. officinalis* species was having the highest basal area, followed by *R.mucronata* and *S. caseolaris*. The mangrove species showing high Importance value index in each habitat was also studied for understanding its habitat preferences. The area that has highest structural development for each species could be selected for its restoration programmes.

2.4.2.3 Importance Value Index (IVI)

It could be seen that for St.1, *Avicennia officinalis* was having higher values in the structural parameters and was the dominant species with IVI of 95.5 within the area followed by *S. caseolaris* (91.2). Even though the latter species was less in number, it possessed higher relative frequency and high relative basal area. Both these species are present in five plots having 100 % frequency. The stem density was higher for *A.officinalis* (2080 stems ha^{-1}) followed by *A. ilicifolius* (Table 2.2). Even though the stem density of *A. ilicifolius* was higher than other mangrove species, the overall structural characteristics had lower values, especially basal area, since it is a herbaceous plant. In St.2, *E. agallocha* was abundant, and it was the dominant species with IVI of 121.7 compared to other seven species present in the area followed by *B.gymnorrhiza.* While in St.3, the important species was *A. officinalis* (IVI = 154.89) as in St.1. However the Importance value index for the species *Avicennia officinalis* was higher in St.3 than St.1 because of high relative basal area of this species in St.3 which clearly indicates its habitat preference. However, the dense species was *A. ilicifolius* (7200 stems ha^{-1}).

In St.4, Chellanam, the important mangrove species was *E. agallocha* followed by *B.cylindrica*. On the other hand, *E. agallocha*, followed by *A. aureum,* were the important species of St.5. In St.6 and St.7, *R.mucronata* was having high IVI value (121.89, 151.37 respectively). Both, density and relative basal area were high for R. mucronata in St.7 and St.8. Station 8 was having high IVI for *B.cylindrica* followed by *A. officinalis*. Puthuvypin area could be visibly stated as an *A. officinalis* dominated habitat. However, the structural characters showed that high density of *B. cylindrica* makes it as important species in that area compared to low dense *A. officinalis* having higher basal area.

Table 2.2 Importance Value index of different mangrove species in the Cochin mangroves during 2013-2014 period

Species	St.1	St.2	St.3	St.4	St.5	St.6	St.7	St.8
A. ilicifolius	25.50	9.43	**60.52**	15.24	42.69	11.28	48.01	0.00
A. officinalis	**94.47**	47.70	**152.84**	50.05	20.16	**68.13**	**63.89**	**73.30**
B. gymnorrhiza	16.39	**52.85**	16.27	0.00	11.30	16.85	0.00	38.52
R.mucronata	40.15	6.92	31.26	50.67	46.49	**121.89**	**151.37**	30.29
B.cylindrica	5.89	40.65	6.76	**58.24**	0.00	0.00	11.53	**83.19**
K.candel	14.98	0.00	0.00	0.00	16.96	0.00	0.00	0.00
S. caseolaris	**89.76**	0.00	0.00	0.00	22.69	0.00	8.80	0.00
R.apiculata	6.08	0.00	0.00	0.00	4.28	0.00	7.82	0.00
B.sexangula	13.18	0.00	13.26	0.00	4.72	0.00	0.00	0.00
A. aureum	8.84	20.78	19.46	9.15	**57.04**	11.14	0.00	0.00
E.agallocha	8.58	**121.67**	0.00	**116.08**	**69.96**	63.05	8.58	10.76
A. marina	0.00	0.00	0.00	0.00	0.00	0.00	0.00	8.00
S. alba	0.00	0.00	0.00	0.00	0.00	7.67	0.00	55.96

2.4.3 Forest structure and community analysis of selected mangrove habitats

2.4.3.1 Forest Structure

The comparison of structural characters mainly density and basal area of mangrove species in three major mangrove habitats of Cochin are depicted in Table 2.3. It could be seen that while considering only these three sites, the mangrove density and basal area varied significantly with the station (Global R=0.54 for density and Global R=0.77 for basal area, P <0.001). Mangrove tree height varied significantly with station ($\chi^2(2)=6.276$, p =0.04, N=135) and species ($\chi^2(2)=39.14$, p =0.000, N=135).

Table 2.3 Summary of structural parameters in selected three stations of Cochin mangroves during 2013-2014 period

Name of the species	Density ha^{-1}			Basal area (m^2 ha^{-1})		
	St.1	St.2	St.3	St.1	St.2	St.3
Acanthus ilicifolius	1680	400	7200	0.73	0.25	1.85
Avicennia officinalis	1840	1120	2240	22.42	10.35	94.32
Bruguiera gymnorrhiza	480	1680	160	1.03	6.68	0.30
Rhizophora mucronata	1440	80	1120	4.10	0.52	5.01
Bruguiera cylindrica	80	1520	160	0.16	5.46	0.42
Kandelia candel	400	0	0	0.92	0	0.00
Sonneratia caseolaris	1120	0	0	39.68	0	0.00
Rhizophora apiculata	80	0	0	0.27	0	0.00
Bruguiera sexangula	240	0	160	0.31	0	0.33
Acrostichum aureum	240	560	560	1.02	2.79	1.35
Excoecaria agallocha	240	6400	0	0.82	28.8	0.00
Total	**7840**	**11760**	**11600**	**71.47**	**54.85**	**103.58**

The mangrove tree height in St.1 ranged from 2.4 to 15.6m. *S. caseolaris* was the tallest tree with an average height of 13.22 ±2.45m. The smallest tree was *B. gymnorrhiza*, with an average height of 2.85 ± 0.63 m.In St.2, the mangrove trees were short compared to St.1 and ranged from 2.34 to 7.7m with *R. mucronata* representing the tallest tree. St.3, Mangalavanam had mangrove trees with a height ranging from 1.4 to 12.13 m and among the mangrove trees, *A. officinalis* was the tallest with an average height of 9.43 ± 2.13 m (Fig. 2.9 a-c).

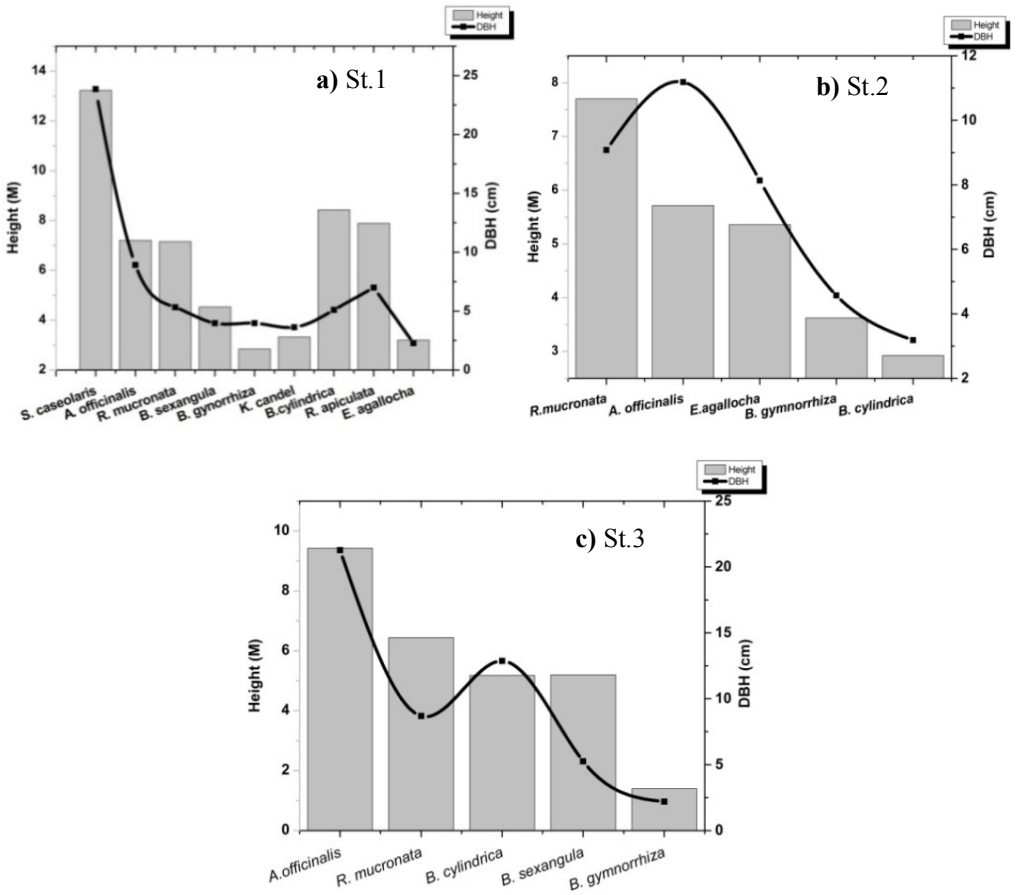


Figure 2.9 a-c. Tree height Vs DBH of mangrove trees in Cochin mangroves during 2013-2014 period

2.4.3.2 Environmental Characters

i. Physico chemical parameters

The mean rainfall in the catchment area of Cochin estuary and surrounding area was 277.37 ± 32.87 mm during the entire study period (2013-2015) (Figure 2.10). The first year, 2013 was having the highest total annual precipitation (3658.37 mm), and there was a gradual decline in rainfall pattern during the second (3435.5mm) and third year (2891.5 mm). The rainfall significantly varied with the season (One Way ANOVA $F_{2,33}$=19.50, p=0.000). The total rainfall during monsoon season was 2774.3 mm during the first year, 2376.1 mm in the second year and the third year it was 1576.1mm. As usual premonsoon received less rainfall compared to other seasons.

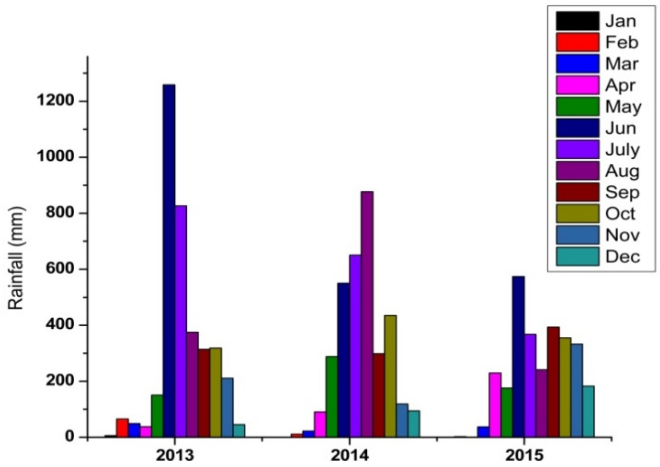


Figure 2.10 Monthly rainfall pattern in Cochin during 2013-2015 period

The water temperature did not show any significant variation among the three stations and also between the years and the average temperature was 28.98 ± 0.40 ^{o}C. However, the temperature showed significant seasonality (ANOVA $F_{2,77}$ =14.53, p=0.000). The highest water temperature recorded was 36.5 ^{o}C during pre-monsoon (PRE) period in St.1, and the lowest temperature

was 24 ^{o}C in St.2 during post-monsoon (POM) period. The mean water temperature was high during premonsoon (30.20 ± 0.08 ^{o}C), followed by monsoon (MON) season (29.13 ± 0.80 ^{o}C) and postmonsoon season (27.29 ±0.59 ^{o}C) [Fig.2.11].

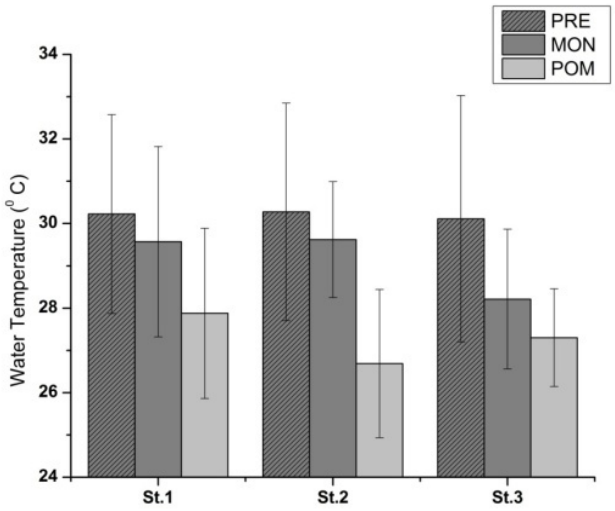


Figure 2.11 Mean seasonal variation of water temperature in Cochin mangroves during 2013-15 period

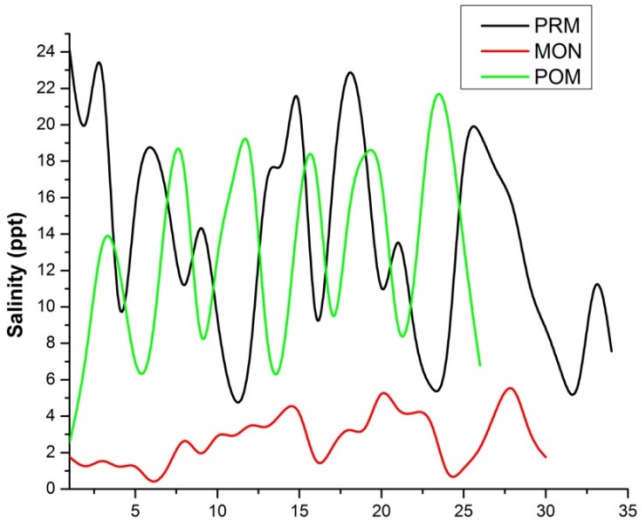


Figure 2.12 Seasonal variation in salinity in Cochin mangroves during 2013-2015 period

Salinity, which is an important driving environmental factor in coastal environments showed significant variation with the season (ANOVA $F_{2, 77}$ = 44.3, p =0.000) during the study period. It was high during premonsoon season followed by postmonsoon season and low values during monsoon season. There was no significant variation for this physical parameter between stations and years. The mean salinity for the three mangrove stations in Cochin estuary was 9.89 ± 7.75 ppt and therefore prevails (mixo-) mesohaline condition. The seasonal average of salinity during the pre-monsoon season was 13.9±7.6 PSU and during post-monsoon it was 13.07 ± 6.9 ppt. The monsoon season exhibits (mixo-) oligohaline condition with an average salinity of 2.75 ± 1.75 ppt (Fig.2.12). The maximum salinity in St.1 was 29.4 ppt while in St.2, the maximum salinity recorded was 26.86 ppt and minimum was 0.5 ppt. The salinity range in St.3 was 0-22.5 ppt. Other physical parameters which are closely related to one another is Total Dissolved Solids (TDS) and conductivity. There was no significant variation for TDS and conductivity between stations.

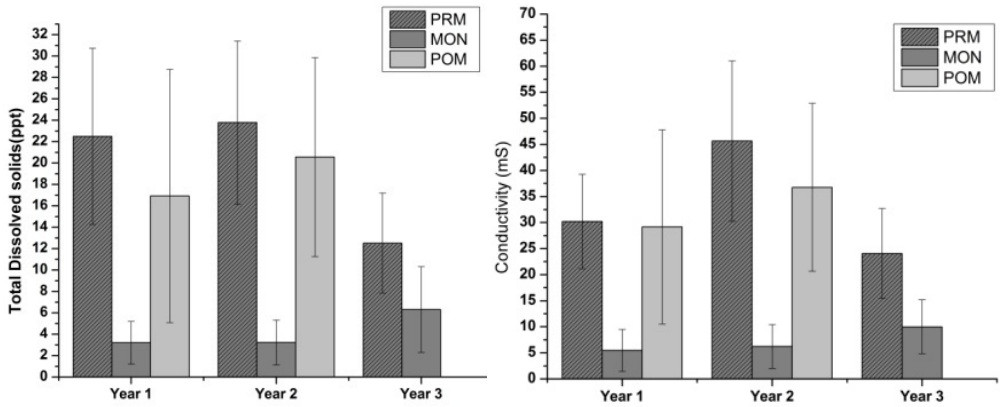


Figure 2.13 Seasonal variation of TDS and conductivity in Cochin mangroves during 2013-2015 period

However both varied significantly with year (ANOVA $F_{2, 77}$ = 3.78, p =0.027 for TDS and $F_{2, 77}$ =5.28, p =0.007 for conductivity) and season ($F_{2, 77}$ = 36.07, p=0.000 for TDS and $F_{2, 77}$ =41.99, p =0.000 for conductivity). Both parameters were high during the PREM period followed by POM and MON (Fig.2.13). TDS ranged from 0.50 to 35.6 ppt, and conductivity ranged from 1.004 to 64.18 mS.

The water pH in the mangrove habitats during the study period ranged from 6.48 (St.1) to 8.5 (St.2). St.2 was slightly alkaline during the study period. There was no significant seasonal variation observed for pH, however there was a marked difference in pH with year (ANOVA $F_{2,77}$ = 3.66, p = 0.030) and station(ANOVA $F_{2,77}$ = 4.14, p = 0.020).During the first year, the mean pH in St.1 was acidic (6.88±0.35), when compared to the other two stations (St.2= 7.15± 0.44, St.3 =7.12 ±0.15). In the second year St.2 and St.3 showed a mean alkaline condition (St.2 = 7.54 ± 0.57, St.3 = 7.54 ± 0.61) when compared to St.1 (7.21 ±0.45). During the third year, only St.3 was alkaline (7.66 ± 0.39) [Fig.2.14].

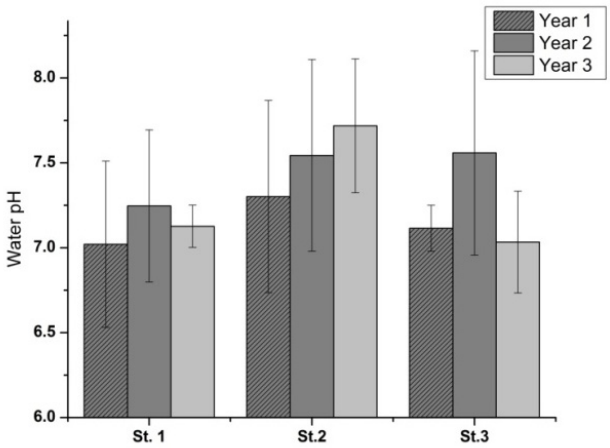


Figure 2.14 Spatio-temporal variation of water pH in Cochin mangroves during 2013-2015 period

The redox potential (Eh) which helps in understanding the oxidizing or reducing nature of the water inside the mangrove habitats was slightly reducing in nature, and it ranged from -130.2 to 127.1 mV in the study area. The dissolved oxygen (DO) is an important environmental variable controlling the life of organisms and also pedals the biogeochemistry in mangrove habitats. It varied significantly with the station (ANOVA $F_{2,77} = 4.52$, $p = 0.014$) and the mean DO in St.1 was 3.4 ± 2.7; St.2 = 4.8 ± 3.9; St.3 = 2.02 ± 1.88 mg L^{-1}. DO ranged from 0 (recorded during PRM) to 11.7 mg L^{-1}(recorded during MON) in St.1; 0.19 (PRM) to 11.8 mg L^{-1}(MON) in St.2 and 0 (recorded in all seasons) to 7.08 mgL^{-1} (POM) in St.3. There was no significant variation of DO with year while displayed clear seasonality (ANOVA $F_{2,77} = 5.77$, $p = 0.005$) (Fig.2.15). Monsoon season was marked high DO and reached a maximum of 12.6 mg L^{-1} in St.2. However, anoxic condition prevailed during post-monsoon and pre-monsoon periods.

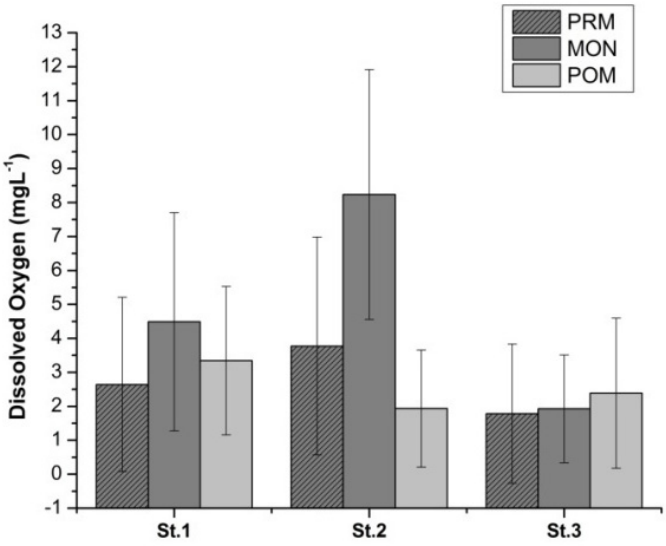


Figure 2.15 Mean seasonal variation of dissolved oxygen in intertidal water from Cochin mangroves during 2013-2015 period

ii. Sediment character

The mean sediment temperature of the three mangrove habitats in Cochin during the study period was 28.51 ± 0.33 ^{o}C. The difference in temperature between stations was not statistically significant. It showed marked variation according to season (ANOVA $F_{2,77} = 26.24$, $p = 0.000$) and year (ANOVA $F_{2,77} = 4.73$, $p = 0.012$). The peak temperature was recorded during, and the mean temperature during this season was 29.98 ±1.46 ^{o}C. The mean temperature during monsoon season was 28.46 ±0.48 ^{o}C. The minimum sediment temperature was recorded in postmonsoon season and mean value was 26.83 ± 1.24^{o}C. The sediment pH is a distinct character that made each station as significantly different (Kruskal - Wallis test, χ^2 (2) =11.07, p = 0.004). It also showed year wise significant variations (Kruskal- Wallis test, $\chi^2(2) = 13.6$, p = 0.001). In the first year, the mean pH was slightly acidic in St.1 (6.55 ± 0.48) and St.3 (6.61 ± 0.32) compared to St.2 (7.14 ± 0.30). During the second year, St.2 was slightly alkaline (7.50 ± 0.69), and in the third year, St.3 was slightly acidic (6.77 ± 0.15)[Fig.2.16].

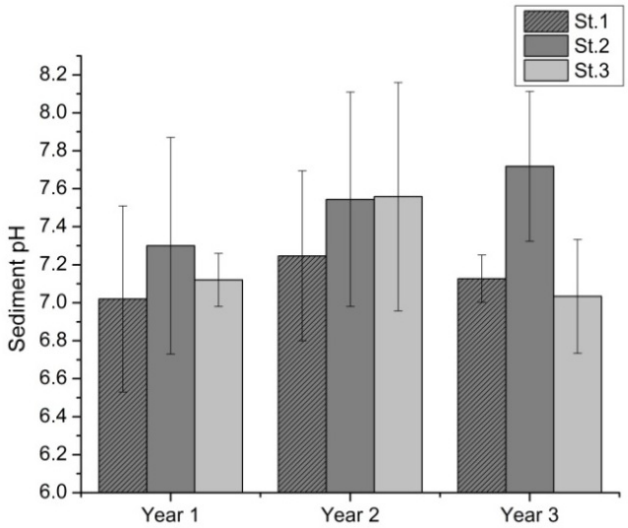


Figure 2.16 Mean spatiotemporal variation of sediment pH from Cochin mangroves during 2013-2015 period

The redox potential of mangrove sediment in the study area was highly reducing in nature, and it varied significantly with stations (ANOVA $F_{2,77}$ = 5.44, p = 0.006) and years (ANOVA $F_{2,77}$ = 7.01, p = 0.002). St.2 was comparatively more reduced than St.1 and St.3.The Eh of the sediment in the study area ranged from -427.4 to -23.3 mV(Fig. 2.17). In the first year (2013), St.1 had a mean Eh of -100.76 ± 51.87 mV; St.2 was having an average Eh of -207 ± 97.55 mV, and in St.3 it was -150.48 ± 49.25 mV. In the second year (2014) the mean Eh in St.1 was -291.40 ± 82.79 mV; St.2 = -253.2 ± 87.80 mV; St.3 = -163.75 ± 104.86 mV. St.1 was highly reduced (-238 ± 82.1 mV) during the third year of the study period. Moisture content was above 50% in mangrove sediments of all stations. It varied significantly with stations (ANOVA $F_{2,77}$ = 62.57, p =0.000) and years (ANOVA $F_{2,77}$ = 6.25, p =0.003). The mean moisture content was very less in St.2 in three years of the study (56.57 ± 6.27 %, 59.07 ± 5.22 %, 61.47 ± 5.52 %) compared to the other two stations. The mean moisture content was gradually increased in St.1 during the study period (69.94 ± 1.93, 70.82 ± 2.63, 75.45 ± 2.32) [Fig.2.18].

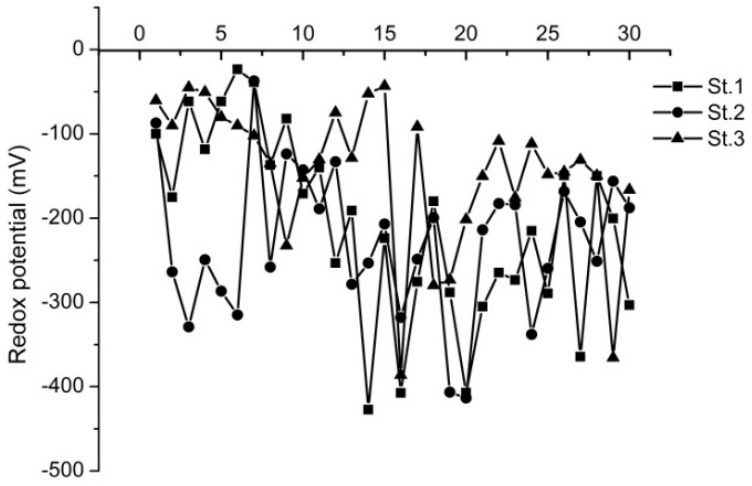


Figure 2.17 Redox potential gradient of sediment from the Cochin mangroves during 2013-2015 period

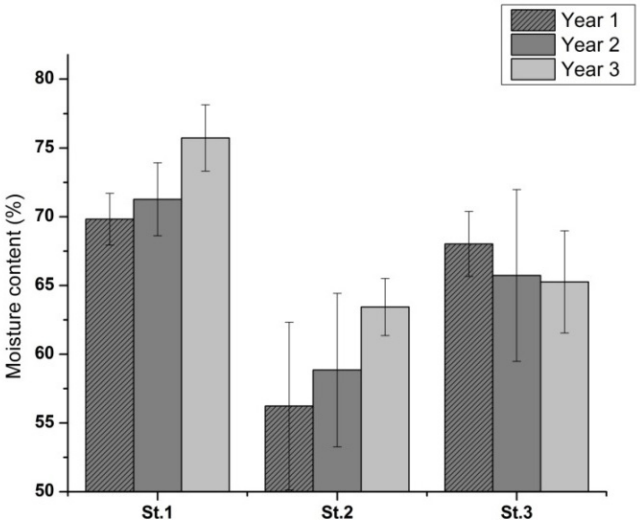


Figure 2.18 Mean moisture content of sediment from Cochin mangroves during 2013-2015 period

Sediment texture in the mangrove habitats is an important character as it determines the organic carbon binding or carbon storage in the sediment. There was a significant variation in sediment texture of three major mangrove habitats (N =118) in the Cochin estuary. The sediment of St.1 was dominated with silt content (60.01 ± 9.09 %) followed by clay (36.26 ± 7.96 %), and only a small portion was made up with sand (3.62 ± 6.66 %). However, the sediment of St.2 was different, and major particle in the sediment was sand (72.56 ±19.95%) followed by silt (16.34 ±14.82 %) and clay (11.10 ± 5.76 %). St.3, Mangalavanam was also sand dominated mangrove habitat with a mean composition of 73.81 ± 14.15 % followed by 15.47 ± 11.17 % silt and 10.72 ± 5.95 % clay (Fig.2.19). Thus each fragment in the sediment like sand ($\chi^2(2)$ = 77.63, p = 0.000), clay (ANOVA $F_{2,97}$ = 203.92, p = 0.000)and silt ($\chi^2(2)$ =75.54, p = 0.000) differed significantly with stations. There was no significant seasonal variation and yearly variation in each fragment of the sediment.

The other major sediment characters like carbon and nitrogen concentration and C/N ratio are described in detail in Chapter 7.4. However, it was included in an abiotic relationship with mangrove density and its community analysis.

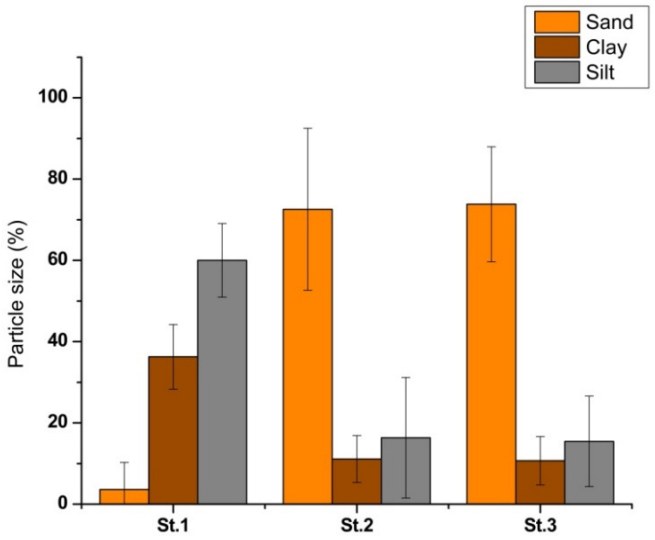


Figure 2.19 Spatial variation in sediment texture in Cochin mangroves during 2013-2015period

2.4.3.3 Principal Component Analysisand Redundancy Analysis

The principal component analysis and Redundancy analysis (RDA) will help to understand the community structure of mangroves. The results of environmental characters for three years were analysed using PCA. The PCA corroborates the spatial variation of environmental parameters of water and sediment (Table 2.4). The first five principal components accounted for 97.1 % of the variability in environmental conditions among three stations (Fig.2.20). Among this, the first two principal components accounted for 63% of the variability in environmental conditions, with 36.9 % on axis 1 (eigenvalue 5.91) and that for axis 2 was 26.1% (eigenvalue 4.18).

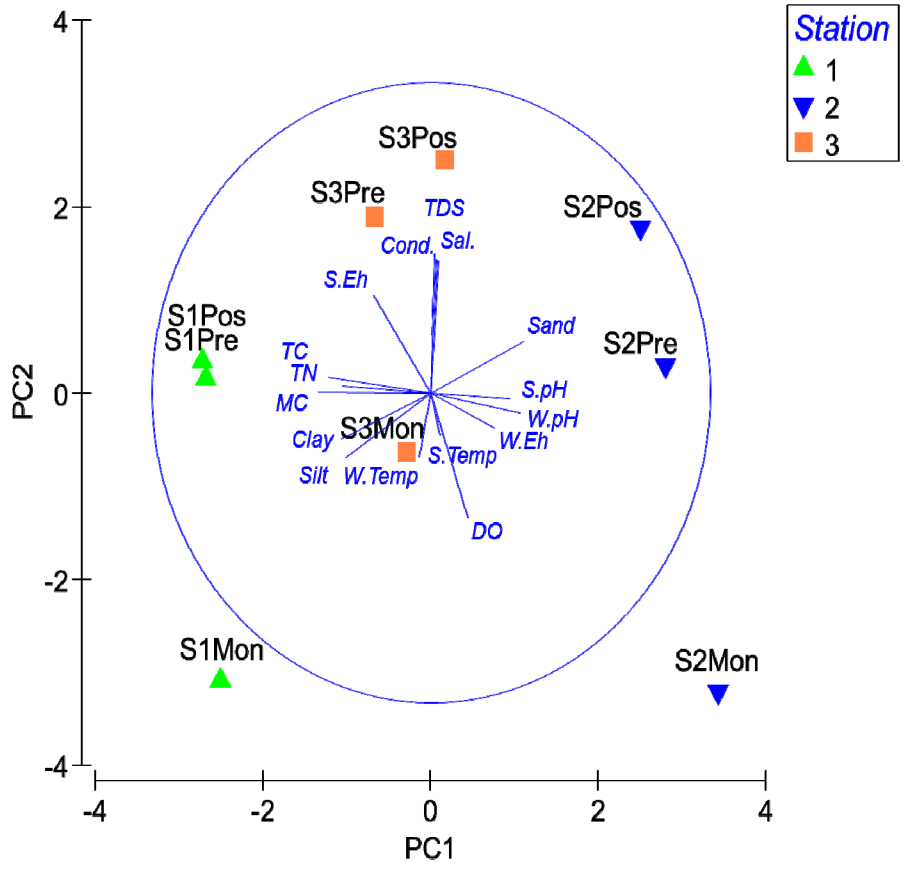


Figure 2.20 Principal component analysis of environmental factors in Cochin mangroves during 2013-2015 period

*(Mon: Monsoon, Pos: post-monsoon, Pre: pre-monsoon, W.Temp: water temperature, Sal: water salinity, TDS: total dissolved solids, Cond. Conductivity, W.pH: water pH, W. Eh: water Eh, DO: water dissolved oxygen, S.Temp. sediment temperature, S.pH: sediment pH, S.Eh: sediment redox potential (Eh), Sand: sand, Silt: silt, Clay: clay)

Moisture content, Particle size (sand, silt, clay content), total carbon, total nitrogen and water pH were the most important characters which contributed to the variation among stations along the first axis, whereas conductivity, TDS, salinity, dissolved oxygen and sediment Eh were influential along axis 2.

Table 2.4 Two-dimensional principal component analysis (PCA) of environmental characters in Cochin mangroves during 2013-2015 period

PCA axis	1	2	3	4	5
Eigenvalues	5.91	4.18	2.49	1.82	1.15
%Variation	36.9	26.1	15.5	11.4	7.2
Cum. %Variation	36.9	63	78.6	90	97.1
Eigenvectors					
W.Temp	-0.04	-0.205	0.542	0.205	0.061
W.pH	0.318	-0.063	-0.201	-0.155	0.456
TDS	0.020	0.430	0.217	-0.237	0.049
Cond.	0.011	0.449	0.211	-0.149	0.017
Sal.	0.026	0.426	0.229	-0.227	0.002
DO	0.132	-0.401	0.065	-0.194	0.246
S.Temp	0.033	-0.135	0.560	0.231	0.019
S.pH	0.283	-0.018	-0.264	-0.308	-0.209
S.Eh	-0.205	0.315	-0.201	0.284	-0.233
MC	-0.404	0.002	-0.049	-0.023	0.058
Sand	0.332	0.165	-0.054	0.324	0.168
Clay	-0.323	-0.147	0.145	-0.342	-0.136
Silt	-0.305	-0.207	-0.053	-0.331	-0.234
TC	-0.367	0.050	-0.148	0.222	0.197
TN	-0.316	0.023	-0.204	0.258	0.319

RDA demarcated spatial variations in environmental parameters during the sampling periods and also represented how they influenced the mangrove plant community (Fig.2.21). The first axis in RDA explains 82.4% variability and two axes together with 100% variability among environmental characters and mangrove species distribution.

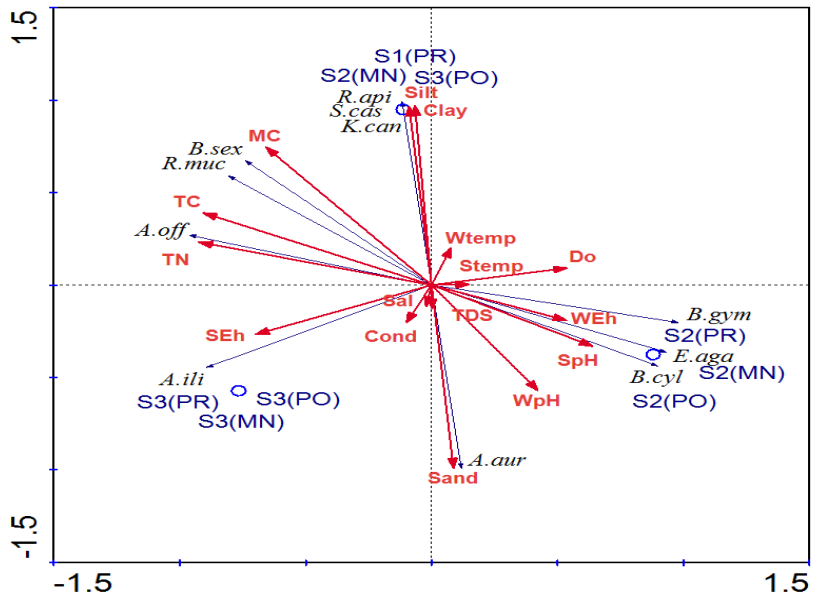


Figure 2.21 Redundancy Analysis (RDA) showing scatter plot for mangrove plans and abiotic characters.

Rhizophora apiculata (*R.api*), *Rhizophora mucronata*(*R.muc*), *Kandelia candel* (*K.can*), *Bruguiera cylindrical* (*B.cyl*), *Bruguiera gymnorrhiza* (*B.gym*), *Bruguiera sexangula* (*B.sex*), *Avicennia officinalis* (*A.off*), *Acanthus ilicifolius* (*A.ili*), *Excoecaria agallocha* (*E.aga*),*Sonneratia caseolaris* (*S.cas*), *Acrostichumaureum* (*A.aur*), (MN- monsoon, PO: post-monsoon, PR: pre-monsoon, WTemp: water temperature, Sal: water salinity, TDS: total dissolved solids, Cond. Conductivity, WpH: water pH, W Eh: water Eh, DO: water dissolved oxygen, Stemp. sediment temperature, SpH: sediment pH, SEh: sediment redox potential (Eh), Sand: sand, Silt: silt, Clay: clay) [**blue:** stations, **red:** environmental parameters, black: mangrove species]

2.5 Discussion

2.5.1 Community structure and Phytosociology

The floristic composition of Cochin mangroves comprised of 13 true mangroves and similar observations were reported by other studies like Vidyasagaran and Madhusoodanan, 2014. However, they reported 11 true mangroves excluding *A. ilicifolius* and *A. aureum* as they considered it as

mangrove associates. Previous studies reported the occurrence of *E. indica* (Suma, 2005) along the Cochin estuary while the present study and other recent studies (Vidyasagaran and Madhusoodanan, 2014; George et al., 2018) did not report the occurrence of this species along the Cochin coast. Therefore it could be considered that this species may be rare or has becomeextinct to Cochin mangroves. *A. marina* and *Sonneratia alba* were observed only at one station, Puthuvypin. Among this the density of *A.marina* was very low (133.3 ha^{-1}, basal area = 0.1±0.09 m^2 ha^{-1}) and could be considered as a very rare species to Cochin mangroves. It was present during the 1990s and mentioned as a sapling with girth size less than 15 cm according to Nameer et al.,1992 in Puthuvypin area. Rane et al. (2006) also mentioned about its structural development and reported a high density range of 625.8 to 2014.1 ha^{-1} with a large basal area of 0.89-45.64 m^2 ha^{-1} in the same area. However, it is now evident that this species was the primary victim of forest clearance for LN G (Liquified Natural Gas) Terminal and other construction activities. On the other hand, there was an increase in mangrove species diversity in Mangalavanam Bird sanctuary compared to previous reports (Suma, 2005; Azzes and Bhupathy,2006).

The mangrove density of Cochin mangroves was compared with global mangroves and Indian mangroves (Table 2.5). Some studies included *A.ilicifolius*, *A.aureum* in their density data, while many others included only mangrove trees. Cochin mangroves could be considered as comparatively dense mangrove habitats even though the extent of mangrove habitat is minimal. The density of Cochin mangroves was comparable with Panama (Central America) mangroves (Lovelock et al., 2005), Bhitarkanika mangroves, Odisha, India (Upadhyay and Mishra, 2014) and Coringa mangroves, Andhra Pradesh, India (Satyanarayan et al., 2009). Basal area was also higher for Cochin mangroves, which indicated its structural development. It is also

comparable with Malaysian mangroves (Shah et al., 2015), Coringa mangroves (Satyanarayana et al., 2009) and Kakinada bay mangroves (Satyanarayana et al., 2002) in Andhra Pradesh. In the instance of Kerala mangroves, only a few studies were reported, and it could be seen that density was comparable with the study from Kerala mangroves (Sreelekshmi et al., 2018), however the basal area was higher for Cochin mangroves. The high basal area was due to the presence of structurally developed *A.officinalis* species especially in three stations, St.1, St.3 and St.8. In St.8, Puthuvypin, the mangrove density reported was 11-1233 ha^{-1} and basal area of 0.03-8.1 m^2 ha^{-1} during 1992 (Nameer et al.,1992). Later Sureshkumar and Mohankumar,1997 reported 3068 ha^{-1} density of mangroves with 10.9 m^2 ha^{-1} basal area and Rane et al. 2006, reported an increase in structural development with a mean density of 5846.7 ha^{-1} with total stand basal area of 48.48 m^2 ha^{-1} in which *A.officinalis* was having a basal area of 54.56 m^2 ha^{-1}. Gradual structural development was evident in this station and reached a current total density of 7866.65 ha^{-1} and total stand basal area of 101.4 m^2 ha^{-1} with *A. officinalis* having 39.4 m^2 ha^{-1}. There was a decrease in the basal area of *A. officinalis* species. As stated before, large scale destruction of mangroves in this area was the reason for the decline in value of the total stand basal area. Therefore immediate actions should be taken for the protection of these habitats.

The DBH frequency distribution of mangrove species in different stations of Cochin estuary revealed that except St.8, St.3 and St. 1; all other sites are in young stage with low DBH class according to Pellegrini et al., 2009. It also revealed the presence of uneven-aged mixed mangrove forest. This structural data could be used for conservation strategies of mangroves with scientific management practices. The area having most structural development for each species can be selected for its restoration programmes.

Table 2.5 Comparison of density and basal area of mangroves from different mangrove habitats

Mangrove forest	Country/Region	Density (trees ha^{-1})	Basal area (m^2 ha^{-1})	References
International				
Samar Island	Philippines	1500-3000	65.0-22.78	Mendoza and Alura,2001
Bocas del Toro Archipelago	Panama	4730-33,570	6.8-30.1	Lovelock et al.,2005
SegaraAnakan lagoon	Indonesia	10-2880	0.02-10.28	Hinrichs et al.,2009
Kelantan Delta	Peninsular Malaysia	790-1360	1.4-49	Satyanarayana et al., 2010
Ceara state	Brazil		0.47-2.9	Maia andCoutinho,2012
Kala Oya estuary	Sri Lanka	10-528	27.10-48.25	Perera et al.,2013
Sibuti mangrove forest	Malaysia	1600-2340	171.10-201.83	Shah et al.,2015
Zambezi river delta	Brazil	158-6000	1.2-40.8	Trettin et al.,2016
Indian Mangroves				
Sundarbans		912-7031	4.2-19.2	Joshi andGhose 2003
Sundarbans		4723-23,751	0.5-20.3	Joshi andGhose 2014
Bhitarkanika	Orissa	7450-17,943		Upadhyayand Mishra,2008
Bhitarkanika	Orissa	11036	26.74	Upadhyayand Mishra,2014
Mundra coast and Kharo creek	Gujarat	1820-4325		Sawale and Thivakaran,2013
Coringa	Andhra Pradesh,	90-17,310	0.01-120	Satyanarayan et al.,2009
Coringa	Andhra Pradesh,	6140		Azariah et al.,1992
Kakinada Bay	Andhra Pradesh,	470-17,310	10-109	Satyanarayana et al.,2002
Krishna mangroves	Andhra Pradesh,	734-5009		Venkanna and Narasimha Rao, 1993
Godavari mangroves	Andhra Pradesh,	874-6895		Venkanna and Narasimha Rao, 1993
All Kerala mangroves	Kerala	250-2636	2.84-44.96	Grinson George et al.,2018
All Kerala mangroves	Kerala, India	10-13846	0.02-20.19	Sreelekshmi et al.,2018
Cochin Mangroves	Kerala, India	3840-11,440	0.1- 94.32	Present study

From the study,the mangrove species shaving higher importance value index in the study area denoted the habitat preferences of the species, that can be adopted for conservation and restoration activities of the respective plants (Table 2.6). Thus this structural data could be used as an excellent tool for the management of degraded ecosystems in the study area.

From the structural analysis, the selected stations (St.1, St.2, St. 3) was differentiated in terms of structural development. Usually, the structural development of the pioneer species of mangrove ecosystem (*A.officinalis*) was considered for checking the maturity of that forest.

Table 2.6 List of mangrove species and its preferred habitat for restoration based on IVI value from Cochin mangroves during 2013-2014 period

Species Name	Preferred habitat
Acanthus ilicifolius	Mangalavanam, Vallarpadam, Valanthakad
Avicennia officinalis	Mangalavanam, Aroor, Puthuvypin
Bruguiera gymnorrhiza	Malippuram , Puthuvypin
Rhizophora mucronata	Panambukad, Vallarpadam
Bruguiera cylindrica	Puthuvypin, Chellanam, Malippuram
Kandelia candel	Valanthakad, Aroor
Sonneratia caseolaris	Aroor, Valanthakad
Rhizophora apiculata	Vallarpadam, Aroor
Bruguiera sexangula	Aroor, Valanthakkad
Acrostichum aureum	Valanthakad, Malippuram, Mangalavanam
Excoecaria agallocha	Malippuram, Chellanam
Excoecaria indica	Valanthakad
Avicennia marina	Puthuvypin
Sonneratia alba	Puthuvypin

The height of mangrove trees also varied between stations. It could be seen that the selected stations were structurally developed station (St.3), structurally developing station (St.1) and a young mangrove patch (St.2) according to the classification by Pellegrini et al., 2009 based on height and DBH. The environmental character also differed in these stations.

2.5.2 Community analysis

The mangrove forests exhibit a character known as zonation, which is a unique type distribution of mangrove plants based on their environmental characters. Therefore abiotic charactersare directly reflected on the community structure and also the structural characters of mangrove plants. It was reported that minimum species richness was reported in mangrove areas having high freshwater inflow or hypersaline conditions (Ball, 1998). The PCA analysis and RDA analysis revealed the influence of environmental variables in differentiating the community structure of mangrove habitat in three stations. The PCA analysis revealed that PC1 explained differentiation in mainly sediment characters among stations with 36.9% variability. The plot explained that St.1 was more influenced by total carbon, total nitrogen, moisture content, clay and silt. St.2 was more correlated to sand, water pH, water Eh, sediment pH and St.3 was influenced by more hydrographic parameters like TDS, conductivity, salinity and also sediment Eh.

From the RDA vectors, it could be seen that distribution of *R.apiculata*, *S.caseolaris* and *Kandelia candel* were most influenced by clay and silt content in the sediment along with its moisture content. These species grew well and had an excellent structural development in clayey silt sediments. Due to the clayey silt sediment texture, structurally developed mangrove species like *R.apiculata*, *S.caseolaris* and *Kandelia candel* inhabited in St.1 but was absent

in other two stations which are sand dominatedareas. On the other hand, *A. aureum* preferred sandy substratum and was abundantly distributed in St.2 and St.3.

A.officinalis, *R. mucronata* and *B.sexangula* were influenced by organic matter and moisture content of the sediment. Salinity and tidal inundation were reported as significant factors affecting mangrove zonation (Ashton and MacIntosh, 2002; Satyanarayana, 2005). The distribution of mangrove species, according to salinity gradient, was evident when eight stations of mangrove habitats in and around Cochin estuary was considered. Bijoy Nandan et al., 2013 described the salinity gradient in these stations, and it was reported that significant salinity differentiation exists between these stations. In the present study, salinity was not an important parameter for differentiating species density and structure among the three selected stations. Therefore habitat preference of each mangrove species and its structure may depend on many other factors like sediment characters and hydrographic parameters (Lovelock et al., 2005). Salinity was almost similar except little variations shown by St.1, which received more freshwater than the other two stations. In the present study area, sediment parameters, especially sediment texture, had a crucial role in differentiating stations and corresponding mangrove species density. The results were in accordance with Maia and Coutinho, 2012. Moisture content was also a very crucial factor which increases species diversity in mangrove habitats (Ball,1998). The present study also confirmed the influence of moisture content in the sediment on species diversity. High species diversity was observed in St.1, which was having high moisture content in the sediment. However, the measurement of soil salinity was not done during the study. Many studies (Ball,1998, Perera et al.,2013) had revealed the influence of soil salinity on vegetation structure.

Thus the present study helped us in understanding of the phytosociology of Cochin mangroves, together with community structure of mangroves in selected mangrove habitats of Cochin mangroves with the help of detailed description on structural characters of mangrove plants and abiotic factors of the ecosystem. The total stand basal area of mangroves in Cochin was exceptionally high in Puthuvypin and Mangalavanam stations. The phytosociology of mangroves of Cochin revealed that many habitats are structurally well developed and could be comparable to various matured mangrove forest of the world. Even though cochin mangroves are in the declining stage, the nutrient-rich riverine and estuarine habitats of Cochin estuary nourishes the surrounding mangroves. It was revealed that many abiotic factors affected in the distribution and also in structural characters of each mangrove species in the study area. Considering the habitat preference of mangrove species, the study also proposed for scientific species-specific restoration of mangrove plants based on the structural data for the conservation of Cochin mangroves.

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Chapter 3

CARBON STOCK ASSESSMENT IN MANGROVE LIVING BIOMASS

3.1 Introduction

Mangrove forests are famous for their high biomass, high productivity and litter production (Odum and Heald, 1972; Mann, 1982; Boto and Bunt, 1981; Alongi, 2009). Since the structure and biomass of mangroves were affected by environmental and climatic conditions, there exists a marked geographical variation in biomass and productivity of mangroves around the globe. It is high in lower latitudinal areas and is also positively correlated to tidal inundation, which controls sediment and water quality in the mangrove habitats (Woodroffe et al., 1988). Quantifying forest biomass is of crucial importance in climate change studies and forest conservation and management as it fixes the atmospheric carbon dioxide into plant biomass. Therefore United Nations Framework Convention on Climate Change (UNFCCC) recognised the importance of forest biomass as a good source for carbon sequestration and it termed forest as potential carbon storage in Article 3.3 and 3.4 of the Kyoto protocol (Brown, 2002; United Nations, 1998). Mangrove plants are not an exemption to this fact, and it has high carbon fixation capacity compared to other plants. From the biomass, carbon pool or carbon stock was determined by multiplying biomass of the plant with carbon concentration (percentage) in

different parts of the plant. The information on mangrove biomass toward carbon stock is needed because when mangroves are destroyed much of carbon stock in the ecosystem is released to the atmosphere contributing to the current climatic problems (Khairunnisa and Mohd Hasmadi, 2012). Several international studies have been reported on primary production from mangrove plant biomass and its carbon sequestration potential (Twilley et al., 1988, 1992; Clarke, 1994; Jennerjahn and Ittekkot., 2002; Kathiresan and Bingham, 2001; Arreola-Lizárraga, 2004; Juman, 2005; Kristensen et al., 2007; Sánchez-Andrés et al., 2010; Bernini et al., 2010).

As a first step for the evaluation of carbon sequestration and stock assessment, globally, many studies were reported on the biomass of mangroves. Forest ecologists and silviculture experts developed several methods to find out the biomass of a particular forest. Over the years, destructive and non-destructive methods were used by the scientists, and destructive method includes direct harvest method and the mean tree method which is used for homogenous plantations. The non-destructive method was done using allometric equations and models as well as by remote sensing methods. The mangrove environment is a very harsh environment with muddy substratum, and field harvest study is a challenging task compared to other forest ecosystems. Also, the mangroves are very precious trees of the coast and major part of the global mangroves has already degraded. Therefore the destructive method is not a good option for degrading mangrove habitats. There lies the significance of the usage of non-destructive allometric models to find out the biomass of mangrove vegetation (Komiyama et al., 2005). Allometry is a term coined by Huxley and Georges Tessier in 1936 (Huxley and Tessier 1936). It was applied to indicate relative growth and means that "the size and the rate at which a part of the living organism grows are

proportional to the size and growth rate of another". In the case of mangrove trees, allometric equations correlate tree diameter with wood density, height, leaf, root, branch and biomass.

3.2 Literature Review

Globally, mangrove biomass was assessed long back ago, and Cintron and Schaeffer-Novelli (1983) summarized the data available up to 1982. After that, Cintron and Novelli (1984) developed allometric equations for biomass estimation. Even though allometric equations were developed, many researchers followed the harvest method for the determination of biomass. In 1993, Mackey estimated above- and below-ground biomass of *Avicennia marina* in Queensland, Australia. Chen and Twilley (1999) estimated biomass and productivity of mangroves along the Shark River estuary, Florida, while Coronado-Molina et al. (2004) used harvest method in the mangroves of Florida for biomass estimation. Other significant works which used direct harvest method to determine the biomass were by Kirui et al.(2006) for Kenyan mangroves that by Chen et al.(2012) from China for AGB, BGB, biomass increment and sequestration potential study that by Sitoe et al.(2014) in Sofala Bay mangroves and that by Adame et al.(2015) for AGB and BGB and carbon stock of Mexican mangroves. The remote sensing method is another approach to study mangrove biomass and the recent studies were carried out by Wicaksono et al., 2016; Aslan et al.,2016; Bindu et al., 2018 and Pham et al., 2019.

The ecologists developed non-destructive allometric models with the help of measurable structural characters of the tree (Clough et al., 1997; Komiyama et al., 2005; Dahdouh-Guebas et al., 2006; Deshar et al., 2012). Several studies used allometric models for the estimation of aboveground biomass of mangrove forest around the globe (Christensen,1978; Tamai et al.,

1986; Day et al., 1987; Lee, 1989,1990; Day et al., 1996; Sherman et al.,2003; Soares and Schaeffer-Novelli, 2005; Khan et al.,2009).The estimation of biomass by using common allometric equation was popular after Cintron and Novelli (1984). Later Saenger and Snedaker (1993) studied 43 above-ground biomass equations of mangroves from the literature around the world and derived a common equation based on a height-biomass and height-productivity equation. Steinke et al. (1995) estimated mangrove biomass by developing the allometric equation using DBH and height. In the same year, Tam et al. (1995) also developed allometric equations based on the same criteria on the mangroves of China. Clough et al. (1997) developed allometric equations for multi-stemmed mangrove trees like *Rhizophora* spp. Another major study was Fromard et al. (1998), and they determined allometric equations between biomass and DBH in the mangroves of French Guinea. The study developed species-specific equations for *A. germinans*, *Laguncularia racemosa* and *Rhizophora* spp. Ross et al. (2001) developed an allometric equation for dwarf mangroves. Other significant studies which reviewed and analysed species and site-specific equations were by Onget al., 2004; Soares and Schaeffer-Novelli, 2005; and Comley and McGuiness, 2005. Soares and Schaeffer-Novelli (2005) analysed different models for estimating AGB of mangroves. They reported that there was a significant differentiation among mangrove tree species with a species-specific trait of allometry.

Since below ground biomass estimation is a very tedious job to excavate root biomass, the studies on that aspect were very scanty. Scientists used different methods for the estimation of root biomass, and Tamai et al. (1986) used physical pulling of the roots. However, this may result in loss of fine roots. Trench method was used by Komiyama et al. (2000) for estimating the horizontal distribution of root density. Ong et al. (2004) used jets of water for

loosening of mud and yielded minimum loss of recovered roots. Later Comley and McGuinness (2005) used a ‘‘root ball’’ method, and it resulted in contamination from roots of nearby trees. Other significant studies on below ground estimation of mangroves were Alongi et al. (2000) and Lovelock (2008). Thus, studies on the allometric relationship of mangrove roots are still needed due to the scarcity of case studies as well as the differences in root extraction methods. Recent studies by Santos et al., 2017 and Adame et al., 2017, also followed trench method for below-ground biomass estimation as per Komiyama et al. (1987, 2000). Adame et al. (2017) compared both trench method and common allometric equations for below ground estimation and reported that the results of the common equation were high compared to biomass obtained by the trench method.

The development of allometric equations for each site and each species need an intensive labour for taking the weight of the tree, it opens up the research on finding common allometric equations for mangrove plantations. In this circumstance, on both the species- and site-specific issues of allometry, Chave et al. (2005) and Komiyama et al. (2005) developed a common allometric equation for mangroves. Pipe model (Shinozaki et al., 1964) and the static model of plant form (Oohata and Shinozaki, 1979) were used by Komiyama et al. (2005) for developing the common allometric equation based on wood density and DBH. These models predict that “the partial weight of the trunk at a certain height physically sustains the weight of the upper tree body, regardless of tree species and locality”. The study used 104 sample trees of 10 mangrove species from Thailand and Indonesia and found out a good fit model. On the other hand, Chave et al. (2005) developed a common equation with DBH and height and also with DBH and wood density for mangroves based on statistical analysis. Both the common equation studies observed that

allometricequation of mangrove species is more species-specific than site-specificity and wood density is a major factor that differentiates mangrove biomass. Komiyama et al. (2008) summarised the different species-specific allometric equations and also compared the common allometric equations.

Even though the development of allometric equations continued for biomass estimation (Kairo et al., 2009 developed allometry for Kenyan mangroves), many researchers used common allometric equations and other published models for estimating the mangrove biomass without destruction or harvest. Abino et al. (2014) used common allometric equation developed by Komiyama et al. (2005) for both AGB and BGB estimation and carbon stock assessment of Philippines mangroves. Svob et al. (2014) used the equation of Chave et al. (2005) for biomass study in Costa Rica mangroves. In the same year, Alemayehu et al. (2014) used both equations for comparison of the biomass of mangroves in Kenya, and they also assessed the carbon stock as biomass. Kamruzzaman et al. (2018) used the equation of Chave et al. (2005) for AGB estimation and used the equation of Komiyama et al. (2005) for BGB estimation and also derived carbon stock of Sundarban mangroves, Bangladesh. The biomass stock and ecosystem carbon stock of Amazon mangroves were studied by Kauffman et al.(2018). They used common allometric equation for below-ground biomass estimation and species-specific equation for above ground biomass estimation. They reported that the Amazon mangrove carbon stock was twice that of upland evergreen forests and approximately ten fold that of tropical dry forests.

In India, the mangrove biomass studies are very less compared to global studies and major studies were limited to Sundarban mangrove forest. A general account of productivity and mangrove biomass of Sundarban mangroves was done by Chakrabarti (1987). Chaudhuri (1991) studied

mangrove biomass using mean stem harvesting method in Sundarban while Mall et al. (1991) in the Andaman Islands, Nameer et al. (1992) in Puduvyppu mangroves, Kerala and Joshi and Ghose, (2002) in Sundarbans. Later studies by Mitra et al. (2011) and Chowdhury (2015) were the significant studies reported on the biomass of mangroves in India. These studies were concentrated on Sundarbans and used Newton's formulae (Husch et al., 1982) for stem biomass estimation and harvesting method employed for branch and leaf biomass estimation. It also included a carbon sequestration assessment through biomass. Another study by Joshi and Ghose (2014) used biovolume method to calculate AGB of Sundarban mangroves. Hossain et al. (2016) conducted an important study which developed allometric equations for Sundarban mangroves by harvest method. Common allometric equation of AGB and BGB by Komiyama et al. (2005) was used by Sahu et al. (2016) for biomass and carbon stock assessment of mangroves in Mahanadi delta. However, these studies used a rough estimate of (50%) biomass as carbon. Later Agarwal et al. (2017) used another equation to estimate the AGB and carbon stock of mangroves in the same region. Prasanna et al. (2017) also developed allometric equation for biomass and carbon stock assessment of mangroves of South- East coast of India. The above ground biomass of mangroves of the entire country was developed by Suresh et al. (2017) using the common equation developed by Chave et al. (2005). Vinod et al. (2018) gave a recent study in the regional scenario, and the study reported the biomass and carbon stock of Kadalundi mangroves, Kerala using the allometric equations of Komiyama et al. (2005). Wood density obtained from the literature was used in many studies which used common allometric equations for the biomass estimation. Wood density is an important parameter which will differ according to species, age and even region. In the present study, attempt

was made to estimate the wood density of each species in each age class. It is clear from literature that biomass and carbon stock of mangroves of Kerala are least studied. It is essential to document the carbon stock of valuable forest of the Kerala coast for restoration and thereby reducing atmospheric CO_2 for the well being of our life forms.

3.3 Materials and Methods

The elaborate description of the study area is provided in Chapter 2 (2.3.1). The study stations of Cochin mangroves St.1(Aroor), St.2(Malippuram) and St.3 (Mangalavanam Bird Sanctuary) were selected for the biomass invessstigations as outlined in this chapter. Biomass was calculated from the structural data (DBH, height and wood density) that was obtained from the five quadrats from each station. The DBH and height data is described in detail in Chapter 2.4. The wood density determination and biomass calculation are described in detail in this chapter.

3.3.1 Biomass and Carbon pool

Biomass is an important factor in forest carbon stock assessment. Since the Cochin mangroves are in the degraded stage, non-destructive method for mangrove trees and destructive method for ferns and herbs was selected for biomass estimation, and this type of methodology was adopted by Kauffman and Donato (2012). The ferns and herbs were harvested and separated into above ground biomass and below ground biomass. The weight of the separated component was measured by drying the material in 60^0C to a constant weight and expressed as dry biomass. A total of 388 samples were taken for biomass estimation (including ferns and herbs) out of which 255 tree samples were measured for DBH and height measurement for mangrove biomass estimation. Common allometric equations described below: based on DBH, wood density

and height was used for the biomass calculation of mangrove trees. The above ground biomass comparison was made by using different equations.

$AGB = \rho * \exp(-1.349+1.980 \ln(D) + .207 (\ln(D))^2 - 0.0281 (\ln(D))^3)$…...Eq.1 (Chave et al.,2005)

$AGB = 0.0509 * \rho D^2 H$ ……..……..Eq.2 (Chave et al.,2005)

$AGB = 0.251 \rho (D)^{2.46}$…….....Eq.3 (Komiyama et al.,2005)

$BGB = .199 \rho^{0.899} 8 D^{2.22}$……...Eq.4 (Komiyama et al.,2005)

Where, AGB= above ground biomass,

BGB= belowground biomass

ρ = wood density

H = height

D = DBH

From the results of these three equations, the selection of good fit model for AGB estimation was analysed using scatter plot analysis in SPSS 16.0 v. The corresponding equation number given above, is used in further description of the data in this chapter.

The diameter at breast height and height was measured using standard procedures described in chapter 2.3.2 and wood density estimation was done following the below procedure by Chave (2006). The wood core was sampled using standard Haglöf 3-Thread Increment Borer (8"L x 0.200" (5.15mm) Dia.). Duplicate wood core samples were taken for each species and each DBH class present in the study area. The samples were immediately kept in thermocol trays without any disturbance. For measurements of green volume, the samples were kept in distilled water for a ½ hour to ensure adequate

swelling and maintaining the constant humidity. Green volume was measured by dimensional method. A digital Vernier Caliper was used for measuring the diameter and height, and green volume was calculated by considering its cylindrical shape:

Volume, $V = \pi r^2 H$ (Where r = radius of the core sample, H= length of the core sample).The measured samples were kept in Hot Air Oven at 60 ^oC upto constant weight, and dry weight was measured. Wood density was calculated as:

Wood density = Oven dry weight/ green volume

The biomass of mangroves was converted into carbon stock or mangrove carbon pool as living biomass. The carbon content in the wood core sample along with branch and leaf sample were pooled to get the conversion of biomass into carbon and the present study obtained an average carbon content in AGB as 45 %. A factor of 39 % of BGB as carbon(Kauffman and Donato, 2012) was taken for estimation of belowground biomass carbon stock.The carbon content in the wood core, branches and leaf were analysed using Analytik Jena TOC analyzer HT 1300 solid module.

3.4 Results

3.4.1 Mangrove living Biomass

3.4.1.1 Wood density

The wood density of mangrove trees is the first database from Kerala mangroves, and limited data are available even from the Indian context. *R.apiculata* and *R. mucronata* were the densest mangrove species (0.83, 0.81 gcm^{-3}). *S.caseolaris* (0.41 gcm^{-3}) and *E. agallocha* (0.42 gcm^{-3}) were the less dense mangrove species (Fig.3.1). When DBH increased, wood density also increased. Matured trees showed a constant wood density. In the case of

A.officinalis, 1-10 DBH class was having a wood density of 0.53 ± 0.02 g cm^{-3}, and maximum density was shown by 31-40 DBH class (0.603 ± 0.003 gcm^{-3}). *S.caseolaris*was represented by DBH class of up to 41-50 cm, having a constant wood density from 31-40 cm DBH class (0.42 g cm^{-3}) and a low wood density of 0.39 ± 0.02 gcm^{-3} for 1-10 cm DBH class. For *R. mucronata*, the wood density of 1-10 cm DBH class was 0.7 ± 0.06 gcm^{-3}, and it gradually increased up to 0.812 ± 0.002 gcm^{-3} in 11-20 cm DBH class. Even though *R. apiculata* tree was represented by only 1-10 cm DBH class in the study area, even the young trees were having a high wood density of 0.83 g cm^{-3}. The wood density of *B.cylindrica* in 1-10 DBH class was 0.68 ± 0.06 gcm^{-3}, and such high value was observed in 11-20 cm DBH class (0.73 ± 0.02 g cm^{-3}). *B. gymnorrhiza* was having a wood density of 0.68 ± 0.006 g cm^{-3} in the first DBH class and 0.763 ± 0.019 g cm^{-3} in 21-30 cm DBH class. *B. sexangula* and *K. candel* were represented by only 1-10 cm DBH class, and the corresponding wood density was 0.65 ± 0.005 g cm^{-3}, 0.557 ± 0.002 g cm^{-3}respectively. *E. agallocha* was having a wood density of 0.41 ± 0.03 g cm^{-3} in 1-10 cm DBH class and 0.43 ± 0.022 g cm^{-3} in 11-20 cm DBH class.

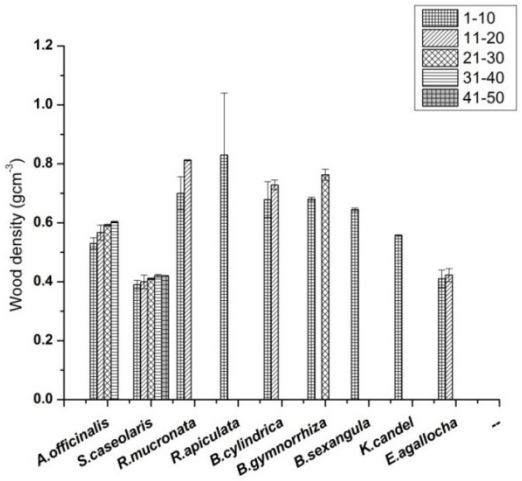

Figure 3.1 Average wood density of different mangrove species of Cochin mangroves in different maturity class

3.4.1.2 Above ground biomass and Below ground biomass

Average total above ground biomass of mangroves from Cochin was 522.81 ± 320.98 t ha^{-1} (Komiyama, 2005), 381.50 ± 232.04 t ha^{-1} (Chave, 2005) and the total belowground biomass was 240.45 ± 152.60 t ha^{-1}. *A. officinalis* was having highest AGB compared to other mangrove species in the study area and contributed 65% of total AGB (Fig.3.2).

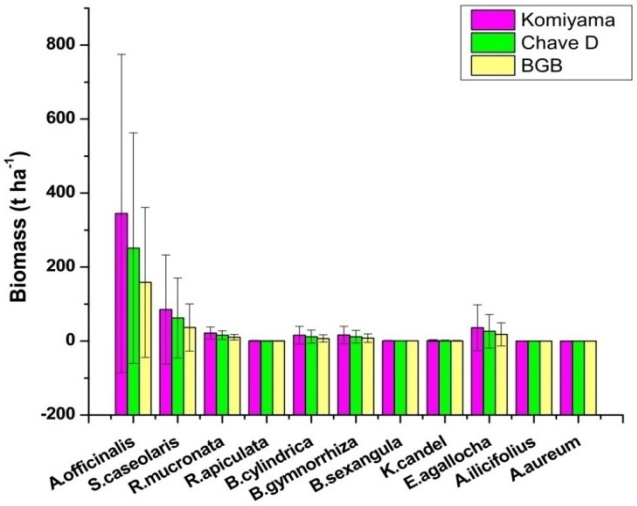

Figure 3.2 Average total above ground biomass of mangroves from Cochin during 2013-2014

Total above ground biomass of mangrove trees (excluding *A.ilicifolius* and *A.aureum*) in St.1 according to height based equation by Chave et al. (2005) (hereafter the equation will be termed as Eq.1) gave very low value (253.66 t ha^{-1}) compared to diameter based equation by Komiyama et al., 2005 (430.31 t ha^{-1}, hereafter the equation will be termed as Eq.3) and Chave et al., 2005 (316.18 t ha^{-1}, hereafter the equation will be termed as Eq.1). Fig.3.3 showed the average AGB of different mangroves around Cochin estuary. It was observed that *A.officinalis* was having the highest above ground biomass, followed by *S.caseolaris* and *E.agallocha* in the study area. *A. officinalis*

contributed around 66.02% of total AGB of mangrove trees in the study area followed by 16.28% by *S.caseolaris*, and all the other mangroves contributed negligibly to the total AGB. The AGB of St. 1 was majorly contributed by *S.caseolaris* (255.21 t ha^{-1}according to Eq.3) followed by *A.officinalis* (187.50 t ha^{-1} according to Eq.3). In St.2, *E.agallocha c*ontributed more to biomass followed by *A.officinalis* and *B.gymnorrhiza*. Fig.3.4 (a-c) compared results of AGB of mangrove trees by using different allometric equations in three stations. It could be observed that diameter based equations showed higher AGB rate than height based equation. In St.3, Mangalavanam, the total AGB of mangrove trees were exceptionally higher (878.33 t ha^{-1} according to Eq.3 and 637.80 t ha^{-1} according to Eq.1) due to the presence of large *A. officinalis* species.

The total above ground biomass of mangroves including ferns and herbaceous mangrove in St.1 was 430.46 t ha^{-1} from Eq.3 and 316.25 t ha^{-1} from Eq.1, where as in St.2, the total biomass was 258.13 t ha^{-1} from Eq.3 and 189.08 t ha^{-1} from Eq.1. The total biomass of mangroves in Mangalavanam Bird sanctuary, St.3 was 879.86 t ha^{-1} from Eq.3 and 639.19 t ha^{-1} from Eq.1.

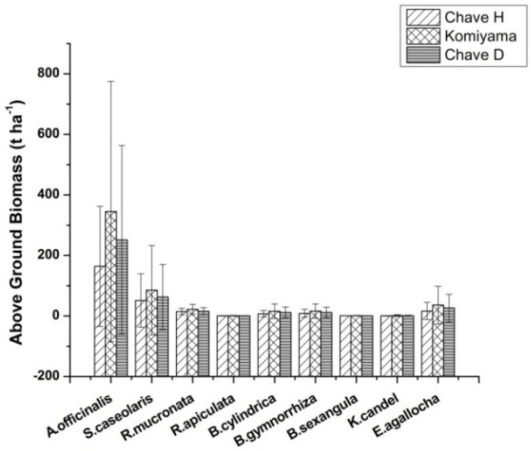

Figure 3.3 Average above ground biomass of different mangrove trees in Cochin during 2013-2014 period

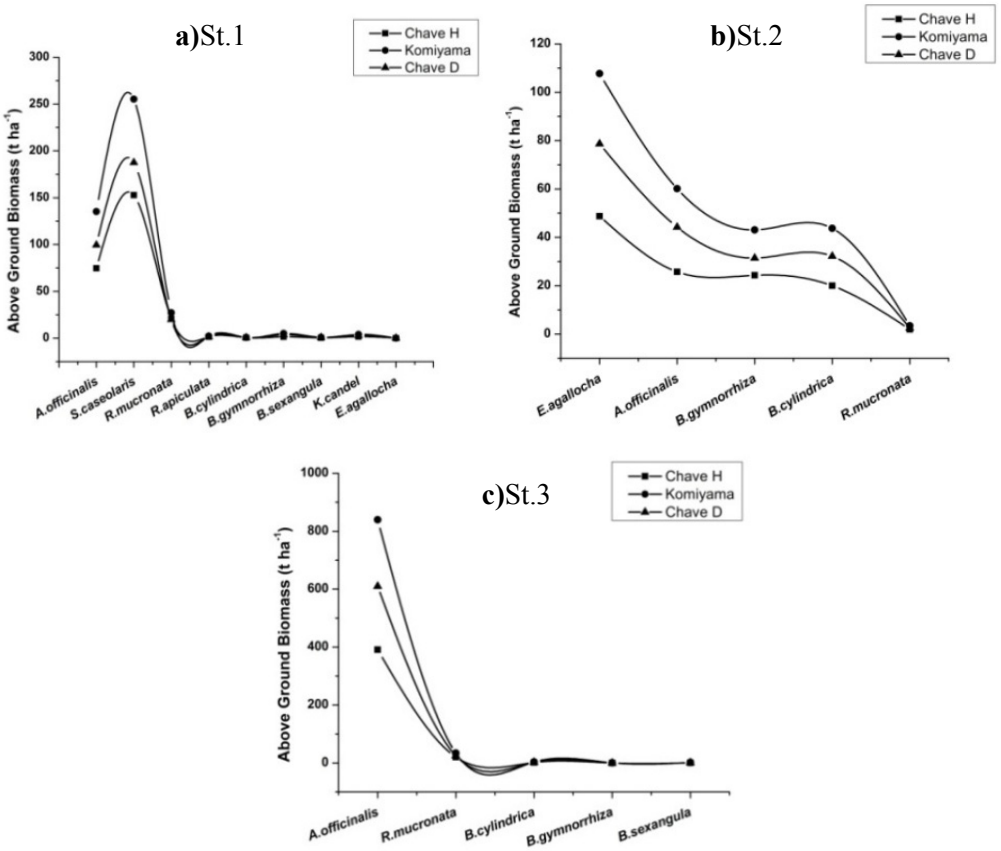

Figure 3.4 (a-c) Comparison of Above ground biomass of different mangrove trees using different allometric equations in Cochin mangroves.
(Chave H- Eq.2. Komiyama-Eq.3, Chave D- Eq.1)

Below ground biomass of mangrove trees was obtained by using only one common equation and average below ground biomass of the study area was 240.43±152.61 t ha^{-1}. It was high for *A.officinalis* (158.59 ± 202.82 t ha^{-1}, range = 27.03- 392.17 t ha^{-1}) followed by *S. caseolaris* (36.80 ± 63.74 t ha^{-1}, range = 0-110.40) (Fig.3.5). In St.1, *S. caseolaris* was having highest BGB (110.40 t ha^{-1}) followed by *A.officinalis* (56.57 t ha^{-1}). In St.2, highest AGB was for *E.agallocha* tree (54.05 t ha^{-1}) followed by *A. officinalis* (27.03 t ha^{-1}). In St.3, *A.officinalis* tree (392.17 t ha^{-1}) was having high BGB followed by *R.mucronata* (16.63 t ha^{-1}). The total belowground biomass of mangroves

(Table3.1, including ferns and herbaceous mangrove) was high in St.3, Mangalavanam (412.60 t ha^{-1})followed by St.1, Aroor (186.90 t ha^{-1}) and St.2, Malippuram (121.80 t ha^{-1}).

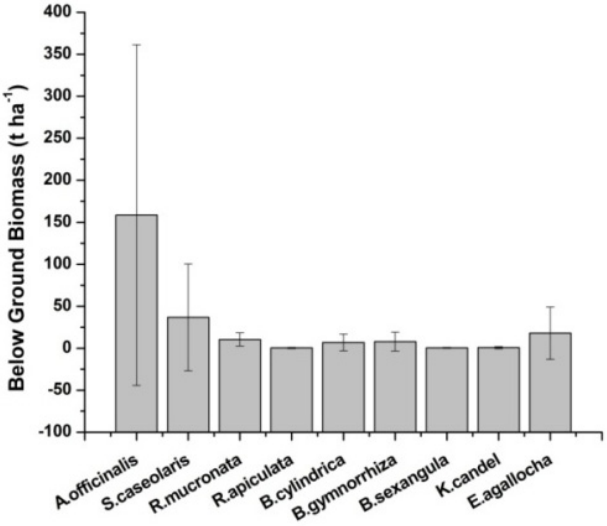

Figure 3.5 Average below ground biomass of mangrove trees in Cochin during 2013-2014

Table 3.1 Belowground biomass of different mangrove plants in the study area during 2013-2014

Mangrove species	Below ground biomass (t ha^{-1})		
	St. 1	St.2	St.3
Avicennia officinalis	56.565	27.034	392.167
Sonneratia caseolaris	110.405	0.000	0.000
Rhizophora mucronata	12.996	1.645	16.632
Rhizophora apiculata	1.014	0.000	0.000
Bruguiera cylindrica	0.417	18.363	1.791
Bruguiera gymnorrhiza	2.701	20.625	0.067
Bruguiera sexangula	0.539	0.000	1.087
Kandelia candel	2.087	0.000	0.000
Excoecaria agallocha	0.085	54.045	0.000
Acanthus ilicifolius	0.028	0.013	0.105
Acrostichum aureum	0.065	0.075	0.753

3.4.2 Carbon Stock Assessment

Average carbon stock as above ground biomass of Cochin mangroves was 235.27 ± 144.44 t ha^{-1} (Eq.3) and 171.68 ± 104.42 t ha^{-1} from Eq.1. Average Carbon stock from below ground biomass of Cochin mangroves was 93.77 ± 59.52 t ha^{-1}. St.3, Mangalavanam Bird sanctuary had the highest carbon stock as biomass (Fig.3.6).

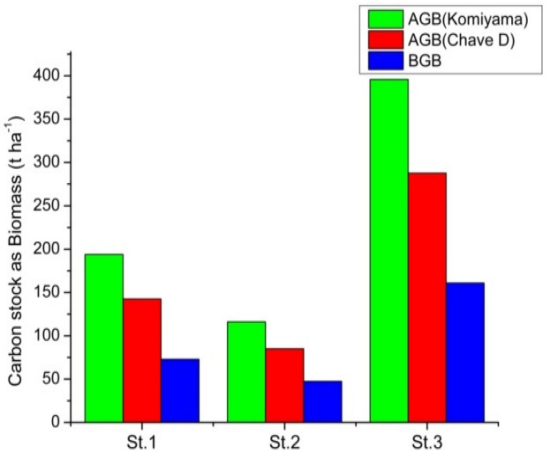

Figure 3.6 Spatial variation in total carbon stock as the biomass of mangroves in the study area during 2013-2014

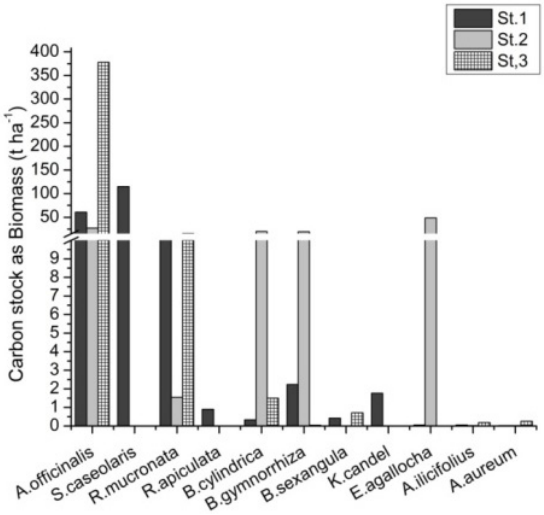

Figure 3.7 Carbon stock as Biomass of different mangrove species in the Cochin mangroves during 2013-2014

The average total living biomass carbon stock of Cochin mangroves was 329.04 ± 203.96 t ha^{-1}(Eq.3) and 265.45 ± 163.94 t ha^{-1} (Eq.1). In St.1, *S.caseolaris* was having the highest carbon stock followed by *A.officinalis* and *R.mucronata*. In St.2 highest contribution to carbon stock as biomass was by species of *E.agallocha*followed by *A.officinalis*, *B.gymnorrhiza* and *B.cylindrica*. In St.3, *A.officinalis* was the major contributor (95.42 %) to carbon stock, and only 3.9 % was contributed by *R.mucronata* (Fig.3.7).

3.5 Discussion

3.5.1 Wood density

Wood density measurement is always a challenging task in forest ecology and silviculture. In the present study area, mangrove plants showed low dense to high dense trees. It is an important physical characteristic of wood and depends on other wood properties such as resistance, porosity and the number, size, and chemical composition of the cells (Noguiera et al., 2005). Tidal resistance and other resistive environmental characters which prevailed in the fringing zone of mangrove ecosystem may result in high wood density in fringing mangroves such as *Rhizophora* spp. In this study, landward scrub mangroves (*E.agallocha*) were having less density compared to fringing mangroves and tall landward mangroves (*Bruguiera*spp.). This observation was well coinciding with the findings of Santini et al. (2012). *Rhizophora* spp. and *Bruguiera* spp. were having high density even though they were in the maturing stage (1-10 cm and 11-20 cm DBH class). In the Global wood density database (Zane et al., 2009) *R. mucronata* had a wood density in the range of 0.74-0.904 gcm^{-3} with an average of 0.814 g cm^{-3} (Desch, 1996; Anonymous, 1971; Bolza,1975; Oey Djoen Seng, 1951). The results of the current study were comparable with the above range. However, Adedeji et al. (2013) reported high density for *Rhizophora* spp. and reported up to 0.96 g cm^{-3} in the

central part of the wood. According to wood database, *Avicennia officinalis* (Oey Djoen Seng, 1951; Desch, 1996) reported 0.59-0.62 g cm^{-3} of wood density; however, the current study reported slightly lower values 0.53 in young plants and reached up to 0.60 g cm^{-3} in matured trees. The wood density of *B. cylindrica* was comparable with wood density database. However, the wood density of *B. gymnorrhiza* and *B. sexangula* were very less compared to the database. The current study area consists of young plants of both species, which may be the reason for lower values compared to that of database which represented matured trees. The results of wood density of *E.agallocha* was in the range of global wood density database (0.379-0.480 g cm^{-3}, Oey Djoen Seng, 1951; Anonymous, 1974; Bolza, 1975; Desch, 1996; Benthall, 1984). The wood density of *K.candel* was comparable with Chinese mangroves as reported by Cheng et al. (1992). In the case of *S. caseolaris*, global database values are lesser (0.387-.390 480 g cm^{-3}) compared to the current study. The results of the current study exhibited higher values as it included young plants to highly maturing tall trees and DBH up to 41-50 cm with a wood density of 0.39 to 0.42 480g cm^{-3}.

3.5.2 Above and Belowground Biomass

The results of aboveground biomass by using different equations showed that diameter based equations were giving high biomass compared to height based equation. Even though biomass results slightly differed according to three equations, statistically, the results did not differ significantly (Kruskal Wallis test ($\chi^2(2) = 0.495$, $p= 0.781$). However, the results of scatter plot analysis for detecting best fit model for Cochin region revealed that height vs AGB was having low R^2 value while diameter based equations showed high R^2 value for all the mangrove species in the study area was indicating a strong relationship of biomass with diameter rather than height. Fig.3.8 a-b Illustrates

an example of scatter plot results of *E.agallocha*. Thus, the diameter based equations were best suited for the Cochin area rather than height based equations.

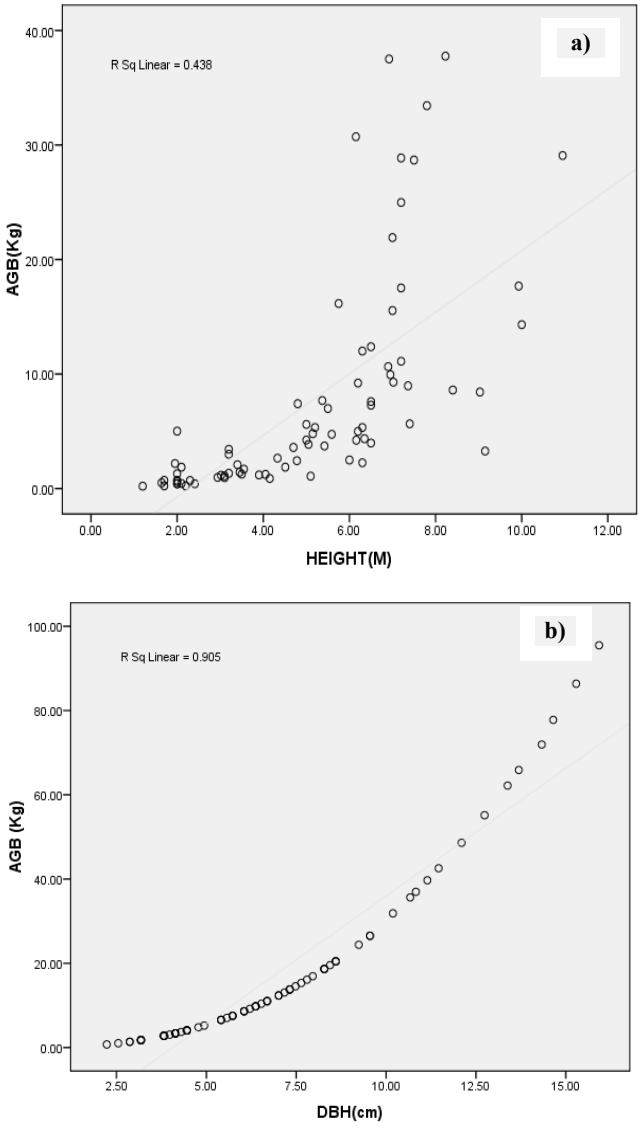

Figure 3.8 a) Scatter plot of biomass vs height **b)** Scatter plot of biomass vs DBH in Cochin mangroves during 2013-2014

Among diameter based equations, Chave et al. (2005) (Eq.1) were having high R^2 value for almost all the mangrove species compared to Komiyama et al., 2005 (Eq.3). Thus it could be observed that for large trunk diameter, the biomass results based on Eq.3 were giving high estimates compared to Eq.1. This problem was also discussed in Komiyama et al., 2008 while reviewing the allometric equations around the globe. Therefore, either we could adopt biomass results calculated by using the equation of Chave et al. (2005)(Eq.1) or we could use the equation of Komiyama et al. (2005) (Eq.3) for mangrove trees except for trees with large DBH class. Since the current study consists of mangroves with large trunk diameter, it is recommended to take the biomass results obtained through Chave et al. (2005) (Eq.1). Alemayehu et al. (2014) reported similar observation by comparing both equation of biomass of mangroves in Kenya and the study also portrayed that height based equation was underestimating the mangrove biomass and diameter was giving significant correlation with biomass.

The biomass of mangroves in the present study was compared with other mangroves of the world (Table 3.2). The above ground biomass obtained through the Eq.1 was comparable with Australian mangroves and mangroves of Indonesia. The AGB results obtained through Eq.3 was also comparable with many mangroves of the world with high biomass. The biomass results of the other studies which used Eq.3 was also very much near to the present study. Above ground biomass of Philippines mangroves by Abino et al., 2014, used Eq.3 for both AGB and BGB estimation and reported an AGB of 561.2 t ha^{-1} which is near to the present study results (522.85t ha^{-1}). Svob et al. (2014) and Kamruzzaman et al. (2018) used Eq.1 for biomass study in Costa Rica mangroves and Sundarban mangroves, Bangladesh, respectively, but the results are less compararable with the present study.

Table 3.2 Comparison of Above ground biomass and belowground biomass of mangroves in different parts of the world with the present study during 2013-2014

Region	Species	AGB (t ha^{-1})	BGB (t ha^{1})	H (m)	BA (m^2 ha^{-1})	Reference
Malaysia	*R.apiculata*	211.8		15		Ong et al.,1982
Malaysia	*R.apiculata* dominated	460.0				Putz and Chan,1986
Indonesia	*B.gymnorrhiza*forest	436.4	180.7	22.4	35.9	Komiyama et al., 1988
Thailand	*Sonneratia*	281.2	68.1		31.30	Komiyama et al.,1987
Srilanka	*Rhizophora*	240		7.2	43.8	Amarasinghe and Balasubramanian, 1992
Australia	*A.marina*	341	121	16.4	-	Mackey., 1993
Kenya, Gazi Bay	*R. mucronata*	**512**				Slim et al.,1996
Thailand	*C.tagal*	92.2	87.5	5.2	15.2	Komiyama et al.,2000
Kenya, Gazi Bay	*R.mucronata*	452.02				Kirui et al.,2006
Philippines mangroves	Mixed forest	561.2	196.5	4-25		Abino et al.,2014
India Sundarbans	Mixed forest	8.9 -50.9				Joshi and Ghose,2014
Sofala Bay, Central Mozambique		10.7 -464.4				Sitoe et al.,2014
Mexico,	*R. mangle* dominated	198.8-706.6				Adame et al.,2015
Karankadu mangrove, South east India	*A. marina*	10.71				Prasanna et al.,2016
Mahanadi Delta, India	Mixed mangrove	178.8 (total)				Sahu et al., 2016
Cochin, Kerala, India	**Mixed forest**	**522.81, 381. 50**	**240.43**	**14 - 13.22**	**76.60**	**Present study**

When comparing to Indian studies, the aboveground biomass was very high in the present study area. Even though some studies (Sahu et al., 2016; Suresh et al., 2017; Vinod et al.,2018) used the common allometric equation of Komiyama (Eq.3), they got less AGB compared to the present study. The carbon stock assessment of Kadalundi mangroves of Kerala (Vinod et al., 2018) was also having less above ground biomass (mean= 166.64 t ha^{-1}).

Below ground biomass was higher in the study area compared to other mangrove ecosystems of the world (Table 3.2). Mangalavanam mangrove forest displayed a significant difference in both above and below ground mangrove biomass estimation due to the presence of large *A.officinalis* mangrove trees. As discussed earlier in the case of above ground biomass estimation, the high below ground biomass may be overestimation due to the existence of error in the calculation for large trunk size of *A. officinalis* species by using Komiyama et al. (2005) equation. Therefore, future studies are required on a global level for correcting the common equation for large mangrove trees. However, the total biomass of mangroves (even though avoiding results of Eq.3) in Cochin estuary was comparable with world mangroves with high biomass stock. Therefore immediate action is needed for the conservation of these precious wetlands.

3.5.3 Carbon stock as biomass

The carbon stock or carbon pool as biomass in the present study was comparable with the same latitudinal (0-10^{o}) average according to Twilley et al., 1992 (287.6 t ha^{-1} as AGB and 171.2 t ha^{-1}as BGB). The major contribution to carbon stock was from *A. officinalis* species (66.05%) followed by *S. caseolaris* (15.33%). Other recent studies were also compared with the present study (Table 3.3.). It could be observed that African mangroves had high carbon stock compared to the present study (Kauffman andBhomia, 2017).

Table 3.3 Comparison of present study carbon stock as AGB and BGB with different studies around the world

Location	Carbon stock (t ha^{-1}) AGB	BGB	Reference
International			
Philippines	263.8 (50%)	92.3 (17%)	Abino et al.,2014
Kenya	148.07		Alemayahu et al.,2014
West-Central Africa	5.2 to 312		Kauffman andBhomia, 2017
Brazilian mangroves		104.4	Santos et al.,2017
Sundarbans, Bangladesh	76.8	41.1	Kamruzzaman et al.,2018
Amazon mangroves	145.17	11.69	Kauffman et al.,2018
Indian mangroves			
Vellar-Coleroon estuarine complex including Pichavaram mangroves	67.47(*A.marina*) 38.05(*R. mucronata*) (total biomass)		Kathiresan et al., 2013
Sundarban	61.35-152.57	11.72-62.37	Rahman et al.,2015
Mahanadi Delta, India	178.8(total)		Sahu et al.,2016
Bhitarkanika wildlife sanctuary, Odisha	43.78-230.09		Bal et al.,2017
Kadalundi	83.32	34.96	Vinod et al.,2018
Cochin Mangroves	**235.27(Eq.3), 171.68(Eq.1)**	**93.77**	**Present study**

However, the carbon stock in the present study was high compared to Sundarban mangroves (Rahman et al., 2015; Kauffman and Bhomia, 2017), Pichavaram mangroves (Kathiresan et al., 2013) and even higher than Amazon mangroves (145.17 t C ha^{-1}, Kauffman et al., 2018). Even though Amazon mangroves are taller than Cochin mangroves, the basal area was lesser (26.33 ±1.1 m^2 ha^{-1}) compared to Cochin mangroves (76.63 ± 24.8 m^2 ha^{-1}), that resulted in high above ground biomass stock in the present study area. It is

comparable with other carbon stock assessment studies in India (Sahu et al., 2016; Bal et al., 2017). The carbon pools of AGB and BGB estimated by Vinod et al. (2018) in the Kadalundi mangroves of Kerala was much lower compared to the present study. The ratio of above-ground biomass to belowground biomass was 1.83 (by using Eq.1 and Eq.4) in the present study. This result is consistent with the reported values of Komiyama et al., 2008, which varied from 1.1 to 4.4. Thus even though the current study did not employ destructive harvest method, the accurate measurements of DBH and field measurement of wood density of each mangrove species in each DBH class interval resulted in more reliable and comparable biomass estimation.

Thus this chapter outlined the primary data on living biomass of mangroves of Cochin by using measured wood density data. The wood density obtained through this study would be useful in estimating the biomass of mangroves elsewhere in Kerala in different age classes. The carbon stock through living biomass of mangroves was very high compared to several other mangrove habitats and therefore would be used in carbon economy of the region for policy-making and thereby mitigating regional climate change problems.

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Chapter 4

PHENOLOGY AND CARBON FLUX THROUGH LITTERFALL DYNAMICS

4.1 Introduction

Globally many studies were focused on litterfall estimation as a proxy of Net primary productivity (NPP) since the direct estimation of NPP is a difficult task, and proper turn over estimates of biomass especially belowground biomass was lacking. Litterfall act as a major component of forest function that is directly coupled to Net Primary Productivity (NPP) and global biogeochemical cycles including carbon and nitrogen since it acts as the source of nutrient to the ecosystem. It is considered as one-third of the net primary production (Alongi et al., 2005). Mangrove vegetation upholds food webs in the adjacent aquatic ecosystems and intertidal mudflats through litter production. In addition to the export of nutrients, it acts as an excellent nutrient source to other organisms within the ecosystem and efficiently helps in recycling of the nutrients within the ecosystem (Robertson and Daniel, 1989; Bouillon et al., 2002). The study on litter dynamics and phenology will be an effective method to understand the ecosystem dynamics and modelling studies. Litter production is the shedding of vegetative or reproductive plant structures

(Ghosh and Banerjee, 2013) which act as a significant component of forest function.

Litterfall depends upon many factors like latitude (Saenger and Snedaker, 1993;Twilley et al.,1992; Alongi, 2002; Bouillon et al., 2008b), season (Williams et al., 1981), mangrove species (Slim et al.,1996), structural characters of the mangrove habitat (Woodroffe,1982), geomorphology, climatic factors, salinity and pollution (Day et al., 1996; Feller et al., 1999) and sediment nutrient availability (Saenger and Snedaker, 1993). Higher litterfall rates are reported from tropical forest compared to sub tropical and temperate forest (Putz and Chan, 1986; Slim et al., 1996, Goulter&Allaway, 1979; Woodroffe, 1982). Seasonal variation or phenology is another significant character in litterfall production (Williams et al., 1981). Among these factors, region wise disparities from its topography and climatic regimes are important (Ghosh and Banerjee, 2013; Twilley, 1995). So region wise studies are required to understand the mechanisms that control litterfall production.

4.2 Literature Review

Several international studies were reported on the litterfall production of mangroves, and the studies were mainly focused on factors influencing litterfall production or its dynamics and relation to nutrient cycling, its role in herbivory and role in carbon sequestration. The importance of mangrove litterfall was first opened to the scientific community by Odum and Heald in 1972 through their study on the concept of outwelling of organic matter and nutrients from mangroves to the adjacent estuary. Later some pioneer studies on litterfall production in mangroves were reported by Pool et al. (1975) and Odum & Heald (1975). Duke et al. (1981) studied about species-specific litterfall production of *Sonneratia alba, Rhizophora apiculata, R. stylosa, R.*

lamarckii, *Avicennia* spp., *Bruguiera gymnorrhiza, B. parviflora* and *Ceriops tagal* in Australian mangroves. In the same year, Ong et al. (1981) studied litterfall production of mixed mangrove habitat of Malaysia. In 1982, Bunt reported bulk litterfall production without considering the litterfall of each mangrove species in the Missionary Bay. Many studies (Twilley, 1982; Sasekumar and Loi, 1983; Woodroffe and Moss, 1984; Brown, 1984; Leach & Burgin 1985; Twilley et al., 1986; Woodroffe et al., 1988; Clarke,1994) were reported on mangrove litter production in different parts of the world. Twilley et al., 1997 studied in detail on litter dynamics, its annual production, seasonal effect, litter turnover rates and even litter removal by tides and crabs. Twilley and Day (1999) also contributed in-depth information on overall productivity, including litterfall estimation and nutrient cycling in the mangrove ecosystem.

Numerous studies (Day, 1987; Woodroffe et al., 1988; Bunt, 1995; Tam et al., 1998; Kathiresan and Bingham, 2001) were focused on litterfall production and various factors which controlled the production rate like species diversity, tidal amplitude and salinity. In 1989, Lee studied in detail about litterfall in monospecific stands of *Kandelia candel* in Hong Kong. Peng and Lu (1990) reported a high litterfall production of 18.70 t $ha^{-1}y^{-1}$ litter in monospecific stands of *Bruguiera* spp. in China, which reported to have the highest litterfall production in a monospecific stand of mangrove from higher latitude. Amarasinghe & (1992) reported comparatively low values of litterfall production from Srilankan mangroves even though the study was in lower latitude and also the habitat was dominated by *Rhizophora* spp. and *Avicennia* spp., where usually high production rate is expected due to large propagules. The litterfall production and its relation to the age of mangroves were done by Hegazy (1998). Clough et al. (2000) reported a high litterfall production in Vietnam mangrove forest dominated with *R. apiculata* stands. A very high rate

of litterfall (20.3 t $ha^{-1}y^{-1}$) was reported from equatorial mangroves (Brazilian mangroves) in 2001 by Mehlig. Higher latitudinal mangrove litter production was estimated by Arreola-Lizárraga et al. (2004) in Mexican mixed mangroves and reported a meagre rate of litter production. Litter production and phenology of subtropical mangroves were done by Tam et al. (1998) and Mfilinge et al. (2005). The litterfall and its C/N ratio and elemental composition was another major study related to litterfall that was carried out by Wafar et al. (1997); Nga et al. (2005); Mfilinge et al. (2005); Silva et al. (2007); Ellis et al. (2006) and Ye et al. (2013). Jennerjahn and Ittekkot (2002) documented the litterfall production and its role as a nutrient source to the adjacent estuary; Sanchez-Carrillo et al. (2009); Bouillon et al. (2008b); Komiyama et al. (2008) and Kristensen et al. (2008). Chen et al. (2009) reported the influence of forest structure on litter dynamics of a monospecific stand of *Sonneratia caseolaris* of China. Ye et al. (2011) and Wang'ondu et al. (2014) studied about the difference in litter production among reforested and restored mangrove plantations. Litterfall production, its turnover rates and factors affecting litterfall were assessed by Coronado-Molina et al. (2012) in mangroves of the Gulf of Mexico. They had almost a decadal data on the litterfall production of these mangroves and reported that riverine mangroves had more litterfall production and significant drivers of litterfall production were geomorphology, latitude, hydrology, soil salinity stress and soil fertility. Edu et al. (2014) studied about carbon credits from litterfall production and litterfall turn over estimates of Nigerian mangroves. Some recent works reported on litterfall dynamics were by Srisunon et al. (2017) and Flores-Cárdenas et al. (2017), on litterfall production of Thailand mangroves and Mexican mangroves, respectively.

Even though the litterfall study is very significant in mangrove ecosystems, there were only limited preliminary reports from India. Singh et al. (1993) studied mangrove biomass, litterfall and litter decomposition in managed and unmanaged mangrove forests of Andaman Islands. A major study on litterfall dynamics, its energy flux, elemental composition and decomposition was studied by Wafar et al. (1997) in Mandovi–Zuari Estuaries, West Coast of India. They studied species-wise litter dynamics of *Rhizophora mucronata*, *R. apiculata*, *A. officinalis* and *S. alba*. Mukherjee and Ray (2012) and Mukherjee et al. (2012) studied in detail about the carbon cycling in mangroves through the litter biomass estimation and related carbon fractionation and formulated a model of carbon cycling from mangroves to the near Hooghly estuary. Whereas the nitrogen aspect of Sundarban mangrove litter and its influence to the adjacent estuary was studied in detail with conceptualized models was reported by Mandal et al. (2009) and Mandal et al. (2012). The relation of litterfall with environmental parameters was studied by Ghosh and Banerjee (2013) in Sundarban mangroves and found out that salinity and wind action were the major influencing factor on litterfall production. On a regional scale, no published data is available on litterfall studies. In this background, the litterfall production and factors influencing its production, phenology and the NPP pathway from the Cochin mangroves, on the south-west coast of India is discussed in this chapter.

4.3 Materials and Methods

Estimation of litterfall in mangrove ecosystems was conducted for one year (2013 January to 2013 December in St.1 & St.2, August 2013 to July 2014 in St.3) based on standard methods (Heald, 1971; Snedaker and Snedaker, 1984) in three selected mangrove habitats in Cochin (St.1, St.2 and St.3, as described in Chapter 2.3.1). Litter was trapped using conical nylon litter traps

(1 m^2 surface area, 1 mm mesh, Plate 4.1), balanced above the maximum tide at the height of 1m above the ground. Five litter traps were installed in each site in proportion to the area of mangroves. Litter was collected from each location on a monthly basis (in monsoon season twice in a month) and sorted into different components like leaves, flowers, seeds and twigs. Sorted litter was dried into constant weight (70 °C for 48 h) in a hot air oven and weighed. Litter production was estimated as dry weight. The dried samples were powdered and sieved for total carbon analysis using Analytikjena TOC analyser HT 1300 solid module, and this data was converted to NPP (Castañeda-Moya et al., 2013;Twilley et al., 1992) by multiplying the litter production value with mean total carbon concentration (%) from different litter components.

Plate 4.1 Trap deployed in Mangalavanm mangrove station for collection of litterfall

The productivity through litterfall was termed as NPP_L. The satellite data was used as the source of temperature (ERA-interim data), and for rainfall, TRMM (Tropical rainfall measuring mission) data was used. The salinity was measured using Mohr-Knudsen method as described in Chapter 2.3. All the parameters were statistically analysed using the package SPSS v16.0. ANOVA and Tukey HSD test for all parameters was done, and correlation was done for environmental parameters.

4.4 Results

4.4.1 Litterfall production and dynamics

The estimated mean annual production of litterfall in Cochin mangroves was 16.57 ± 6.58 t $ha^{-1}y^{-1}$ in which the major contribution was by leaves (53.90 %) followed by flowers + propagules (28.66 %) and twigs (17.44 %) (Fig.4.1). The average monthly litterfall (Fig.4.2) was high in April month (198.04 ± 24.37 g Dw m^{-2} $month^{-1}$) and lowest during September (83.61 ± 3.28 g Dw m^{-2} $month^{-1}$).

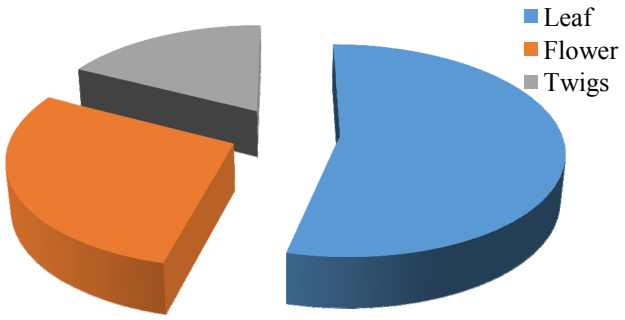

Figure 4.1 Percentage composition of mangrove litter components in the Cochin mangroves during 2013-2014 period

The total litter production was two-fold higher in St.1(2413.36 ± 873.7 g DW m^{-2} y^{-1}) compared to St.2 (1295.65±401.1 g DWm^{-2} y^{-1}) and St.3 (1263.28 ± 255.3 g DWm^{-2} y^{-1}).

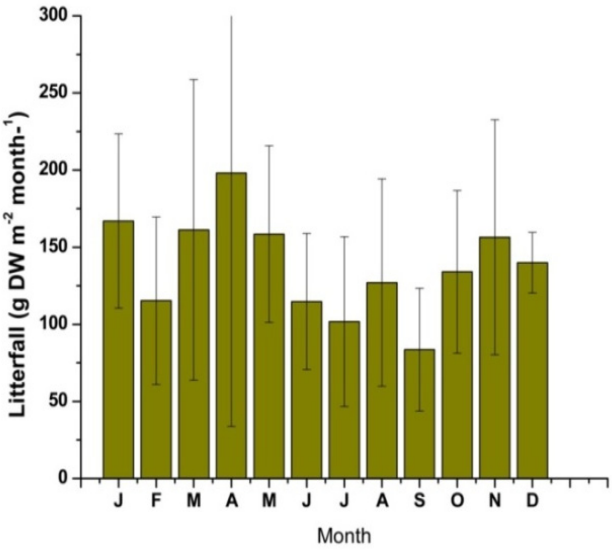

Figure 4.2 Monthly average of mangrove litter production in the Cochin mangroves during 2013-2014 period

Spatial differences in litter production were statistically significant between three mangrove habitats (p <0.001, followed by Tukey HSD, Table 4.1). The interaction between sites with litter components also showed significant (Tukey HSD p <0.05) variation (Fig.4.3). In St.1, leaf component was having high production (1122.68 g DWm^{-2} y^{-1}) followed by flowers + propagules (785.85 g DWm^{-2} y^{-1}) and twigs (504.83 g DWm^{-2} y^{-1}). St.2 was having leaf production of 783.58 g DWm^{-2} y^{-1} and very low flowers + propagules production (352.63 g DWm^{-2} y^{-1}) and twigs production (159.44 g DWm^{-2} y^{-1}). Leaf production and reproductive parts production in St.3 was comparable with St.2 (773.59 g DWm^{-2} y^{-1} and 286.68 g DWm^{-2} y^{-1}), and twigs production was high (203.01 g DWm^{-2} y^{-1}) in St.3 than St.2. It depicts the spatial variation in mangrove phenology within the common estuarine habitat. Leaves contribute a major part of the total litterfall in all the stations followed by reproductive parts and twigs.

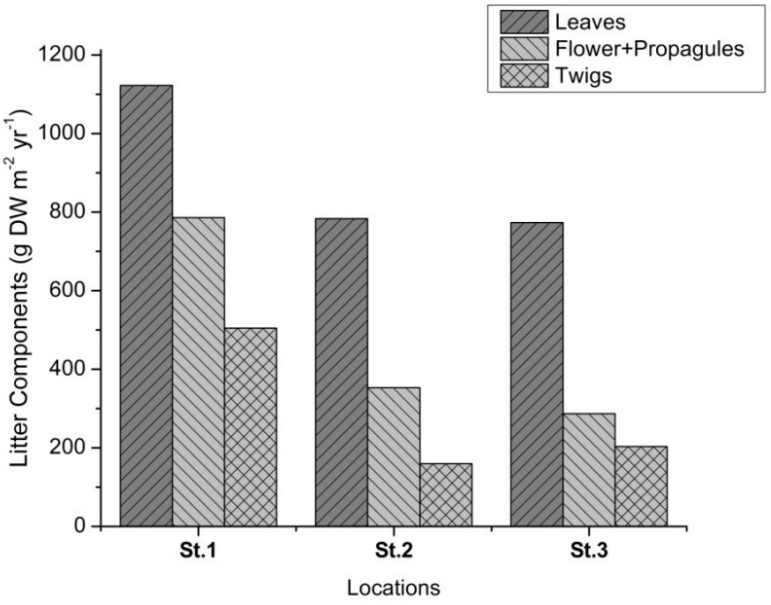

Figure 4.3 Spatial variation in total production of litter components in the Cochin mangroves during 2013-2014 period

Significant temporal variation was observed for total litterfall($p \leq 0.001$) and interaction of station and season with litterfall. In the study area, highest average litterfall was observed in premonsoon period (February–May, 158.27 g DWm^{-2} $month^{-1}$) and least in monsoon season(June–September, 106.78 g DWm^{-2} $month^{-1}$). The total litter production during postmonsoon period was 149.33g DWm^{-2} month¯1. The litter components also showed high seasonality (Fig.4.4). Even though total litterfall production was high in the pre-monsoon period, leaf production was high in the post-monsoon period (103.48 ± 20.4 g DWm^{-2} $month^{-1}$). Flowers + propagules were high during the pre-monsoon season (65.73 ± 34.34 g DWm^{-2} $month^{-1}$), and twigs fall was high during monsoon season (26.66 ± 4.05 g DWm^{-2} $month^{-1}$).

Table 4.1 ANOVA results of litterfall dynamics of Cochin mangroves during 2013-2014 period

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	3994.003[a]	134	29.806	5.876	.000
Intercept	18813.157	1	18813.157	3.709E3	.000
Station	654.750	2	327.375	64.542	.000
Season	68.327	2	34.164	6.735	.001
Components	1504.415	2	752.207	148.298	.000
Station * season	199.758	4	49.939	9.846	.000
Station * components	61.918	4	15.479	3.052	.017
Season * components	625.319	4	156.330	30.821	.000
Error	2054.265	405	5.072		
Total	24861.425	540			
Corrected Total	6048.268	539			

a. R Squared = .660 (Adjusted R Squared = .548)

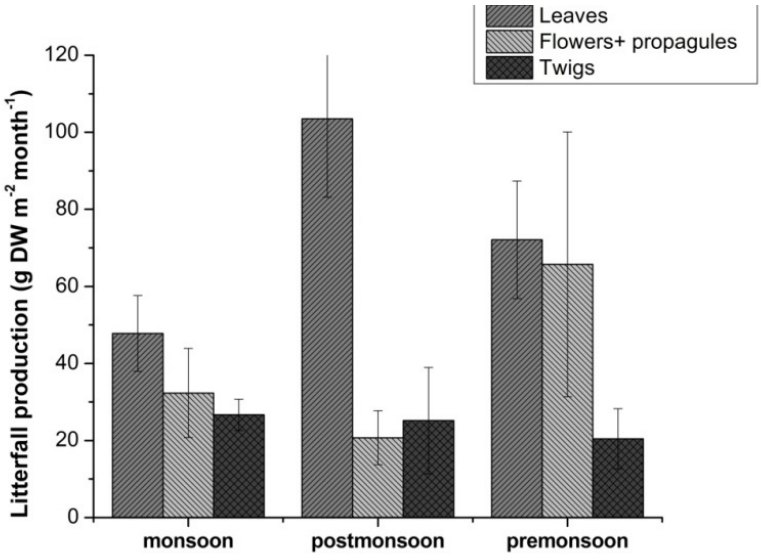

Figure 4.4 Temporal variation in average production of mangrove litter components of Cochin mangroves during 2013-2014 period

The average leaf fall during monsoon season was 47.78± 9.83 g DWm^{-2} $month^{-1}$, and flowers+propagules fall was 32.34 ± 11.57 g DWm^{-2} $month^{-1}$while during the post-monsoon season it was 20.7 ± 7.0 g DWm^{-2} $month^{-1}$. The average leaf fall in the pre-monsoon season was 72.07 ± 15.27 g DWm^{-2} $month^{-1}$ and twig fall production was20.47 ± 7.8 g DWm^{-2} $month^{-1}$.

4.4.2 Environmental Factors

The rainfall data showed that peak monsoon rainfall was recorded during June 2013 (685.74 mm) and the lowest was recorded during February 2014 and January 2013 months (4.98 mm, 6.06 mm) (Fig.4.5 a-b). The atmospheric temperature and rainfall data showed slight variation in relationship with litterfall production. Therefore both these parameters were shown in different graphs for stations. However, litterfall production with salinity showed a uniform relation in all stations and depicted in one figure.

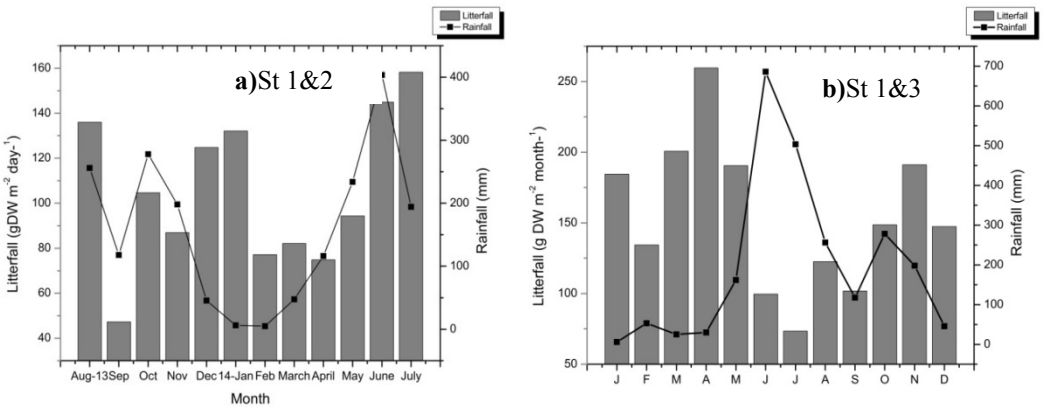

Figure 4.5 a-b Litterfall production of Cochin mangroves with monthly rainfall during 2013-2014 period

The atmospheric temperature data ssuggested that the lowest temperature was during monsoon season (24.37 ^{o}C; August 2013), and the highest temperature was during the pre-monsoon season (27.21^{o}C, May 2014) (Fig.4.6a-b). The average salinity of the three stations was also high during the

pre-monsoon period (24.37 ± 6.30 ppt), and low salinity was recorded during monsoon season (1.6 ± 1.97 ppt) (Fig.4.7).

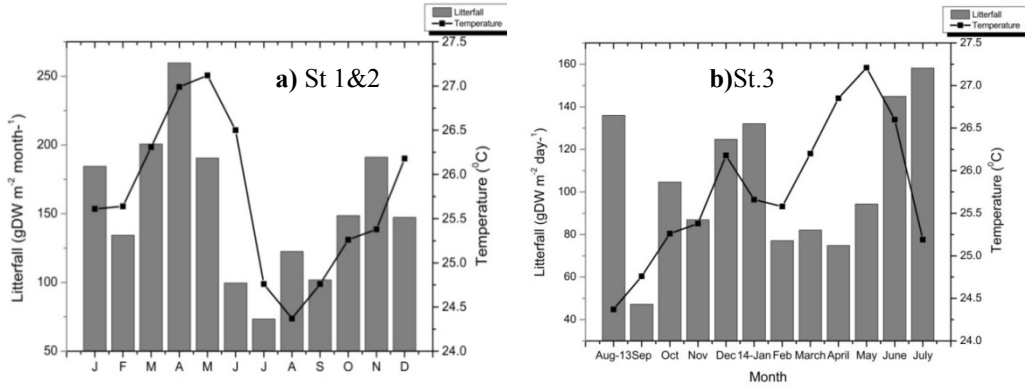

Figure 4.6 a-b Litterfall production of Cochin mangroves with monthly atmospheric temperature during 2013-2014 period

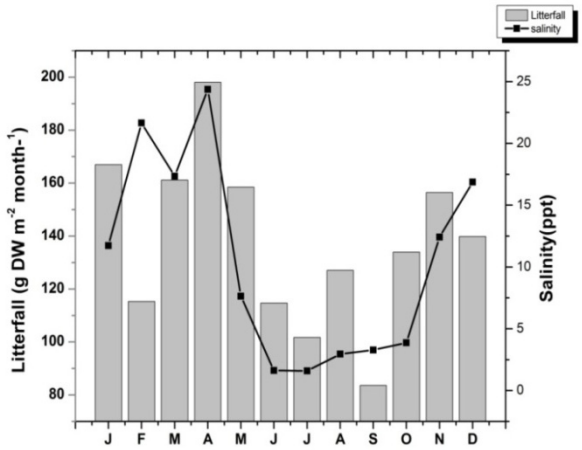

Figure 4.7 Litterfallproductionof Cochin mangroves with monthly salinity during 2013-2014 period

4.4.3 Litter carbon and Primary productivity

The total carbon concentration in litterfall revealed that average carbon concentration was high in twigs (442.3 ± 15.3 g kg^{-1}) followed by leaves (428.6 ± 12.3 g kg^{-1}) and flowers + propagules (417.8 ± 13.4 g kg^{-1}). Slight spatial variation was recorded for carbon content in different litter components and

St.3 was having a comparatively high carbon content in litter compared to the other two stations (Fig.4.8). Leaves, flowers and propagules showed seasonality but twigs having comparatively constant carbon content (Fig.4.9). The carbon content of leaf litterfall was high during monsoon season (447.4 ± 15.25 g kg^{-1}) and decreased during premonsoon (427.4 ± 0.14 g kg^{-1}), and lowest was recorded during postmonsoon (406.02 ± 40.38 g kg^{-1}). In the case of twigs, almost 44% was carbon content (444.8,423.4, 446.83 g kg^{-1} during POM, PRE and MON respectively).

Carbon concentration in flowers +propagules also showed the same trend like leaf litterfall and highest was during monsoon (436.73± 31.05 g kg^{-1}) followed by premonsoon (419.25 ± 1.48 g kg^{-1}) and lowest during postmonsoon (378.27 ± 2.60 g kg^{-1}) season

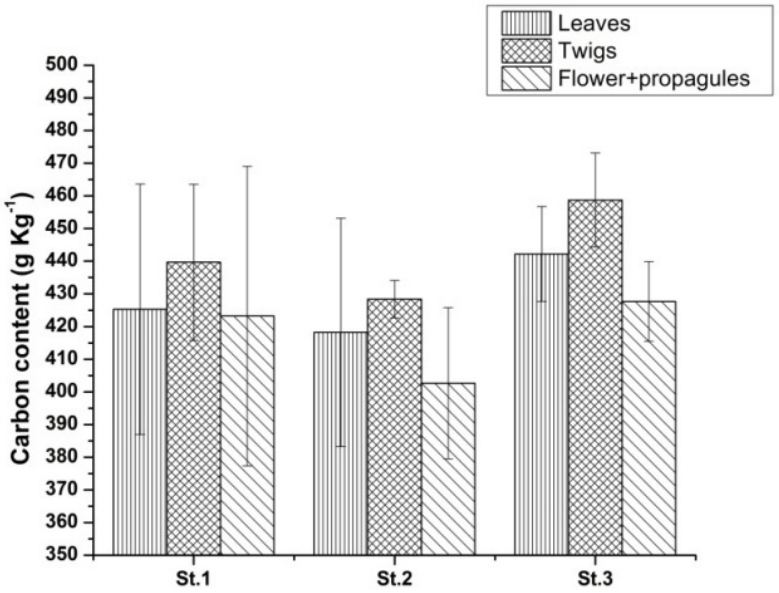

Figure 4.8 Spatial variation of mean carbon content in mangrove litter components of Cochin mangroves during 2013-2014 period

From the carbon analysis, the mean carbon content in the litterfall was estimated as 42.96% of the dry weight, and the primary productivity through litterfall (NPP_L) for Cochin mangroves was estimated to be 7.12 ± 2.81 t C $ha^{-1}y^{-1}$. In St.1 the NPP_L was very high, 10.36 t C $ha^{-1}y^{-1}$ and in other stations, the net primary productivity through litterfall was estimated to be 5.57 t C $ha^{-1}y^{-1}$ in St.2 and 5.42 t C $ha^{-1}y^{-1}$ in St.3.

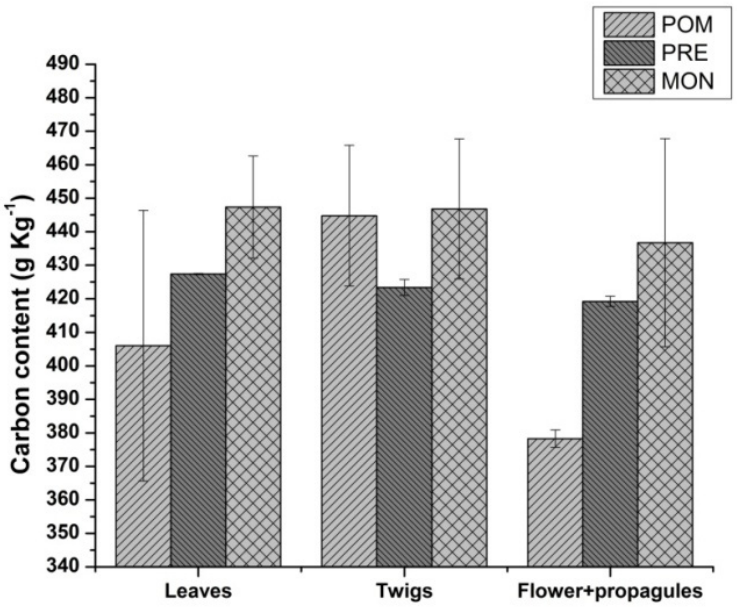

Figure4.9 Seasonal variation of mean carbon content in mangrove litter components of Cochin mangroves during 2013-2014 period

4.5 Discussion

4.5.1 Litterfall Production

The annual litterfall was high in the study area and was comparable with riverine type and lower latitudinal mangrove forests of the world. On a global scale, litter production varied between 1.30 and 20.3 t $ha^{-1}y^{-1}$. Usually, lower latitudinal tropical mangroves exhibited higher litter production than higher latitudinal regions (Saenger and Snedaker, 1993; Komiyama et al., 2008;

Bernini and Rezende, 2010). The highest litterfall was reported in Brazilian mangroves, 00°52′S (Mehlig, 2001) and lowest in 26° latitude in USA (Teas, 1979). Exceptionally higher litterfall rate was reported (Alongi et al., 2005) in Australian mangroves (34.4 t ha^{-1} y^{-1}) even though it falls in higher latitude (21°).

Litter production reported from the current study was compared with other tropical and subtropical mangrove forests (Table 4.2). The pantropical trend for the litterfall according to latitude, was seen from the literature. This high litterfall production in the lower latitudinal tropical areas may be the reason for high carbon sequestration from these areas (Duke et al., 1981; Leach and Burgin, 1985; Clough et al., 2000). Mangrove litter production is closely related to mangrove type, which is higher in riverine forests (Pool et al., 1975; Lugo and Snedaker, 1974). The highest litterfall production was reported from St.1, which is a riverine type mangrove that fit in the range observed for this physiographic type. The other stations also received considerable river discharge and are not fringing to marine coastal areas.

The significant spatial variation in litter production was observed during the study. The mixed mangrove nature in the first site might be one of the reasons for higher litterfall production compared to the other two sites. The high relative density of *A.officinalis* (36.3), *R.mucronata* (16.0) and *S. caseolaris* (14.1) gave larger propagules and fruits compared to other species, also contributed to higher litter production in St.1 whereas in St. 2, it was dominated by *E. agallocha* which is having small sized flowers and seeds. Thus the variation in species diversity and biomass in each site also affected the total litter production. The nutrient inputs, geomorphology and soil texture, may also influence on mangrove litter phenology even within a small area (Coronado-Molina et al., 2012).

Table 4.2 Latitudinal trend of litter production (t ha^{-1} yr^{-1}) in different parts of the world

Location	Latitude	Forest	Litter production	Reference
Acarajó e Furo do Meio, Bragança, Pará, Brazil	00º52'S	*A. germinans, L. racemosa*&*R. mangle*	20.3	Mehlig, 2001
Guayas estuary, Ecuador	$2^0$25'S	*Rhizophoraharrisonii*	10.64	Twilley et al., 1997
Gazi BAY, Kenya	4°25'S	Mixed mangrove	4.3	Kihia et al.,2010
Gazi BAY, Kenya	*4°25'S*	*Rhizophora*and *Sonneratia*stands	6.61–10.15 8.36–11.02	Wang'ondu et al.,2014
Malaysia	5^0	Mixed mangrove	10.07	Ong et al.,1981
Srilanka	8.15^0N	*Rhizophora+Avicennia*	5.52	Amarasinghe and Balasubramaniam, 1992
Vietnam	$8^0$50'N	*Rhizophoraapiculata*	9.41-18.79	Clough et al.,2000
Papua New Guinea	9.5	*Rhizophora*	14.30	Leach and Burgin 1985
Kerala, India	**9-10^0N**	**Mixed mangrove**	**16.57**	**The present study**
Australia	18	*Bruguiera*	10.00	Duke et al.,1981
China	20	*Bruguiera*	18.70	Peng and Lu 1990
Estuary of the Paraíba do Sul River, Rio de Janeiro, Brazil	21º36'S	*A. germinans* *L. racemosa* *R. mangle*	12.5 12.3 14.6	Bernini et al.,2010
Hong Kong	22.2	*Kandeliaobovata*	12.08	Lee.,1989
Jiulongjiang estuary, China	24^0N	*Kandeliaobovata*	12.49	Ye et al.,2013
USA	26	*Avicennia*	4.69	Twilley, 1982
Gulf of California, Mexico	27^0N	*Mixed mangrove*	1.75	Arreola-Lizárraga et al.,2004
Australia	38^0	*Avicennia*	2	Clough and Attiwill, 1982

4.5.2 Environmental factors

The phenology in litterfall could be explained through various abiotic environmental factors. The rainfall played a major role in litterfall dynamics and was found to be significantly (p <0.05) negatively correlated (r = −0.999) to litterfall. The effect of rainfall on litterfall is shown in Fig. 4.5a-b in three stations and the effect is slightly different in Site 3 since the study period was different. The temperature played a significant role in defining litterfall production and was positively correlated (r = 0.614, p < 0.05). The peak litterfall was observed in the dry season with high temperature which might be due to the response to water stress (Fig.4.6 a-b). The low rainfall or high evaporation leads to higher salinities, transpiration becomes metabolically too expensive, and thinning of the canopy becomes necessary (Wafar et al., 1997). This stressed condition followed by little rainfall in the last phase of pre-monsoon season resulted in mass shedding of leaves, twigs and reproductive parts.

The seasonality of litterfall showed different patterns globally. However, several authors (Pool et al., 1975; Leach and Burgin, 1985; Woodroffe et al., 1988; Lee, 1989) relate maximum litterfall to wet, rainy season probably due to higher nutrient supply with freshwater enhancing litter production. Few works also suggest that incident radiation (Steinke and Ward, 1988) and wind run (Sasekumar and Loi, 1983) have effected the litterfall rate. Rainfall affects positively on litterfall in mangroves of arid regions. The maximum litterfall rate was observed in rainy seasons in various areas (Twilley et al., 1986; Arreola-Lizárraga et al., 2004; Sánchez-Andrés et al., 2010). However, in humid and sub-humid regions, the dry season was having peak litterfall (Flores-Verdugo et al., 1992), which is due to moisture stress, and it is comparable with the current study. The results of the present study indicate the

effect of regional monsoonal climate on litterfall. Among different abiotic factors that affect litterfall rate, salinity, which varies according to evapotranspiration, was a major factor compared to temperature and rainfall. The litterfall rate increases with increase in salinity (Fig.4.7) and decreases with decreasing salinity which was statistically significant ($r = 0.628$, $p < 0.05$), exhibiting similartrend to that for other tropical mangroves (Ghosh and Banerjee, 2013; Wafar et al., 1997). The increase in air temperature increases evapotranspiration, that increases salinity, causing a stressed condition, which leads to litterfall.

4.5.3 Primary Productivity

The primary productivity through litterfall was very high in the study area. It acts as the primary source of carbon that will bury in the soil leading to long term carbon sequestration and also serves as a nutrient source for adjacent coastal habitats. The global average of litterfall rates is in the range of ~38 mol C m^{-2} y^{-1} (Twilley et al., 1992; Jennerjahn and Ittekkot, 2002). Lugo and Snedaker, 1974 reported 2.24 t dry wt C ha^{-1} y^{-1} from litterfall contributing to ecosystem productivity which is very low compared to the present study estimates (7.12 t C ha^{-1} y^{-1}). Since the total litterfall was higher in the study area, the contribution of litterfall to ecosystem productivity as carbon was also higher. The productivity data through litterfall indicates the potentiality of these habitats for carbon sequestration, which is little understood from the West coast of India. Litterfall plays a crucial role in maintaining the stability of the ecosystem, which behaves as a repository of carbon nourishing organic matter for nearshore food web processes. The carbon export is mainly in the form of POC (particulate organic carbon), which is ultimately derived from litterfall through crab faeces along with the mechanical breakdown of leaves by crabs and tidal action. Litter from trees and subsurface root growth provide

significant inputs of organic carbon to mangrove sediments, which results in long term carbon sequestration, thus acting as a sink of carbon. Significantly higher concentrations of POC and SOC (soil organic carbon) were reported in seasons when litterfall is higher (Mukherje and Ray, 2012; Rajkaran et al., 2007), which indicates the crucial role of litterfall in carbon budgeting. Higher litterfall reflects higher carbon sequestration capacity, and lower litterfall, in turn, causes less carbon storage.

The results of this study and other reports confirmed the role of species biomass, environmental and geographical conditions that play a significant role in determining the litterfall production rate. Most of the reported studies on litterfall production were in monospecific mangrove stands. Even the studies on a few mixed mangrove stands reported less litter production; however, the present study proved there could be higher litter production even for mixed mangrove stands, and environmental conditions determine its production rate. The potentiality for carbon sequestration of Cochin mangroves in terms of litterfall could be understood from the study. However, the ultimate fate of litterfall actually determines whether the mangrove ecosystem act as source or sink. Recently anthropogenic activities have alarmingly lead to the decline of mangrove area resulting in the imbalance of litterfall and possibly affecting the POC and SOC speciation of carbon. This will invariably affect the carbon sequestration potential of the mangrove habitats whereby having negative effects on climate change related problems. Proper management and conservation measures are needed to protect these ecosystems for balancing the carbon budget and in turn, for mitigating climate change.

Thus from the preset study,highlitterfall production was observed in Cochin mangroves and the rate was comparable with lower latitudinal mangrove regions with similar climatic conditions. Significant spatial and

temporal variation could be seen for total litterfall and litter components. The seasonality of litterfall production could be explained through atmospheric temperature, rainfall and salinity. This environmental relation was comparable with other litterfall studies in tropical regions whereas it is reverse in arid regions. Thus the study again confirms the influence of climatic conditions in regional litterfall production. The typical monsoonal climate, prevailed in the study area controls the total litter production. This litterfall production and its seasonality in mangrove forest could be used as an important tool to understand ecosystem processes and biogeochemical cycles in future studies. This study has contributed to our knowledge on litterfall and productivity estimates to global litter production and blue carbon budgets. It would further augment carbon export and carbon sequestration studies in mangrove ecosystems and adjacent coastal wetlands.

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Chapter 5

SESARMID CRABS AND CARBON SEQUESTRATION POTENTIAL

5.1 Introduction

Crabs are essential parts of mangrove ecosystems playing an important role in the cycling of nutrients and therefore considered as keystone species of mangrove ecosystem (Smith et al., 1991). Their burrowing activity and leaf consumption help in nutrient retention and overall nutrient cycling in the mangrove ecosystem. Brachyuran crabs, primarily fiddler crabs (family Ocypodidae) and leaf-eating sesarmid crabs (family Grapsidae), dominate the mangrove fauna in number and biomass (Tan and Ng, 1994; Kristensen, 2008). They account for over 80% of the species diversity (Tan and Ng, 1994). In almost all the mangrove habitats raound the world, Sesarmidae and Ocypodidae process, retain, macerate and ingest large amounts of litter and micro- algal mats, contributing consistently to the retention of mangrove organic matter and, acts as ecosystem engineers (Kristensen, 2008). Most of the crab species belonging to these two families actively dig and construct burrows as a refuge from predation and to escape from environmental extremes, as well as for reproductive purposes. Burrowing activities will help in modifying particle size distribution, affecting the topography, improving aeration, reducing pore water salinity, providing microhabitats for other fauna

and contributing to secondary production, thus affecting the nutrient release and increasing mangrove productivity. By consuming leaf litter, mangrove crabs substantially reduce export, shorten decomposition time and enhance nutrient cycling (Robertson, 1986; Robertson and Daniel, 1989; Lee, 1989; Ashton,2002).

In mangroves, Grapsoid crabs are the most abundant brachyuran crabs (Jones, 1984). The members of Sesarmidae (Ng et al., 2008) are the major family represented by mangrove grapsoids. Indo-Pacific region is the most diverse region (Lee, 1998) for grapsoids with 51 species (44 sesarmid species) recorded in Singapore-Malaysia (Tan and Ng, 1994) and 61 species (48 sesarmid species) in Australia (Davie, 2002). Sesarmidae is mostly seen in mangrove habitats typically having a squarish carapace. They are often good climbers, with the tip of their legs pointed and hook-like, allowing them to climb up trees or mud soil easily. They are the initial processors of mangrove leaf litter or primary production, and thus have an essential role in the cycling of organic matter in the mangroves. Even though there was a variation in the percentage of leaf litter removal by sesarmid crabs in different parts of the world, almost all studies showed very high removal rate (Thongtham and Kristensen, 2005) and retain a significant amount of autochthonous primary production in the mangroves (Cannicci et al., 2008; Lee, 1998) thereby helps in long term carbon sequestration or sediment burial within the mangrove ecosystem. Aged leaves are consumed by crabs than fresh leaves. This preference for aged leaves is also related to leaf availability on the ground. Leaf choice or feeding preference of sesarmid crabs is also controlled by the C/N ratio and tannin content.

Crab litter processing will produce faecal material and a substantial amount of leaf litter detritus, therefore, becomes available to decomposers and

detritus feeders in the form of crab faecal material thereby having an important trophic role in the mangrove and nearshore food web. The gut passage of litter inside the crab will increase microbial biomass and thereby increases nitrogen content. This microbial enrichment will improve nutritive values and smaller fragment sizes than mangrove litter help in easy intake as food by nearshore consumers (Lee, 1997; Werry and Lee, 2005). There were reports that grapsoid crabs itself act like food to fishes (Sasekumar et al., 1984; Leh et al., 2012; Sheaves and Molony,2000). The faecal material and dead crab biomass may be colonised by the decomposing microbial community and may enrich the sediment with organic matter and thereby increasing the carbon storage or burial of the mangrove ecosystem.

The crab burrows in the mangrove environment have a direct connection influencing the biogeochemistry of that ecosystem. It promotes the movement of water and air deep into the sediment (Ridd, 1996; Stieglitz et al., 2000). It can change the oxidation status of the surrounding sediment and thereby influencing on sulfur and iron reduction processes in anaerobic oxidation of organic carbon (Kristensen, 2008). This process may help in the export of salt from mangrove sediments and decreases salinity stress to mangrove plants. These changes in sediment biogeochemistry due to the crab bioturbation activity will positively influence mangrove forest productivity. Smith et al. (1991) found out there was an increase in soil sulphide and ammonium concentrations and decrease in the productivity and reproductive output of the forests when the sesarmid crabs from *Rhizophora* forests in north Queensland, Australia was removed, and he reported sesarmid crabs as 'keystone species' of the ecosystem while in another study by Kristensen (2008) regarded it as 'ecosystem engineers' of mangrove ecosystems.

Another interesting service of mangrove crabs is its role in biogeochemistry of sediment. Crab foraging helps in the more efficient transfer of organic matter from mangrove litter to sediments. Nerot et al. (2009) reported that there was an increase in the amount of long-chain fatty acids and the C/N ratio and decrease in the $\delta^{13}C$ values of surface sediments while introducing the sesarmid crab *Parasesarma erythodactyla* in mesocosms containing senescent *Avicennia marina* leaves. High C/N ratio, organic carbon and total nutrient content in surface mangrove sediments was recorded while allowing foraging on *Kandelia obovata* leaves by *Parasesarma plicatum* (Chen and Ye, 2010). It could also be observed that crab's faecal matter was rich in 70x higher microbial density than the whole leaf litter (Werry and Lee, 2005). Similarly, 55x faster microbial decomposition was observed in faecal materials of *Neoepisesarma versicolor* fed with green *Rhizophora apiculata* leaves compared to unprocessed leaf litter (Kristensen and Pilgaard, 2001).

5.2 Literature Review

The ecological role of grapsids in mangroves was first reported by the early observations of Macnae (1968). Ingestion of mangrove detritus by the crabs was first documented by Malley (1978) and found out the presence of considerable amounts of mangrove detrital materials in the stomach of the sesarmid crabs. Later Robertson, 1986; Poovachiranon and Tantichodok, 1991 and Olafsson et al., 2002 confirmed this observation with field study and laboratory experiments was conducted by Giddins et al.,1986; Camilleri, 1989; Lee, 1989 and Micheli, 1993. Among these works, the major and milestone work in the role of crabs in litter removal was by Robertson (1986). He was the man who first time conducted a field study in a mangrove forest of tropical north-eastern Australia in grapsid crabs (*Sesarma messa*) and found out that these organisms removed 28% of mangrove (*Rhizophora* spp.) leaf litter. After

this decisive work of Robertson (1986), numerous researches have been conducted on the role played by grapsid crabs in mangrove ecosystem structure and function. The litter removal rate, according to Lee (1989), was high (57%) compared to Robertson (1986), and he conducted a laboratory experiment in *Perisesarma bidens* using *Kandelia obovata* mangrove leaves. Emmerson and McGwynne (1992) found out that around 44 % of litter was removed by *Neosarmatium africanum* in Mgazana estuary, South Africa. However, a large litter removal rate (67%) was reported for the same crab species in a field study in East African mangroves by Olafsson et al. (2002). In Malaysian mangroves, Ashton (2002) studied especially *Avicennia officinalis* and *Bruguiera gymnorrhiza* leaf removal rate for *Perisesarma eumolpe* crab species and *B. parviflora* and *R. apiculata* leaf removal rate for *Perisesarma onychophorum* crab species and found out that these crabs removed 42-54 % litter. Later Thongtham and Kristensen (2005) conducted an experimental study on *Neoepisesarma versicolor* crab species for the litter removal rate of *Rhizophora apiculata* mangrove litter and found out a very high litter removal rate (87%) by the crabs. They conducted an extensive experimental study on ingestion, and egestion assay and estimated assimilation efficiency for the crab species feeding by different stages of mangrove litter and they also found out the carbon and nitrogen balancing by this crab species through the litter consumption. Robertson et al. (1992) found out that the litter removal rate may depend on mangrove forest type, and Lee (1990) suggested that it may be depending on the tidal position.

Crab secondary production and their faecal materials were having a significant contribution to the mangrove food web and also in nutrient cycling together with litter removal. Lee (1997) emphasised the potential trophic importance of crab faeces in the mangrove ecosystem. The study reported

significantly lower C/N ratio, and tannin concentration in the faecal material of *Perisesarma messa* fed *Rhizophora stylosa* leaf litter than the leaf litter itself. Another study which was based on field and experimental study by Nordhaus and Wolff (2007) on *Ucides cordatus* (Ocypodidae) was an interesting study based on the field gut content analysis of the crabs and found high percentage composition of mangrove-derived plant material in its gut. The study revealed that for *Ucides cordatus* tannin content was not a problem for leaf choice and C/N ratio was the significant factor for its leaf preference. Another interesting observation was the leaf ageing hypothesis (according to which crabs allowed leaves to age in burrows to gain a more palatable and nutritive food) was rejected for *U. cordatus*. They did not find any significant difference in C/N ratio and microbial content between senescent leaves and leaves from crab burrows. They also estimated that a large amount of (7.1-ton dry matter ha^{-1} $year^{-1}$ in a *R. mangle* forest) faecal matter was produced which is enriched in C, N and bacterial biomass compared to the sediment by the crab stock. Thus crab stock in a mangrove ecosystem significantly affects the carbon and nitrogen stock in the sediments of that ecosystem.

Chen and Ye (2008) reported the feeding ecology of crab species, *Sesarma plicata* based on the field (Jiulongjiang Estuary, China) and experimental studies. *Kandelia candel* dominated the mangrove forest, and they used mature, senescent and decomposed leaves of *Bruguiera gymnorrhiza, Kandelia candel* and *Aegiceras corniculatum* for the leaf choice experiment and revealed that leaf choice was differed according to mangrove species and state. The study reported that tannin content, crude fibres, C/N ratio and high water content in decomposed leaves determines the leaf preference by the crabs. They estimated leaf litter removal rate of 1.33 g DW m^{-2} d^{-1} by the sesarmid crab during neap tide. The feeding choice of

Perisesarma bidens was estimated by Mchenga and Tsuchiya (2010) by including algae, mangrove leaf and propagule to the diet. They compared C/ N ratio and fatty acid profiles for leaf choice and also calculated assimilation efficiency and the fate of the organic materials. For male crabs, algae were the preferred food. However, for females, there was no significant difference between mangrove leaf and algae consumption and the crabs had less preferred to mangrove propagules.

At regional level, only a few studies were reported by Ravichandran et al. (2006) on leaf litter processing, and leaf choice by sesarmid crabs in Pichavaram mangrove forest, and Praveen (2014) studied about mangrove crab biodiversity and its role in mangrove seedling predation and forest structure. Shanij et al. (2016) reported leaf litter removal by *Neosarmatium malabaricum* in an *ex- situ* experiment simulating field conditions. They found out the translocation rate of mangrove litter by these crabs.

Since there have been no studies reported from Kerala on litterfall, however with very few reports on crab's role in litter processing (Praveen, 2014; Shanij et al., 2016) the present study will be the pioneering attempt from Kerala to understand the role of mangrove crabs in litter processing and carbon assimilation in mangrove ecosystems of Cochin coast. In the present scenario, increasing pollution level due to anthropogenic activities has detrimentally affected the mangrove habitat, tending to global warming and depletion of global carbon sink which would eventually lead to the extinction of key stone species like mangrove crabs and other associated flora and fauna. The current scenario emphasis the fact that the taxonomic study on mangrove crabs and its role in carbon dynamics need immense development and the gap areas in the mangrove crab taxonomy has to be filled to create a wider platform for the study. Therefore, an attempt was also made in the present study for resolving

the taxonomic ambiguity and misidentification among mangrove crabs together with its role in litter processing.

5.3 Materials and Methods

5.3.1 Taxonomic identification of crabs

Individuals of different species of crabs were collected during day time when they emerged from their burrows during feeding, from the three stations (St.1, St.2 and St.3 as described in Chapter 2.3). The morpho-taxonomic identification of the crab samples was made up to the species level based on standard references (Chhapgar, 1957; Sethuramalingam and Ajmal Khan,1991; Ng et al., 2008; Ajmal Khan and Ravichandran, 2009). The crab samples were preserved in 90 % ethanol for molecular analysis.

Total genomic DNA extraction from the tissue of individual specimens was done using the DNeasy Blood and Tissue Kit (Qiagen) following the spin column protocol for purification of total DNA from animal tissue. The elution volume ranged between 100 and 200 µL in AE buffer. The isolates were stored at -20 °C for further analysis. PCR amplifications were performed in 25 µL reaction volumes using a gradient thermal cycler (Bio-Rad, Hercules, CA, Model Number 621BR07085). The primer pair LCO-1490 (Forward) (5′-GGTCAACAAATCATAAAGATAT TGG-3′) and HCO-2198 (Reverse) (5′-TAAACTTCAGGGTGACCAAAAAATCA-3′) was used for amplifying partial mitochondrial COI gene sequences from the selected specimens (Folmer et al., 1994). The PCR kit used was the Takara Clontech Emerald Amp® GT PCR Master Mix (Takara Bio, Otsu, Shiga Prefecture, Japan). The reaction mixture consisted of 12.5 µL PCR Master Mix, one µL LCO1490 (forward) primer, one µL HCO2198 (reverse) primer, 4µL template DNA and 6.5 µL dH_2O. Thermal regime consisted of an introductory denaturation step for for 5

min, at 95°C which was followed by 35 repeats of 94°C for 1 min, a gradient program of 46°C to 50°C as annealing temperature, with an extension period of 1 min at 72°C and final extension was done for 10 minutes at 72°C . Amplicons exhibiting intense bands after Agarose gel electrophoresis (1.2%) products were sent to SciGenom Labs (SciGenom Labs Pvt, Ltd., Kerala, India) for sequencing. Sequences were compiled using BioEdit 7.0.9 (Hall, 1999). The alignment was performed using Clustal X (Thompson et al., 1997). Phylogenetic analysis with Neighbor-Joining (NJ) tree and intraspecific pairwise sequence distance were calculated using the Kimura-2 parameter model in MEGA 5 (Tamura et al., 2011). Bootstrap analysis was conducted using 1000 pseudo replications, and aligned sequences were submitted to the National Center for Biotechnology Information (NCBI).

5.3.2 Crab Density

Crab density was computed from five equidistant 1 m^2 quadrats laid in three stations with a total of 15 quadrats. As the crab density measurement was done by long term evaluation at definite intervals, a nonintrusive 'time based visual count method' was preferred rather than traditional intrusive methods like 'pitfall trapping' and 'time-based capture' according to Ashton (1999) and Ashton et al. (2003). The advantage of this technique was the minimum ecosystem disturbance. It involved 15 minutes crab count in each quadrat by keeping a distance of 1 m away from crab vicinity since crabs are sensitive to disturbance. The adults and juveniles were counted separately. No regular sampling was done for density measurement. Only three post-monsoon (November, December, January) sampling (usually this season shows maximum crab density in mangrove habitats) was done in the study area during 2014, 2016 and 2017.

5.3.3 Feeding Ecology

Feeding ecology of the selected crab species was studied through gut content analysis (Ravichandran et al., 2006; Williams, 1981) and leaf choice experiment by ingestion-egestion assay (Thongtham et al., 2005). Gut content analysis was performed for ten individuals of each crab species randomly collected from the mangrove study area during 2015-2016 period (St.1 and St.3). Entire contents from the stomach and rectum was removed and stirred with distilled water at 1:2 volumes in a petri-dish. The contribution of each dietary item from the total diet was expressed in terms of percentage of the visual field of the microscopic view occupied by the different categories of food (Poovachiranon and Tantichodok, 1991).

I. Leaf choice experiment

Different species of crabs collected from the field was brought to the laboratory. The experimental set up was adopted for this study was that by Thongtham, and Kristensen's model (2005) with necessary modifications as per the requirements and tropical climatic conditions. Carapace length and width, weight and sex of the species were adequately documented. Acclimatisation of crabs and optimisation of salinity was done prior to the experiment. The experimental set up consisted of aquarium of dimensions 16×16×10cm, the aquaria were slightly tilted, elevating one side about 2 cm, to provide a dry refuge for the crabs (Plate 5.1). The aquarium was filled with sea water (UV filtered) with salinity equivalent to that of the estuary during the collection period. The experimental set up was kept at average room temperature. One crab belonging to each species were added to each aquarium. The crabs were fed with mangrove leaves of *Avicennia officinalis,* which was the abundant species in both the collection sites. The acclimatisation was

carried out for four weeks at salinities 10 and 15 ppt (which was the range of salinity during the crab collection). Sea water was periodically changed, and aquariums were cleaned and properly monitored for any fungal infestation since crabs were highly sensitive to the clogging conditions caused by the accumulation of food and faeces. The crabs were removed if they were found dead and replaced with a new one from the field. The survival rate and mortality rate were assessed. A crab species that best suits to the laboratory conditions was selected for the experiment. Selection of experimental crab was based on acclimatisation, leaf consumption in laboratory and gut content analysis from the field.

Triplicates and one control with one crab in each were established for each leaf category (fresh, yellow and brown leaves of 11 mangrove species collected from the study area) of each mangrove species. Before the experiment, the mangrove leaves were soaked in 35 ppt sea water for 24 hr for leaching of impalatable substances in the leaves like tannin. The crabs were also starved for 24 hr prior to experiment. The selected leaves of each category with similar colour and morphology were divided into two halves along the midrib and labelled. One half was used for the feeding experiment, and the other half was used for determination of dry (D)/fresh (F) weight (D/F) correlation factor. The experiment was started by feeding each crab with a pre-weighed, half portion of the mangrove leaves of the selected category. After 24 hr, all uneaten leaf residue were collected, rinsed carefully with distilled water, dried and weighed. The ingestion rate was calculated as the difference between the estimated initial dry weight calculated from the leached D/F ratios and the measured final dry weight of uneaten leaves and was expressed as g dry weight.

II. Ingestion-Egestion assay

Ingestion and egestion assay were performed based on the procedure of Thongtham and Kristensen, (2005). From the results of leaf preference experiment, green, yellow and brown leaves with maximum ingestion rate were chosen for the ingestion and egestion assay. The fresh leaves of *Avicennia marina* and *Avicennia officinalis,* yellow leaves of *Rhizophora apiculata* and brown leaves of *Avicennia officinalis* were selected. In the literature, *Avicennia marina* species showed more ingestion rate of mangrove leaves, and it is associated with more crab activity (Ravichandran et al., 2006). Therefore, it was selected for the study even though the species were absent in the study area. The leaves were collected from Puthuvypin LNG area and Puthuvypin Fisheries station, Vypin Island. *Rhizophora apiculata* yellow leaves were collected from Aroor and *Avicennia officinalis* green and brown were collected from Mangalavanam Bird Sanctuary. All the leaves were presoaked in 35ppt sea water for 96 h prior to experiment for removing leachates.

Ingestion assay (6 replicates with one control for each leaf type)for a period of 24 hr was carried out as mentioned in the leaf choice experiment, and ingestion rate was calculated. All crabs from the ingestion experiment were kept in the experimental aquaria under the same conditions for another 24 hr to defecate. Faeces left in the dry area of each aquarium were picked manually using forceps, while faeces in the water were collected by passing the water through a pre-combusted (520 °C) and pre-weighed GF/C filters. The dry weight of the collected faeces was measured by drying it in a hot air oven at 60° C for 48 hr. The weighed faecal matter was stored for later elemental carbon analysis. The egestion rate was calculated as the 24 hr accumulated faecal material and expressed in dry weight, g C (gww) $^{-1}$ day ^{1} (gww = the wet weight of the crab in g).Assimilation was calculated as the difference between

ingestion and egestion rates and assimilation efficiency (%) was calculated by dividing assimilation with ingestion rate.

Plate 5.1 Experimental set up with each crab in each aquarium

Plate 5.2 Soaking of mangrove leaves in each category prior to leaf choice experiment

Chemical analysis of dried leaf, faecal material from the various treatments and water sample from the tank were analyzed for carbon and nitrogen. The variants of carbon and nitrogen like Total carbon (TC), Total organic carbon (TOC), Particulate organic carbon (POC), Dissolved organic carbon (DOC), Total inorganic carbon (TIC), Dissolved inorganic carbon (DIC), Total Nitrogen (TN) and Dissolved Nitrogen (DN) are analysed in Analytik Jena 2100 S, TOC analyzer liquid module and HT 1300 solid module at DOECC (Directorate of Environment and Climate Change) lab in

the Department of Marine Biology, Microbiology and Biochemistry, Cochin University of Science and Technology (CUSAT) and CHN analyzer of the model Elementar Vario EL III, of STIC(Sophisticated Test and Instrumentation Centre), CUSATand Kel plus KES 12 LR Digestion unit and Kjeldhal Nitrogen distillation unit (Kjeldahl method, AOAC, 2000). Tannin and lignin-like substances (TALLS) in leaves samples were estimated based on the Folin – Denis Method (APHA, 2005; Nair et al., 1989).

5.4 Results

5.4.1 Taxonomic identification of crabs

Seven species of crabs were identified from the study area, including *Scylla serrata* (Forskål, 1775), *Scylla tranquebarica* (Fabricius, 1798), *Uca (Austruca) annulipes* (H. Milne Edwards, 1837) (Fiddler crab), *Parasesarma plicatum* (Latreille, 1803), *Neosarmatium malabaricum* (Henderson, 1893), *Parasesarma bengalense* (Davie, 2003)(previously *Perisesarma bengalense*, genus changed to *Parasesarma*) and a new species *Pseudosesarma glabrum* (Ng, Rani and Nandan, 2017). Among this *Parasesarma bengalense* was a new record to India. St.1 was dominated by *Parasesarma plicatum* followed by *Neosarmatium malabaricum*. *Parasesarma plicatum* and fiddler crabs dominated in st.3. St.2 had less crab activity (absence of burrowing activity and also not observed any tree-dwelling or climbing crabs in first three quadrats in the station throughout the study period). Species of *Scylla* along with very few numbers of *Parasesarma plicatum* (that also occasionally) were observed in this area. The crab density was high in St.1 with a total of 13.8 ind.m^{-2} (including juveniles and adults) followed by St.3 (11.8 ind.m^{-2}). The crab density was very low in St.2 with 0.35 ind.m^{-2} including adults and juveniles. The taxonomic description of the experimental crab and new species is given in detail.

i. Parasesarma plicatum (Latreille, 1803)

The selected experimental crab was identified as *Parasesarma plicatum* (Latreille, 1803).

Taxonomic position

Kingdom	:	Animalia
Phylum	:	Arthropoda
Sub Phylum	:	Crustacea
Class	:	Malacostraca
Sub Class	:	Eumalacostraca
Super Order	:	Eucarida
Order	:	Decapoda
Infra Order	:	Pleocyemata
Super Family	:	Grapsoidea
Family	:	Sesarmidae
Genus	:	*Parasesarma*
Species	:	*plicatum*

The carapace is broader than long, mesogastric, well defined cardiac regions; strong oblique striae in lateral carapace surface; sparsely scattered tufts of setae was present in carapace surface; short setae was present in lateral margins. Four distinct, similar lobes, separated by narrow grooves, are present in post frontal margin. Triangular external orbital tooth directed upward. It was fused with entire lateral carapace margin; width of the carapace was more at the external orbital tooth. Small second anterolateral tooth, shallowly separated from the former; dorsal surface of palm with two oblique ridges; 8-9 coarse tubercles are present in the upper surface of the movable finger and close to this row is about 10-12 smaller tubercles. Large, subequal and robust chelipeds were present. Distinctive male first gonopod with hook-shaped with a rounded

tip is another distinguishing character. Colour of the carapace is brownish orange, with brownish yellow to orange chelipeds.

Plate 5.3 *Parasesarma plicatum* live photos with true colour collected from St.1 Aroor

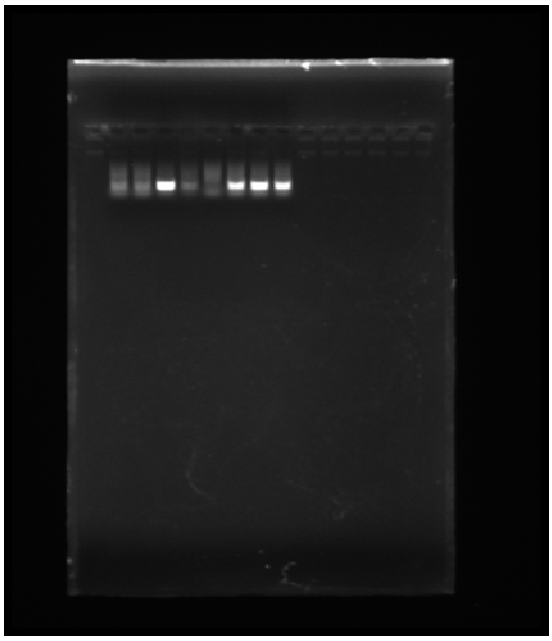

Plate 5.4 Gel image showing DNA bands of *Parasesarma plicatum*

The molecular taxonomy also confirmed the species identity with the sequenced nucleotide having 99% similarity to the already submitted sequences in the NCBI site. The present study obtained base pairs ranging from 627-642 and the Genbank accession numbers obtained were KX228912-KX228915. The NJ tree (Fig.5.1) clearly indicated the differential assemblage of crab individuals according to their speciation. *Parasesarma plicatum* (KX228914.1, KX228913, KX228912 and KX228915) sequences developed from the present study were grouped into single cluster with a mono nucleotide (KY284643.1) acquired from the NCBI site with 95% bootstrap value. *Parasesarma indiarum* (MK033177.1, MK033176.1), *P.foresti* (MK033175.1), *P.messa* (MK033185.1), *P. eumolpe* (MK033174.1, MK033173.1 and MK033172.1) clustered together and formed sister clade with *P. peninsulare* (MK033184.1, MK033183.1 and MK033182.1) with 69% bootstrap value. *P. lividum* (MH552914.1) assembled next (95% bootstrap value) and formed sister clade with *P. samawati* (MH552917.1 and MH552916.1) with 99-97% bootstrap value. *P. plicatum* assembled next as a single cluster with 53% bootstrap value thus, validate it as a different species and confirmed its species status. According to the speciation, other species are assembled and out group *Sylla serrata* (AF097016) formed a diverged array.

In order to justify the results of the phylogenetic tree, genetic distance persisting within the selected individuals was analysed. The level of intra- and interspecific divergence persisting within the species was evident from distance matrix data. Specifically, *Parasesarma plicatum* individuals possessed an intraspecific sequence divergence (0%) within the standard range of 0-4% (Jungbluth and Lenz 2013) for the confirmation of species status of the four individual samples taken for the molecular taxonomic analysis. Thus, intraspecific sequence divergence also reflected and justified the results

inferred from the NJ tree. *Sylla serrata* the selected out group exhibited maximum genetic distance.

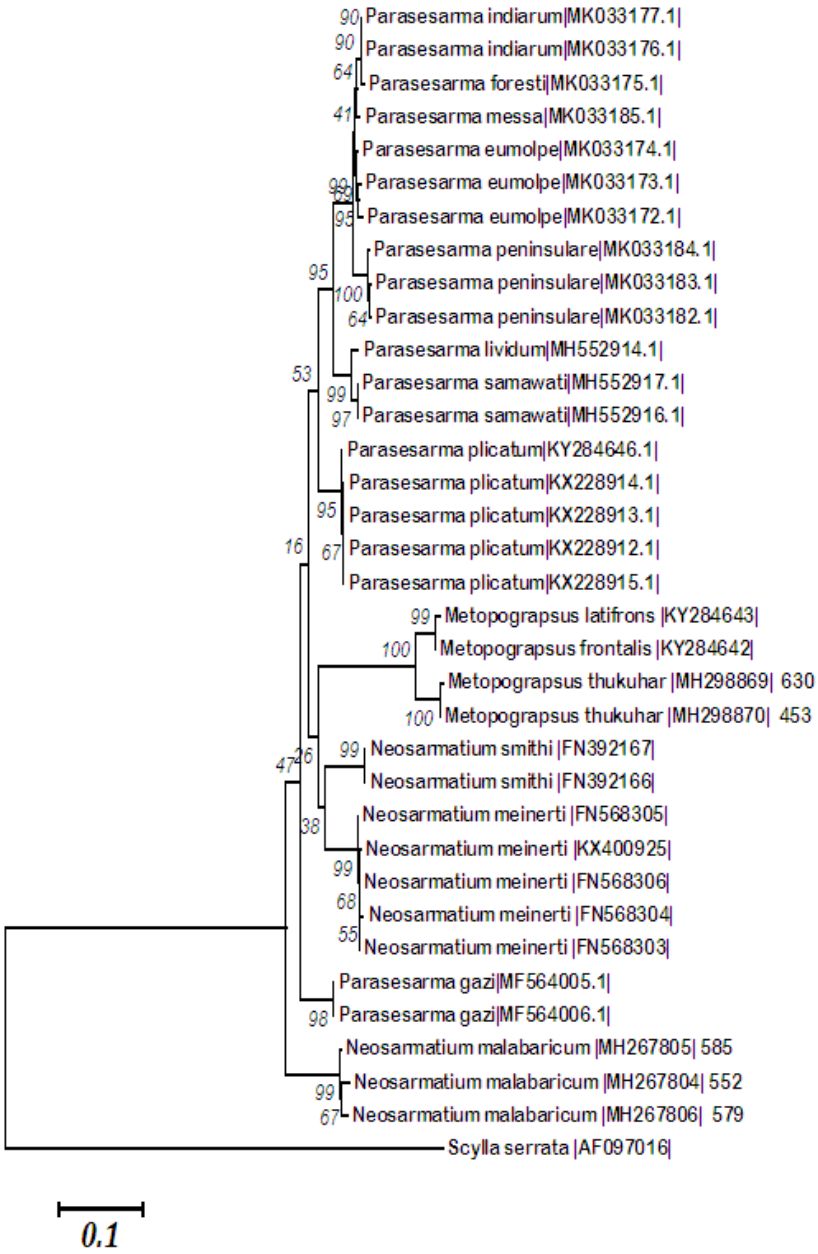

Figure 5.1 Neighbor-Joining tree from phylogenetic analysis constructed for *P. plicatum*

ii. *Pseudosesarma glabrum* Ng, Rani and Nandan 2017

A new species, *Pseudosesarma glabrum,* was identified during the study by both morphometric and molecular systematic protocols. The holotype described was collected from St.1, Aroor. Superficially it resembled *P. edwardsii* in general features but differed markedly in having a more glabrous carapace. It was misidentified as *P. edwardsii* and also as *Perisesarma bidens.* Many of the previous literature on *P. edwardsii* in the southwest coast of India was questioned after this discovery. The taxonomic position of this species is as followed:

Kingdom	:	Animalia
Phylum	:	Arthropoda
Sub Phylum	:	Crustacea
Class	:	Malacostraca
Sub Class	:	Eumalacostraca
Super Order	:	Eucarida
Order	:	Decapoda
Infra Order	:	Pleocyemata
Super Family	:	Grapsoidea
Family	:	Sesarmidae
Genus	:	*Pseudosesarma*
Species	:	*glabrum*

The main morpho-taxonomic characters of this species are carapace slightly wider than long. Dorsal surface, including anterior part, is almost glabrous, without dark setae, with only short, barely visible scattered setae on posterolateral regions. Frontal margin wide, gently convex frontal lobes, wide median concavity separating lobes, shallow; postfrontal lobes prominent, high, level with each other. Short external orbital tooth, anteriorly directed, not reaching to level of the front, separated from rest of margin by deep, V-shaped

cleft; one distinct low epibranchial tooth is present in the lateral margin. It was separated from rest of margin by a small U-shaped notch; gently sinuous, subparallel posterolateral margins. Longitudinally ovate merus was present in the third maxilliped, longer merus than ischium - short and stout chela with numerous small rounded granules present in the outer surface of the palm. Ventral margin of the fixed finger and distal half of palm was straight - broadly triangular male pleon with six somites; wide with distinctly convex lateral margins. First male gonopod was stout, and its distal part was dilated, forming a bulbous structure, relatively broad chitinous tip and appeared bifurcated (Fig.5.2). Colour of the carapace is dark grey with patches of lighter grey, and the walking legs are light brown with some parts orange. Orange coloured merus with bright purple coloured palm and white fingers (Plate.5.5). This crab was found in mangrove habitats, and it was seen in more number during the post-monsoon period (October–January) with a mixo-mesohaline salinity.

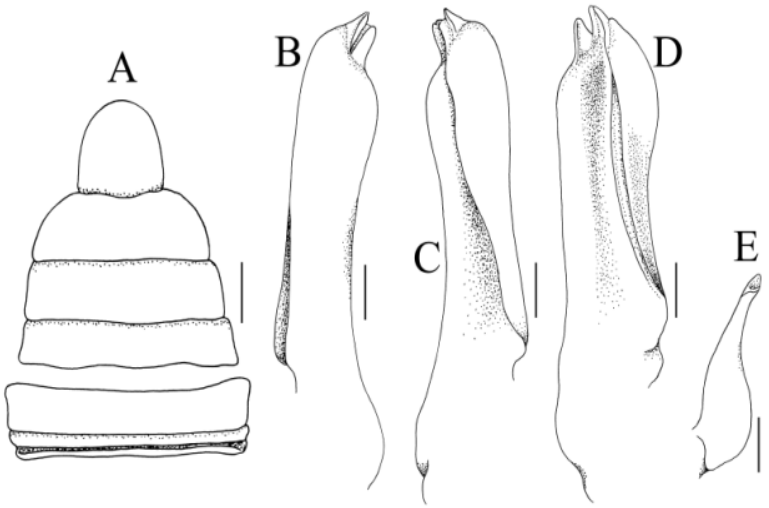

Figure 5.2 ***Pseudosesarma glabrum*** **:** A, pleon; B, dorsal view of left G1; C, ventro-mesial view of left G1; D, ventral view of left G1; E, left (G2. Scales: A = 2.0 mm; B–E = 0.5 mm).

Plate 5.5 *Pseudosesarma glabrum* live photo with external colours

The molecular analysis resulted in mitochondrial cytochrome oxidase (MtCOI) sequences ranging from 570 to 648 base pairs (n=4) were developed and submitted to NCBI database as primary barcode and the accession numbers obtained were: KY828234, KY828235, KY828236 and KY828237. The phylogenetic analysis was unable to be conducted due to the unavailability of base sequences of other species in this genus in NCBI database.

5.4.2 Gut content Analysis

The results of gut content analysis of *Parasesarma plicatum* indicates that it prefers mangrove litter (more than 75%) in the field and thereby indicates its role in nutrient cycling. The highest contribution of average gut content of *Parasesarma plicatum* collected from St.1, Aroor was plant material (81.86 ± 5.75 %). The other materials found in the gut of *Parasearma plicatum* included sand/silt/clay, ribbon worms, nematodes, fungal material, algae and other unidentified substances. The sediment contributed an average of 7.96 ± 3.50 % of the gut content, and the next contributor was ribbon worms (4.07 ±

2.92 %). Nematodes contributed 1.79 ± 3.16 % of the gut content followed by fungal material (0.23 ± 0.228 %) and algae (0.14 ± 0.38 %). Unidentified substances contributed 3.96 ± 3.25 % of its gut (Fig.5.3).

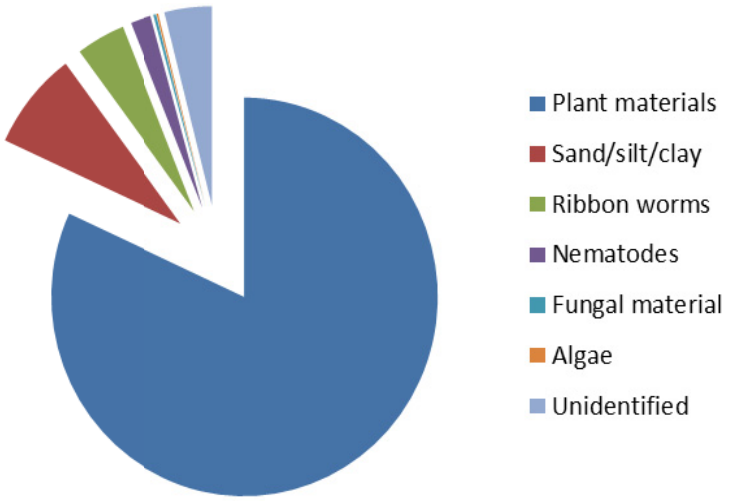

Figure 5.3 Average percentage contribution of different materials in the gut of *P. plicatum* collected from Aroor during 2015-2016

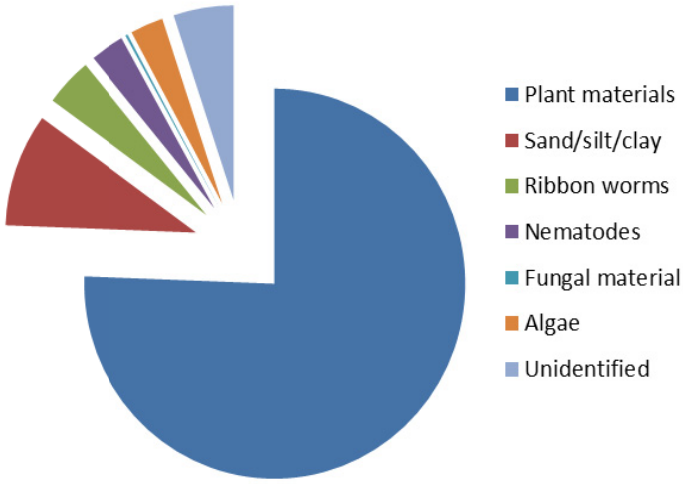

Figure 5.4 Average percentage contribution of different materials in the gut of *P. plicatum* collected from Mangalavanam Bird Sanctuary during 2015-2016.

The gut of *P.plicatum* collected from St.3, Mangalavanam Bird Sanctuary showed 75.6 ± 4.45% of plant material, 9.4 ±3.4 % of sediment particles,4.0 ± 2.5 % of ribbon worms, 2.90 ±1.7 % of nematodes, 0.20 ± 0.4 % of fungal materials, 2.8 ± 4.2 % of algae and 5.1 ± 2.7 % of unidentified substances (Fig.5.4).

5.4.3 Leaf Choice experiment

The feeding experiments with different species and with different state of leaves revealed that senescent partially degraded brown leaves were preferred by the crabs compared to green and yellow leaves (Fig.5.5). All the eleven mangrove species showed the same trend for brown leaves. Ingestion rate of mangrove leaves varied significantly with mangrove species (n= 99, Kruskal-Wallis test, $\chi^2(10) = 30.60$, $p = 0.001$) and leaf state (n= 99, Kruskal- Wallis test, $\chi^2(3) = 20.172$, $p = 0.000$). *A. officinalis* was the most preferred from mangrove leaf in brown leaf category with an ingestion rate of 0.271±0.009 g crab^{-1} day^{-1} followed by *Bruguiera cylindrica* (0.249 ± 0.005 g crab^{-1} day^{-1}) whereas *A. ilicifolius* fresh and brown leaf, *A.aureum* fresh, *B.gymnorrhiza* fresh, *B.sexangula* fresh leaf were least preferred (not ingested by the crab). Among green leaves, *A. officinalis* (0.18 ± 0.085 g crab^{-1} day^{-1}) and *A. marina* (0.16 ± 0.047 g crab^{-1} day^{-1}) were consumed more. The ingestion rate of other mangrove species under **fresh green leaves** were: *R.apiculata* = 0.057 ± 0.01 g crab^{-1} day^{-1}, *R.mucronata* =0.03 ±0.005 g crab^{-1} day^{-1}, *B.cylindrica* = 0.016 ± 0.004 g crab^{-1} day^{-1}, *S. caseolaris* = 0.022 ±0.009 g crab^{-1} day^{-1}, *E.agallocha* = 0.0168 ±0.003 g crab^{-1} day^{-1}. In yellow leaves *R.apiculata* (0.108 ±0.028 g crab^{-1} day^{-1}) was consumed more and the ingestion rate of mangrove leaves in **yellow condition** were: *A. aureum* = 0.053 ±0.004 g crab^{-1} day^{-1}, *A. ilicifolius* = 0.056 ±0.018 g crab^{-1} day^{-1}, *R.mucronata* = 0.022 ± 0.008 g crab^{-1} day^{-1}, *A. marina* = 0.97 ± 0.01 g crab^{-1} day^{-1}, *A. officinalis* = 0.072 ± 0.013 g crab^{-1}

day^{-1}, *B.cylindrica* = 0.008 ± 0.0 g crab^{-1} day^{-1}, *B. gymnorrhiza* = 0.079 ± 0.034 g crab^{-1} day^{-1}, *B.sexangula* = 0.104 ± 0.030 g crab^{-1} day^{-1}, *S.caseolaris* = 0.061 ±0.01 g crab^{-1} day^{-1}, *E.agallocha* = 0.005 ± 0.008 g crab^{-1} day^{-1}. In **brown leaf** category as stated before *A. officinalis* was having highest ingestion rate and the ingestion rate of other mangrove species were : *A. ilicifolius* = 0.151 ± 0.035 g crab^{-1} day^{-1}, *R.apiculata* = 0.073 ± 0.027 g crab^{-1} day^{-1}, *R.mucronata* = 0.046 ± 0.012 g crab^{-1} day^{-1}, *A. marina* = 0.161 ± 0.020 g crab^{-1} day^{-1}, *A. officinalis* = 0.271 ± 0.009 g crab^{-1} day^{-1}, *B. gymnorrhiza* = 0.071 ± 0.010 g crab^{-1} day^{-1}, *B.sexangula* = 0.136 ±0.005g crab^{-1} day^{-1}, *S. caseolaris* = 0.089 ± 0.049 g crab^{-1} day^{-1}, *E.agallocha* = 0.022 ± 0.002 g crab^{-1} day^{-1}.

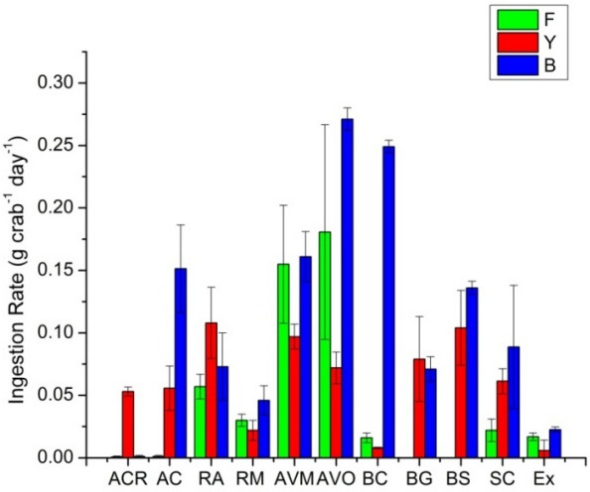

Figure 5.5 Average ingestion rate of *Parasesarma plicatum* feeding with different mangrove species in different leaf stage

5.4.3.1 Factors influencing leaf choice

i. Carbon

The total carbon in mangrove leaves used in the leaf choice experiment ranged from 205.8 ± 8.0 mg g^{-1} (*B. cylindrica* fresh leaves) to 414.4 ± 34.51 mg g^{-1} (*S. caseolaris* yellow leaves) (Fig.5.6 a). There was no significant

variation in carbon content with respect to species and leaf state. In fresh green leaf category, the highest carbon recorded was in *S. caseolaris* (340.9 ± 40.87 mg g^{-1}) and the least carbon was recorded in *B.cylindrica* leaves. In yellow leaf category carbon was more in *S. caseolaris* and *B. cylindrica*, the carbon was recorded minimum (234.7 ± 49.07 mg g^{-1}). Carbon concentration was high in *R. mucronata* (372.1 ± 45.11 mg g^{-1}) and low in *B. gymnorrhiza* (235 ± 64.35 mg g^{-1}) in brown leaf category.

ii. Total Nitrogen

Total nitrogen concentration in different mangrove leaves used in leaf choice experiment ranged from 3.15 ± 0.7 mg g^{-1} (*R.mucronata* brown) to 24.5 mg g^{-1} (*A. ilicifolius* green = 24.5 ± 2.25 mg g^{-1}, *E. agallocha* green = 24.5 ± 1.6 mg g^{-1}) (Fig. 5.6 b). There was no significant variation of nitrogen with mangrove species. However it varied significantly with leaf state (One way ANOVA, $F_{2, 30} = 22.89$, $p = 0.000$, $n = 33$). The fresh green leaves had high nitrogen compared to yellow leaves and even brown leaves. The nitrogen concentration in fresh green leaves was high in *A.ilicifolius* and low in *R.apiculata* leaves (14 ± 0.45 mg g^{-1}). In yellow leaf, category nitrogen was more in *A. aureum* (18.2 ± 0.2 mg g^{-1}) and recorded minimum in *B. gymnorrhiza* (3.5 ± 0.26 mg g^{-1}). Nitrogen concentration was higher in *A. aureum* (19.25 ± 0.65 mg g^{-1}) but lower in *R.mucronata* in brown leaf category.

iii. C/N ratio

The C/N ratio of different mangrove leaves in different stage ranged from 11.04 (*E.agallocha* fresh green leaves) to 118.13 (*R. mucronata* brown). The C/N ratio did not vary significantly with mangrove species but marked significant variation with leaf state (one way ANOVA, $F_{2,30} = 11.84$, $p = 0.000$, $n = 33$). C/N ratio was high in brown senescent leaves compared to yellow and

fresh green leaves (Fig.5.6 c). In fresh green leaf category, the highest C/N ratio recorded was in *R.apiculata* (22.89 ± 4.1 mg g^{-1}) and the least C/N ratio was recorded in *A. ilicifolius* (11.4 ±1.7 mg g^{-1}) leaves. In yellow leaf category, C/N ratio was more in *B. gymnorrhiza* (80.66 ± 6.5 mg g^{-1}), and in *A. aureum*, C/N ratio was recorded minimum (16.7 ± 3.6 mg g^{-1}). C/N ratio was higher in *R. mucronata* but lower in *A. aureum* (15.55 ± 2.2 mg g^{-1}) in brown leaf category.

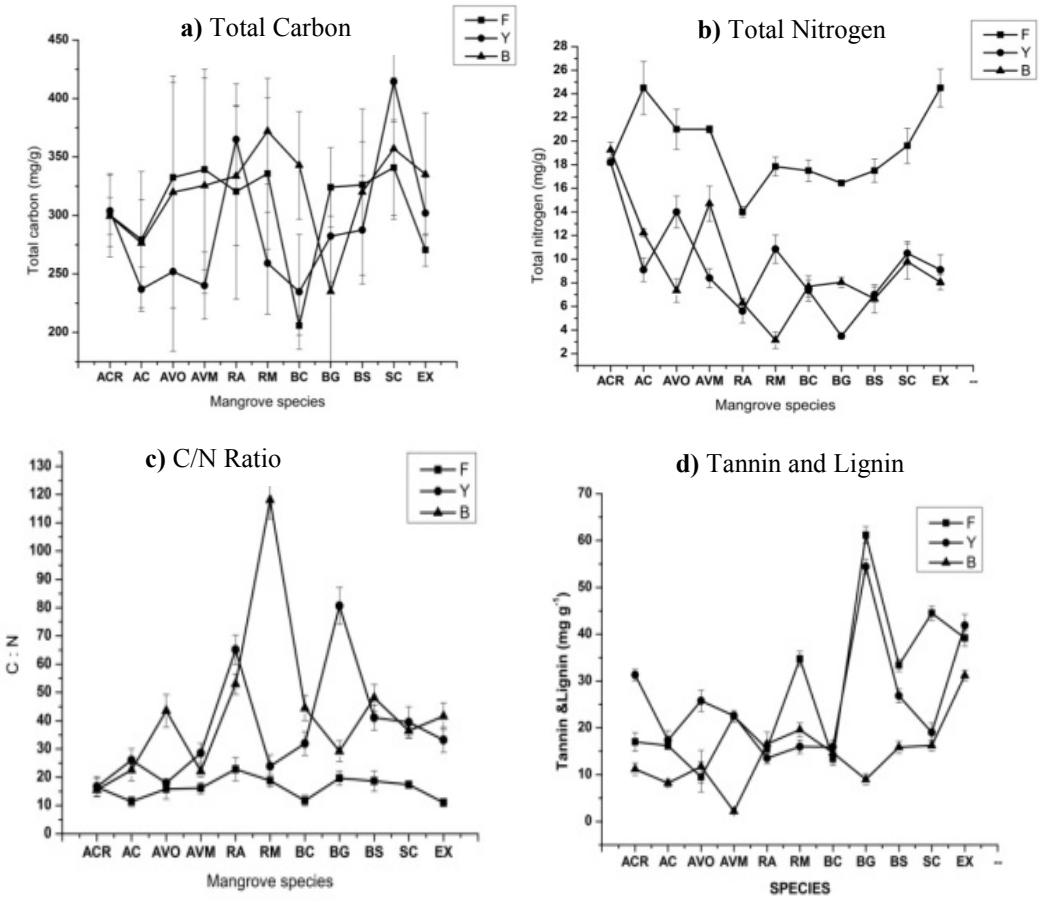

Figure 5.6 (a-d) Variation in concentration of different chemical parameters in selected mangrove species for the leaf choice experiment

[F: Fresh green leaves, Y: Yellow leaves, B: Brown senescent leaves, ACR (*A. aureum*), AC (*A. ilicifolius*), AVO(*A. officinalis*), AVM (*A. marina*), RA(*R.apiculata*), RM (*R.mucronata*), BC (*B.cylindrica*), BG (*B. gymnorrhiza*), BS (*B. sexangula*), SC (*S. caseolaris*), EX (*E.agallocha*)].

ii. Tannin and lignin

The tannin and lignin were high in *B. gymnorrhiza* green leaves (61.2 ±1.8 mg g^{-1}) followed by *B. gymnorrhiza* yellow leaves (54.42 ± 1.6mg g^{-1}) but low tannin content was recorded in *A. marina* brown leaves (2.17 ± 0.5 mg g^{-1}). The tannin and lignin content significantly varied with the mangrove species (One way ANOVA, $F_{2, 20} = 2.672$, p= 0.029, n = 33) and leaf state (One way ANOVA, $F_{2, 20} = 5.965$, p = 0.009, n = 33). Tannin and lignin were high in fresh green leaves followed by yellow leaves, and minimum content was recorded in brown senescent leaves (Fig.5.6 d, Table 5.1). In fresh green leaf category the highest TALLS recorded was in *B. gymnorrhiza* and the least TALLS was recorded in *A. officinalis* (9.51 ± 3.2 mg g^{-1}) leaves. In yellow leaf category, TALLS was more in *B. gymnorrhiza* but was minimum in *R. apiculata* leaves (13.51 ± 1.2 mg g^{-1}). Tannin and lignin were higher in *E.agallocha* (31.21 ± 1.1 mg g^{-1}) but lower in *A.marina* in brown leaf category.

Table 5.1 Concentration of Tannin and Lignin like substances in various mangrove species in each leaf category

Species	Tannin and Lignin content (mg g^{-1})		
	Green	Yellow	Brown
A. aureum	16.99±2.0	31.31 ± 1.2	11.2 ±1.3
A. ilicifolius	16.2 ± 0.8	17.40 ± 2.0	8.2 ± 0.8
A.officinalis	9.51 ± 3.2	25.76 ± 2.3	11.71 ± 3.5
A. marina	22.46 ±1.18	22.57 ± 0.57	2.17 ± 0.5
R.apiculata	15.52 ± 1.5	13.51 ± 1.2	16.57 ± 2.5
R.mucronata	34.77 ± 1.6	15.98 ± 1.5	19.57 ± 1.5
B.cylindrica	13.45 ±1.5	15.92 ± 1.46	14.68 ± 2.12
B. gymnorrhiza	61.2 ±1.8	54.42 ± 1.6	8.99 ± 1.16
B.sexangula	33.4 ± 1.3	26.83 ± 1.5	15.85 ± 1.3
S. caseolaris	44.50 ± 1.5	19.03 ± 2	16.22 ± 1.2
E.agallocha	39.17 ± 1.7	41.86 ±2.4	31.21 ± 1.1

5.4.4 Ingestion-Egestion Assay

The ingestion rate of the mangrove leaves was highest for *Avicennia officinalis* brown leaves (0.063 ± 0.02 g dw (gww)$^{-1}$ day^{-1}) followed by *Rhizophora apiculata* yellow (0.045 ± 0.03 g dw (gww)$^{-1}$ day^{-1}), *Avicennia officinalis* green leaves (0.025 ± 0.01 g dw (gww)$^{-1}$day^{-1}) and *Avicennia marina* green leaves (0.046 ± 0.02 g dw (gww)$^{-1}$ day^{-1}). The egestion rate was also high for *A.officinalis* brown leaf category (0.021 ± 0.014 g dw (gww)$^{-1}$ day^{-1}) followed by *A. marina* green leaves (0.017 ± 0.015 g dw (gww)$^{-1}$ day^{-1}), *Rhizophora apiculata* yellow (0.016 ± 0.005 g dw (gww)$^{-1}$ day^{-1}) leaves and *A. officinalis* green leaves (0.0048 ± 0.003 g dw (gww)$^{-1}$ day^{-1}).

Table 5.2 Carbon and nitrogen ratio of different mangrove leaves and corresponding faecal matter of crab in the ingestion-egestion assay

Sl. No.	Sample Name	Carbon (mg g^{-1})	Nitrogen (mg g^{-1})	C: N
1	*Avicennia officinalis green*	368l.l6± 10.5l	24.00 ±2.2	15.35±1.4
2	*Avicennia marina green*	413.03± 14.2	16.40 ± 3.3	25.20±2.0
3	*Rhizophora apiculata yellow*	440.64 ± 20.5	6.15 ± 1.3	71.61± 1.7
4	*Avicennia officinalis brown*	433.34 ±17.1	11.24 ±1.5	38.54±2.6
	Faecal matter			
1	*Avicennia officinalis green*	169.00±5.66	5.88 ±1.87	28.73 ±3.77
2	*Avicennia marina green*	272.32 ±10.35	7.65 ±1.77	35.58±6.06
3	*Rhizophora apiculata yellow*	370.65 ±8.61	12.24 ±1.70	30.27±5.16
4	*Avicennia officinalis brown*	194.53 ±16.02	4.66 ±1.50	41.79 ±16.5

The control aquaria showed only negligible weight loss during the ingestion assay. The carbon, nitrogen and C/N ratio of the mangrove leaves in the experiment was shown in Table 5.2. The carbon was higher in *R.apiculata* yellow leaf category (440.64 ± 20.5mg g^{-1}) but lower in *A.officinalis* green leaf category (368.6± 10.5 mg g^{-1}), whereas the concentration of nitrogen was

higher in *A. officinalis* green leaves (24.00 ±2.2mg g^{-1}). The C/N ratio was higher (71.61± 1.7mg g^{-1}) for *R.apiculata* yellow leaves with the minimum for *A. officinalis* green leaves(15.35±1.4mg g^{-1}) leaf category.

The tannin content of leaves used for ingestion-egestion assay revealed that 96 h presoaking of leaves again removed a substantial quantity of tannin and lignin from the leaves and improved the ingestion rate (Fig.5.7). It was much reduced to 2.06 mg g^{-1} in *A.officinalis* brown leaves. The tannin content in *A.officinalis* green leaves was 9.54 mg g^{-1}; *R.apiculata* yellow leaves was 13.51 mg g^{-1} while *A. marina* green leaves showed comparatively high tannin content (18.07 mg g^{-1}) even after 96 h presoaking.

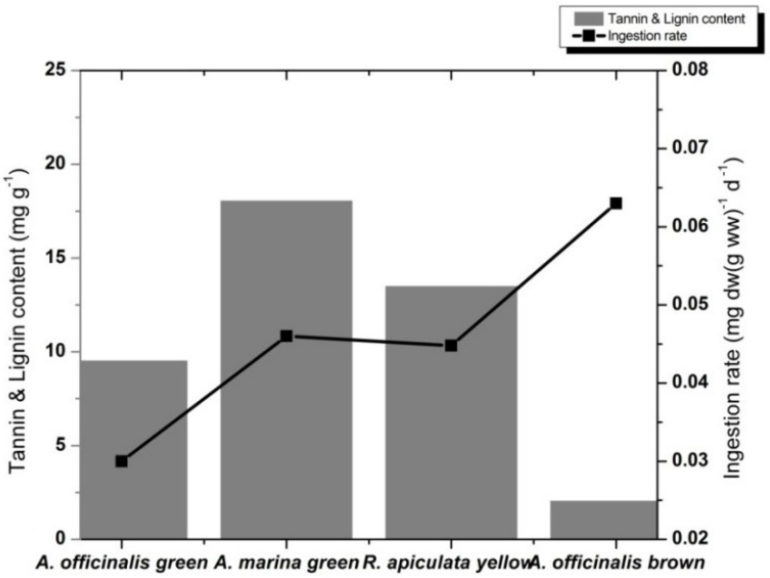

Figure 5.7 Tannin and Lignin content of mangrove leaves vs ingestion rate

From the ingestion – egestion assay, the assimilation of mangrove leaves by the crab *Parasesarma plicatum* was calculated and a high assimilation was obtained for *A.officinalis* brown leaves (40.89 ± 16.5 mg dw $(gww)^{-1}$ day^{-1}) and low assimilation was obtained for *A. officinalis* green leaves (20.36 ±10.1 mg dw $(gww)^{-1}$ day^{-1}). The assimilation of the *P.plicaltum* for *A. marina* green

leaves was 29.20 ± 16.50 mg dw (gww)$^{-1}$ day^{-1}, and for *R.apiculata* yellow leaves, the assimilation was 28.27 ± 9.3 mg dw (gww)$^{-1}$ day^{-1}. However, the assimilation efficiency was higher for *A.officinalis* green leaves (80.4 ± 8.48%) compared to *A. officinalis* brown leaves (61.33 ± 20.05%). The assimilation efficiency of *A. marina* green leaves by *P. plicatum* was 64.63 ± 21.2% and for *R.apiculata* yellow leaves was 56.62 ±15.2%.

5.4.4.1 Fate of Carbon and Nitrogen

i. Ingestion-egestion mechanism

The fate of carbon and nitrogen in terms of ingestion, egestion, assimilation and assimilation efficiency is showed in Table 5.3. The carbon reached back to the environment through egestion was high for *R.apiculata* yellow leaves (6.15 ± 1.6 g C (gww) $^{-1}$ day $^{-1}$), and it was 31.11% of the ingested carbon. This was followed by *A. marina* green leaves, as its egestion converted 24.29% of ingested carbon. The *A.officinalis* green leaf consumption resulted in the conversion of only 8.83% of carbon through egestion while *A. officinalis* brown leaf consumption removed 15.64% of ingested carbon through egestion. The carbon assimilation of *P.plicatum* for *A. officinalis* green leaves was lower (8.47 ± 1.7 g C (gww)$^{-1}$ day^{-1}) compared to other leaf categories; however, its assimilation efficiency was very high (91.21 ± 5.5%). *A.officinalis* brown leaves showed higher assimilation (22.93 ± 3.3 g C (gww)$^{-1}$ day^{-1}) with an efficiency of 84.37 ± 6.6% compared to other leaf categories. The carbon assimilation of *P. plicatum* for *R.apiculata* yellow leaves was 13.62 ± 2.7 g C (gww)$^{-1}$ day^{-1} with carbon assimilation efficiency of 68.88 ± 6.3%. For *A. marina* green leaves, the carbon assimilation was 14.46 ± 3.3 g C (gww)$^{-1}$ day^{-1} with carbon assimilation efficiency of 75.7 ± 6.8%.

The nitrogen was also balanced within the ecosystem by *P. plicatum*. The highest removal of nitrogen (0.20 ± 0.06 g N (gww)$^{-1}$ day $^{-1}$, 71.43% of

ingested carbon) through egestion mechanism of *P. plicatum* was exhibited when fed with *R.apiculata* yellow leaves. The crab removed a meager percentage of ingested nitrogen (5 %) through the egestion process while fed with *A. officinalis* green leaves as in the case of carbon. The consumption of *A.officinalis* brown leaves removed 14.08 % of ingested nitrogen while that of *A. marina* green leaves was 17.11 % by *P. plicatum*. The nitrogen assimilation by the *P. plicatum* was high (0.63 ± 0.1 g N (gww)$^{-1}$ day $^{-1}$) for *A. marina* green leaf consumption with assimilation efficiency of 82.79 ± 8.1 %. The nitrogen assimilation efficiency was very high (95.30 ± 7.7 %) for *A. officinalis* green leaves even though it was having lower assimilation (0.58 ± 0.33 g N (gww)$^{-1}$ day $^{-1}$). *A. officinalis* brown leaves was having assimilation of 0.60 ± 0.2 g N (gww)$^{-1}$ day^{-1} with assimilation efficiency of 85.58 ± 5.5%. Very low (26.38 ± 3.3 %) nitrogen assimilation efficiency was obtained during *R. apiculata* yellow leaf consumption by the sesarmid crab *P. plicatum*.

Table 5.3 Carbon and nitrogen balance through ingestion, egestion, assimilation and assimilation efficiency of *P. plicatum* while consumption of different mangrove leaves

	AVG	**AVB**	**RAY**	**AMG**
Carbon (g C (gww) $^{-1}$ day $^{-1}$)				
Ingestion	9.29±3.2	27.18±4.7	19.77±4.2	19.1±4.8
Egestion	0.82±0.2	4.25±1.1	6.15±1.6	4.64±1.8
Assimilation	8.47±1.7	22.93±3.3	13.62±2.7	14.46±3.3
Assimilation efficiency (%)	91.21±5.5	84.37±6.6	68.88±6.3	75.7±6.8
***Nitrogen*(g N (gww)$^{-1}$ day $^{-1}$)**				
Ingestion	0.60±0.23	0.71±0.05	0.28±0.01	0.76±0.25
Egestion	0.03±0.01	0.10±0.05	0.20±0.06	0.13±0.05
Assimilation	0.58±0.33	0.60±0.2	0.07±0.01	0.63±0.1
Assimilation efficiency (%)	95.30±7.7	85.58±5.5	26.38±3.3	82.79±8.1

AVG-*A. officinalis* green, AVB- *A. officinalis* brown, RAY-*R.Apiculata* yellow
AMG-*A.marina* green

ii. Leaching of carbon and nitrogen

All carbon fragments (TOC, DOC, POC, TIC, DIC, TN, DN) leaching into the experimental water showed significant variation with respect to mangrove species used in the experiment with the exemption of dissolved nitrogen which did not exhibit significant variation (Table 5.4). There was high leaching of particulate organic carbon than dissolved organic carbon (POC range = 0.3 to 59.88 mg L^{-1}), and *Avicennia officinalis* showed high DOC and POC compared to other species.

Table 5.4 Kruskal Wallis test results for carbon and nitrogen leachates to the experimental water

Test Statistics [a,b]							
	TOC	**DOC**	**POC**	**TIC**	**DIC**	**TN**	**DN**
Chi-Square	20.007	16.449	18.000	13.886	9.126	10.887	2.100
Df	3	3	3	3	3	3	3
Asymp. Sig.	.000	.001	.000	.003	.028	.012	.552

a. Kruskal Wallis Test

b. Grouping Variable: species

The average leaching of carbon and nitrogen fragments from the experiment are shown in Fig.5.8 and 5.9. The *A.officinalis* green leaf category showed an average leaching of TOC = 65.11 ± 3.2 mg L^{-1}, DOC = 11.63 ± 1.44 mg L^{-1}, POC = 53.48 ± 4.12 mg L^{-1}, TIC = 1.45 ± 0.85 mg L^{-1}, DIC = 1.36 ± 0.95 mg L^{-1}, TN = 4.21 ± 3.08 mg L^{-1} and DN = 1.39 ± 1.27 mg L^{-1}. The leaching of carbon and nitrogen from *A. marina* green leaves were: TOC = 37.69 ± 11.9 mg L^{-1}, DOC = 11.2 ± 1.23 mg L^{-1}, POC = 26.49 ± 12.43 mg L^{-1}, TIC = 5.13 ± 1.76 mg L^{-1}, DIC = 3.45 ± 2.09 mg L^{-1}, TN = 4.77 ± 1.73 mg L^{-1}, DN =1.9 ± 0.52 mg L^{-1}. *A.officinalis* brown leaves also showed leaching of

carbon and nitrogen with: TOC =19 ± 12.58 mg L^{-1}, DOC = 5.12 ± 12.35 mg L^{-1}, POC =13.88 ± 11.73 mg L^{-1}, TIC =1.5 ± 0.9 mg L^{-1}, DIC = 0.85 ± 0.6 mg L^{-1}, TN = 3.1 ± 0.44 mg L^{-1}, DN =1.41 ± 0.48 mg L^{-1}. *R.apiculata* showed low amount of leaching and was TOC = 8.08 ± 1.27 mg L^{-1}, DOC = 5.02 ± 2.69 mg L^{-1}, POC =3.06 ± 1.81 mg L^{-1}, TIC = 2.61 ± 0.59 mg L^{-1}, DIC =1.7 ± 0.77 mg L^{-1}, TN = 1.52 ± 0.94 mg L^{-1}, DN = 1.36 ± 0.88 mg L^{-1}.

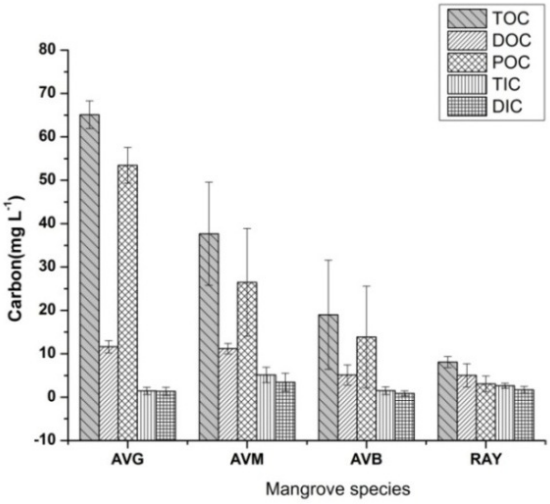

Figure 5.8 Mean leaching of carbon fragments from different mangrove leaf category in the experimental water

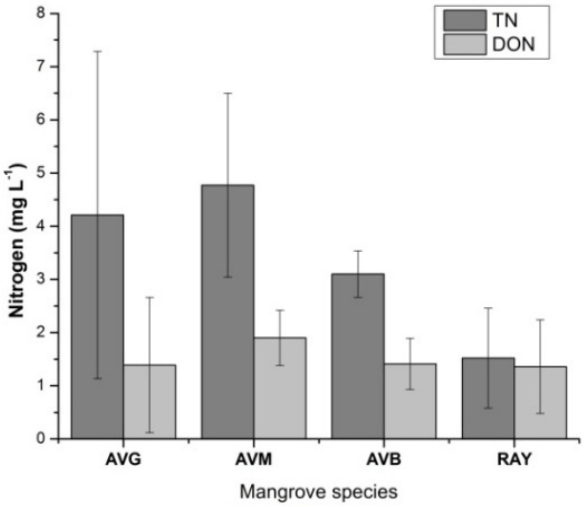

Figure 5.9 Mean leaching of nitrogen fragments from different mangrove leaf category in the experimental water

5.5 Discussion

5.5.1 Crab Taxonomy

The present study recorded a total of seven species of brachyuran crabs from the mangrove areas which contributed 26.92% of the total mangrove crabs (26 species) recorded from Kerala (Dev Roy and Nandi, 2013). The diversity of brachyuran crabs in the study area will go further high if sampling was done on a regular monthly or seasonal schedule. Since the objective of the present study was principally concerned with sesarmid crabs; thus, the diversity of only this family was more focused. However, the present study could identify more species of sesarmid crabs and could resolve many ambiguities in this family. Recent study by Devi et al. (2015), also from the same study area (Aroor) did not reported the abundant mangrove crab, *Parasesarma plicatum* and also species like *Neosarmatium malabaricum* (exclusively seen along mangroves of Kerala) from the Cochin coast. This missing may be due to ambiguity in taxonomic identification of mangrove crabs. However, the present study could able to identify both these species from the Cochin mangroves.

The new species *Pseudosesarma glabrum* in Sesarmidae family, discovered in the present study had been misidentified for a long time and are even reflected in many recent research works (Praveen, 2014; Devi et al., 2015). Praveen, 2014 reported *P. edwardsii* from the Mangalavanam Bird sanctuary but based on the present identification, this report is quite questionable and requires to be reviewed. Alcock (1900: 416) in his compendium of the Indian brachyuran fauna reported the mangrove crab *Sesarma edwardsii* De Man, 1887, from various locations in Sri Lanka, Myanmar, the Gangetic area in India and the Andamans. In India, the species has since been reported from Kerala (Dev Roy 2013; Dev Roy and Nandi

2008; Shet et al., 2016), Goa (Dev Roy 2013; Dev Roy and Bhadra 2007), Maharashtra (Dev Roy, 2008; Pati et al., 2012), Tamil Nadu (Kathirasan, 2000), Karnataka (Haragi et al., 2010), Andaman and Nicobar Islands (Dev Roy and Nandi, 2012) and West Bengal (Mandal and Nandi, 1989; Paul et al., 2012). Later in 1970, Serène and Soh revised the classification of the Indo-West Pacific Sesarmidae and made *Sesarma edwardsii* De Man, 1887, the type species of their new genus, *Pseudosesarma.* During the discovery, only nine species were belonging to this genus.

The new species superficially resembled *P. edwardsii* in certain features (the colour is same with white fingers in the chelate leg), but differed markedly in having a more glabrous carapace. *P. edwardsii* has a quadrat carapace while in *P. glabrum*, the carapace is slightly wider than long. It also resembled *P. crassimanum* in their carapace and male pleonal proportions. *P. glabrum* however, can easily be separated by the median cleft of the frontal margin being relatively more shallow (deeper in *P. crassimanum*, Ng and Schubart, 2017); the anterior part of the dorsal surface of the carapace is almost glabrous except for a few very small scattered setae on the posterolateral regions (most of the surface covered with scattered but distinct stiff setae in *P. crassimanum* (Ng and Schubart 2017). The ventral margin of the fixed finger and distal half of the palm of the adult chela is almost straight in the new species. However it is distinctly concave in *P. crassimanum*; Ng and Schubart (2017). The male pleon is relatively wider (relatively narrower in *P. crassimanum*, Ng and Schubart 2017); and the distal chitinous process is relatively shorter, wider and appears bifurcated (distal chitinous process beak-like, longer and narrower in *P. crassimanum*; Ng and Schubart, 2017). On the basis of geography, the records of "*P. edwardsii*" from the west coast of India (Maharashtra, Karnataka, Goa, Kerala and probably parts of Tamil Nadu) by Kathirasan,

2000; Dev Roy and Bhadra, 2007; Dev Roy, 2008; Dev Roy and Nandi, 2008; Dev Roy et al., 2009; Haragi et al., 2010; Pati et al., 2012; Dev Roy, 2013 and Shet et al., 2016 may belong to *P. glabrum* as well and hence requires to be verified and confirmed. The specimens reported from other parts of India also needs to be re-examined to ascertain if they are really *P. edwardsii* (Ng and Schubart, 2017), *P. crassimanum* (Ng and Schubart, 2017) or otherwise.

The most abundant mangrove crab in the present study area was *Parasesarma plicatum*, which showed wide distribution throughout the Indo-West Pacific region (Rahayu and Ng, 2010). In India, *P. plicatum* was reported from Tamil Nadu (Khan et al., 2005; Dev Roy and Nandi, 2013), Andhra Pradesh (Bouillon et al., 2004; Dev Roy and Nandi, 2013), Gujarat (Saravnakumar et al., 2007; Trivedi et al., 2012), Orissa (Dev Roy and Nandi, 2013), Goa (Deshmukh, 1994) and Kerala (Dev Roy and Nandi, 2013; Praveen, 2014). *Parasesarma bengalense* is another sesarmid crab which was earlier reported from the Bay of Bengal with its type locality in Sri Lanka. Hence the identification of this species from the present study area is a new record to India. There also exists a probability of misidentification of *P.bengalense* as *P. bidens* due to their similarity in external morphological characters. Therefore all the earlier reports could be *P. bidens* [Maharashtra (Dev Roy, 2013); Goa (Deb Roy and Bhadra, 2007; Dev Roy, 2013); Karnataka (Dev Roy, 2013); Kerala (Shet et al., 2016); Tamil Nadu (Alcock, 1900; Thomas, 1969; Ravichandran and Kannupandi, 2007; Venkataraman et al., 2007; Varadharajan and Soundarapandian, 2014); Andhra Pradesh (Rath and Dev Roy, 2009); Orissa (Deb, 1998; Rath and Dev Roy, 2011; Rao and Rath, 2013; Dev Roy and Rath, 2017); West Bengal (Alcock, 1900; Ghosh, 1995, 1998; Khan, 2003); Andaman and Nicobar islands (Heller, 1865; Alcock, 1900; Thomas, 1969; Das and Dev Roy, 1989; Dev Roy and Das, 2000;

Venkataraman et al., 2004] from Indian waters and should be rechecked for the confirmation. The results of the present study indicated the need for more detailed and in-depth taxonomic studies on brachyuran crab diversity from the mangrove habitats in India especially from Kerala.

5.5.2 Gut content analysis

Many field and laboratory studies have documented the fact that sesarmids ingest mangrove leaves. The stomach contents of *Parasesarma plicatum* in both the collection sites revealed thatthey are mainly detritivorous. This feeding choice confirms the result of previous studies in related species of sesarmid crabs which are significant players in leaf degradation and nutrient regeneration in mangroves (Islam et al., 2002; Dahdouh-Guebas et al.,1999; Smith et al.,1991). Dahdouh-Guebas et al.(1999)reported that sesarmid stomach contents comprised more than 85 % of mangrove leaves (1999) and sesarmid crabs remove 79 to 95 % of mangrove leaf fall from the forest floor (Sheaves and Molony, 2000).

From the gut composition of the wild species, it was observed that the dominant materials present were fresh and degraded leaf tissues. Leaf tissue may be originated from the mangrove species present in the vicinity of the crabs collected. The leaf fragments with hairs was lumped together along with undigested leaf parts, twigs, and also leaf with stomatal openings. The inorganic particles in the gut content of the crab were primarly clay, sand and debris which might have been incidentally eaten with leaf materials. The nitrogen need of the crabs may be satisfied with the animal debris like nematodes and ribbon worms. Algae contributed little to the gut content of crabs from Aroor where as it contributed more in the gut content of crabs from Mangalavanam regions and were arbitrarily lumped together. Nematodes were few in number, but they were distinct. The unidentified material included

spicules, body with hairs and some fruiting bodies. The experimental crab contained 100% mangrove plant debris in the gut with respect to the ones caught from the wild.

The average percentage composition of mangrove litter in the stomach of *P. plicatum* in the present study was 79.25 ± 5.95 %. Gut analysis of *Neosarmatium smithi* from the Australian mangroves reported 90% mangrove plant material in the sesarmid guts (Giddins et al., 1986). Gut content of *Aratus pisonii* from USA mangroves recorded 84 % of the gut contents as leaf fragments (Erickson et al., 2003). Nordhaus and Wolff, 2007 studied gut content of *Ucides cordatus*, under Ocypodidae and found comparatively low percentage of plant material (68.6 %) compared to sesarmid crabs. The gut content of different mangrove crabs were analysed by Ravichandran et al., 2006 and reported that the gut content of *Sesarma brockii, S. andersoni* and *S. plicatum* are almost similar and contained mangrove plant material ranging from 58.33 to 72.54 % of the total diet. However, *Metopograpsus messor* and *M. maculatus* showed very low percentage composition of plant material in their gut (40.27 % to 52.94 %). Thus the sesarmid crabs are the primary plant litter feeders compared to other mangrove crabs. The new technology for assessing the food source using stable isotopes also proved that major food of sesarmid crabs was mangrove plant material contributing ~ 60 % of the total diet and rest of the diet contributed ~40 % of other sources such as animal tissue and benthic microorganisms (Kristensen et al., 2010).

Thus from the gut composition of the crabs from the wild as well as the experiment, it is evident that *Parasesarma plicatum* is a voracious mangrove litter feeder since plant debris was pronounced in the guts in both states. Hence the result of gut content analysis is an indication of crab herbivory. The crab

herbivory can be directly correlated with the nutrient cycling of the mangrove ecosystem.

5.5.3 Leaf choice Experiment

Higher ingestion rates were observed for mangrove leaves in the category of brown leaves compared to green and yellow leaves. This higher ingestion rates established the strong tendency of crabs towards decomposed brown leaves. This preference of sesarmid crabs was comparable with many studies which reported high ingestion rate for partially decomposed brown leaves or senescent brown leaves of mangroves by sesarmid crabs (Thongtham and Kristensen, 2005; Nordhaus and Wolff, 2007). Chen and Ye, 2008 revealed that the sesarmid crab preferred decomposed mangrove leaf compared to matured and senescent leaves.The crab least preferred *A. ilicifolius* fresh and brown, *A.aureum* fresh, *B. gymnorrhiza* fresh and *B. sexangula* fresh leaves from which it was clear that there must be an important factor that restricted the herbivory of the crab. *E.agallocha* also had very low ingestion rate by the mangrove crab, *P. plicatum*. While *E. agallocha* leaves were the most preferred leaf by another mangrove crab *Neosarmatium malabaricum* (Shanij et al., 2016). In many studies, *A. marina* brown leaves were preferred by sesarmid crabs and herbivorous mangrove crabs (Kwok and Lee, 1995; Werry and Lee, 2005; Ravichandran et al., 2006, 2007; Bui and Lee, 2014). However, these studies did not include *A. officinalis* leaves (except Shanij et al., 2016) in the experiment. Kwok and Lee, 1995 found out that when fed with yellow and brown leaves of *K. candel* and *A. marina*, resulted in the long survival and high moulting frequency in *P. plicatum* The leaf preference of *P. plicatum* with mature, senescent and decomposed leaves of *Kandelia candel*, *Bruguiera gymnorrhiza* and *Aegiceras corniculatum* showed maximum preference for *K. candel* leaves (Chen and Ye, 2008). The

present study showed that for *P. plicatum*, *A. officinalis* was the preferred leaf compared to *A. marina*. There is no reported study to compare the feeding preference of *P. plicatum* for *Avicennia officinalis* leaves.

It was clear that some factors greatly influenced the leaf preference of crab. Thus to understand the influence of various components like carbon, nitrogen, C/N ratio and tannin, the results were compared with ingestion rate and found that tannin content was negatively correlated to ingestion rate while all other factors had lesser influence compared to tannin content (Fig.5.10-12). The correlation analysis showed that carbon and nitrogen were not correlated significantly with the ingestion rate. However C/N ratio was significantly positively correlated (r_s = 0.406, p = 0.019, n=33) with ingestion rate and showed significant negative correlation with tannin and lignin-like substances (r_s = -0.430, p = 0.015, n = 33). Many studies also revealed that the C: N ratio determined the palatability of mangrove leaves. However, the present study revealed that more than its nutritional value, crabs preferred leaves with less inhibiting factors like tannin (TALLS). It is more explainable in the ingestion-egestion assay, in which *A. officinalis* green leaves had low C/N ratio, but the most preferred leaf was *A. officinalis* brown leaves which had comparatively higher C/N ratio with low tannin content (Fig.5.7). The current study results confirmed the observations of Giddins et al., 1986; Neilson et al., 1986; Kathiresan, 1992; Feller, 1995 and McKee and Feller, 1995 where, inhibition of mangrove leaf grazing by the crabs due to high tannin content in the fresh green leaves compared to decomposed leaves was reported. Another study by Conde et al., 1995 found out that feeding of mangrove leaves with high tannin levels can result in smaller body size for *A. pisonii*.

Another contrasting factor is that many studies (Ravichandran and Kannupandi, 2004; Ravichandran et al., 2006; Kathiresan,1990) reported *A.*

marina having high ingestion rate due to low tannin content while in the present study, it was observed that, the crabs preferred fresh green state. However, it had high tannin content (Table 5.1, low tannin content only in brown leaves) compared to other leaves even during the ingestion-egestion assay (96 h presoaking in 35 ppt sea water also resulted in tannin content of 18.07 ± 2.3 mg g^{-1}).

The correlation between C/N ratio and ingestion rate portrayed contrasting results while comparing with majority of the feeding experimental studies which reported a negative correlation of food choice with C/N ratio (Onuf et al., 1977; Feller, 1995; McKee and Feller, 1995; Nordhaus and Wolff, 2007; Chen and Ye, 2008; Islam and Uehara, 2008). However, it was comparable with Erickson et al., 2004 which reported a positive correlation of grazing of a mangrove crab *Aratus pisonii* with C/N ratio and indicates that mangrove leaf was not a nitrogen source for the crab. Usually, marine invertebrates prefer food with a C/N ratio less than 17 (Russel-Hunder, 1970). However, C/N ratios in mangrove leaves reported by the majority of studies far exceeded the Russel-Hunter ratio of 17. Leaves usually take a very long duration to reach their lowest C/N values and even the most decayed leaves also had double the Russel-Hunter ratio for C/N (Skov and Hartnoll, 2002). Therefore *P. plicatum* preferred other animal tissue and edaphic nitrogen as its nitrogen source. These results could be related with field gut content results of the present study and also with other studies (Erickson et al., 2003, Nordhaus and Wolff, 2007); which reported nematodes, other animal matters and sediment in the stomach of herbivorous mangrove crabs. The recent works on stable isotope studies for determining the source of food in the gut of mangrove crabs also suggested that many mangrove crabs fed animal tissues for meeting their nitrogen need (Kristensen et al., 2010).

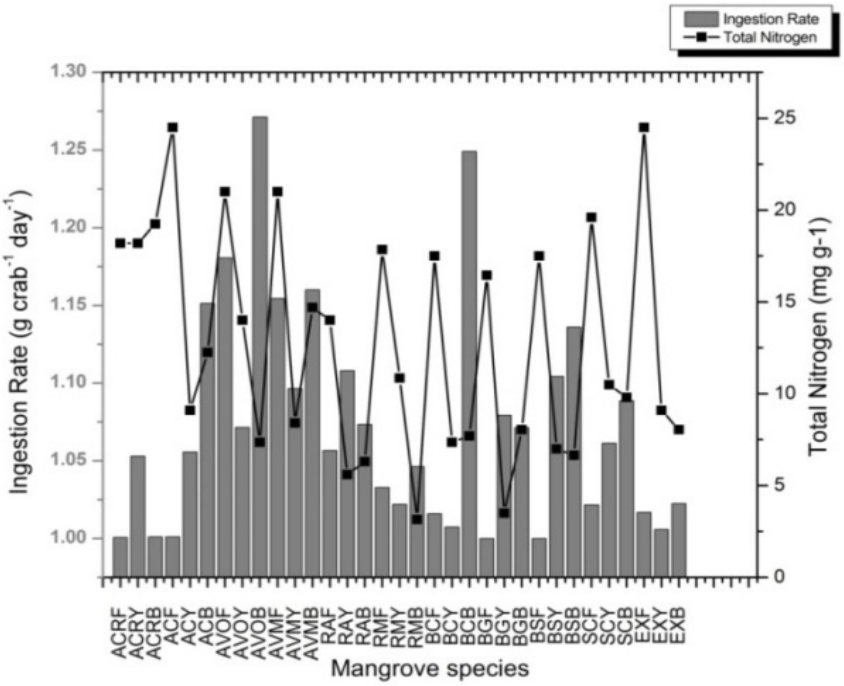

Figure 5.10 Ingestion rate of *P. plicatum* with different mangrove leaves and its total nitrogen content

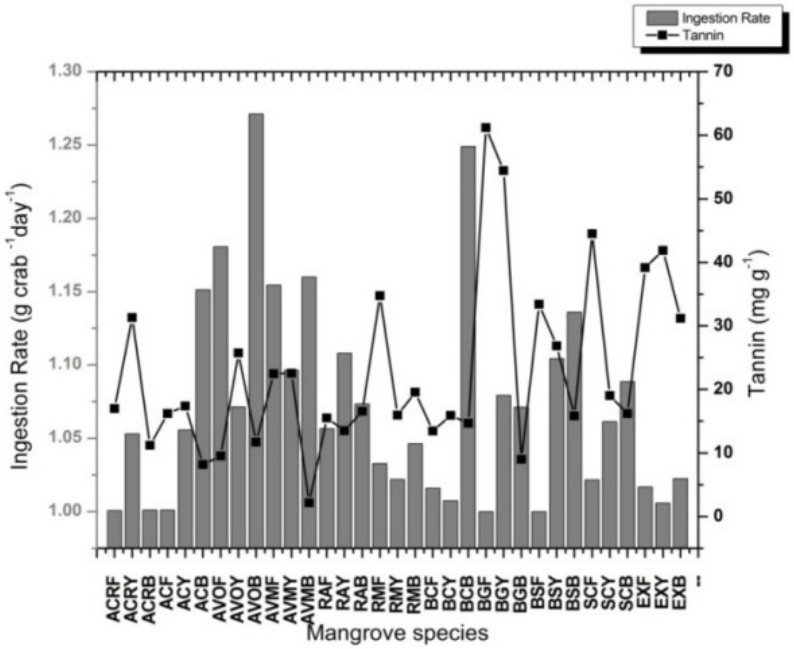

Figure 5.11 Ingestion rate of *P.plicatum* with different mangrove leaves and its tannin content

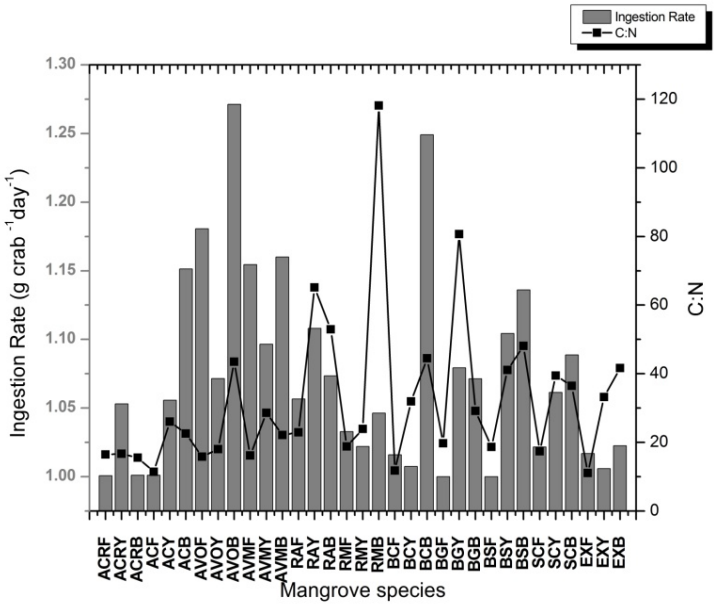

Figure 5.12 Ingestion rate of *P. plicatum* with different mangrove leaves and its C/N ratio

Table 5.5 Correlation analysis table for different chemical parameters controlling mangrove leaf preference

	Species	**Colour**	**Ing**	**TC**	**CN**	**N**	**TN**
Species	1.000						
Colour	.000	1.000					
Ing	-.145	.429*	1.000				
TC	.215	.115	.224	1.000			
CN(r_s)	.332	.639**	.406*	.314	1.000		
N	-.245	-.673**	-.295	-.075	-.778**	1.000	
TN(r_s)	.436*	-.421*	-.430*	.123	-.020	.090	1.000

* Correlation is significant at the 0.05 level (2 tailed)

** Correlation is significant at the 0.01 level (2 tailed)

r_s - Spearman rank-order correlation coefficient for Non-normal data

The results of the present study and literature confirmed that there was a combination of multiple factors influencing on leaf preference by the mangrove crabs. The water content, crude fibre content, fatty acid content and nitrogen compound composition also contributed (Chen and Ye, 2008; Mchenga and Tsuchiya, 2011; Nordhaus et al., 2011) to mangrove leaf choice by the mangrove crabs in addition to tannin and C/N ratio.

5.5.4 Ingestion-egestion assay and fate of carbon and nitrogen

The crabs help in the shredding of fresh or aged leaf litter and thereby makes it small sized but results in an increased surface area to volume ratio. This fragmentation process will enhance microbial colonization (which will enhance decomposition) and leaching (Lee, 1997; Werry and Lee, 2005). Thus the crabs act as an initial processor for low-quality mangrove leaf litter into biomass and eventually help in carbon storage consumers. However, the ability of mangrove crab in nutrient cycling ultimately depends on crabs ability to effectively digest and assimilate the low-quality mangrove leaf litter into its biomass.

The ingestion- egestion assay showed that *A. officinalis* brown leaves were most preferred by the mangrove crab, *P. plicatum* and egestion rate as well as assimilation was also high for the same species. However, assimilation efficiency was highest for *A. officinalis* green leaves followed by *A. marina* green leaves. The real physiological reason for this high assimilation for green mangrove leaves is unknown. However, it was reported by Thongtham and Kristensen (2005) and Nordhaus and Wolff (2007). In laboratory condition, the crab may be trying to save its available food even though fresh leaves was not a preferring food in the field and may be converting it into maximum biomass due to the absence of other preferring leaf and other food items. So

egestion rate became very low for this mangrove leaf category compared to other leaves and thereby resulted in high assimilation for green leaf category.

The corresponding C and N assimilation efficiency was also high for *Avicennia officinalis* brown leaves makes it evident that the litter processing ability of mangrove crab for senescent leaves. *R. apiculata* yellow leaves had very low C and N assimilation efficiency compared to other leaves. This low assimilation may be due to low digestion of *Rhizophora* spp. due to tough leaf morphology as reported in many studies (Camilleri, 1989; Micheli, 1993; Hogarth,1999; Ashton, 2002). This assimilated carbon is either respired as carbon dioxide or incorporated into crab biomass which will eventually enter into sediment pool when the crab dies. The mangrove forest having species of high carbon assimilation efficiency will be helping in carbon storage majorly through crab biomass and the mangrove species having low assimilation efficiency (*R.apiculata*) will bring the carbon to the ecosystem majorly through faeces and minor amount through crab biomass. In both case crab act as a helping agent for retaining the nutrients within the ecosystem and forms the keystone species.

The assimilation efficiency of the crab for the mangrove leaves had a significant role in retaining the carbon in mangrove ecosystem and thereby sequestering the carbon without releasing it to adjacent wetlands. However, this was questioned in some recent research works. Bui and Lee, 2014 confirmed the role of grapsid crabs in assimilating low-quality mangrove litter into biomass and thereby played a significant role in the food web and carbon cycling. With evidence from stable isotope analysis, Mazumder and Saintilan (2010) and Skov and Hartnoll (2002) questioned and solved some of the misunderstandings of recent researches which claimed that mangrove litter is not the primary food of grapsid crabs. However, Bui and Lee (2014) solved the

anomaly in taking the stable isotope ratio in consumer level and confirmed the primary diet of grapsid crabs as mangrove litter even though it is taking some other food items occasionally.

Comparing the ingestion, egestion and assimilation efficiency of *Neoepisesarma versicolor* and *Parasesarma plicatum* (Thongtham and Kristensen, 2005), *Parasesarma plicatum* was having high ingestion rate and low egestion rate with high assimilation efficiency. *N. versicolar* was having high assimilation efficiency for green leaves (68.7 %) and very low for yellow leaves (25.9 %) and brown leaves (6.5 %). Bui and Lee, 2014 also reported low assimilation efficiency for C and N in *P. erythodactyla* fed with *A. marina* (36 % for C and 57 % for N), *Neosarmatium smithi* fed on *Ceriops tagal* leaf detritus which also showed lower assimilation efficiency (Giddins et al., 1986) compared to *P. erythodactyla.* However, the present assimilation efficiency was comparable (82.44 %) with consumption of *A. marina* leaves by *Sesarma meinerti* (Emmerson and Mc Gwynne, 1992) and also with Ravichandran et al., 2006.

The analysis of TOC, DOC, POC, TIC DIC, TN, DN in the experimental water indicates that handling of leaves by the crab also helps in the export of nutrients to adjacent water bodies. There was a considerable amount of leaching of carbon and nitrogen to the water, and this leaching significantly differed among mangrove species. This leaching mechanism was comparable with Thongtham and Kristensen, 2005.Among the mangrove species used in the experiment, *Avicennia officinalis* species was having high leaching of carbon mainly in the form of DOC and POC compared to other species. It indicates that in the field also there will be a large amount of physical leaching of carbon from the mangrove leaves, and it is also evident that there is the probability of leaching of organic matter through the skin of aquatic animals to

the water (Schmidt-Nielsen, 1997) which may also be happening in the case of crabs.

Thus the study shows that *P. plicatum* is an efficient mangrove litter feeder (from field gut content and experimental study) and assimilate a large portion of mangrove primary production into its biomass thereby helps in the carbon and nitrogen cycling in the mangrove ecosystem. The handling and fragmentation of mangrove leaves by the crab also facilitates a large amount of carbon into the water. Therefore crab density, especially grapsid crab density will ultimately determine the carbon storage in mangrove sediment pool and will also help in the export of carbon to adjacent coastal waters through the leaching process and also as food to consumers.

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Chapter 6

CARBON FLUX IN MANGROVES OF COCHIN

6.1 Introduction

The fate of mangrove primary production is always a matter of debate in the scientific world. The carbon which reaches the sediment through litterfall will undergo various biogeochemical pathways and will either undergo burial in sediment or is exported through water or will return to the atmosphere via Green House Gas (GHG) emission. The mangrove litter usually gets exported as particulate organic matter or in the form of DOC or DIC to adjacent oceans through the estuary (Twilley, 1992; Dittmar et al., 2006; Bouillon et al., 2008; Alongi, 2014). The mangrove ecosystems account for 10-15 % of the organic carbon burial in the oceans (Jennerjahn and Ittekkot, 2002; Duarte et al., 2005). The export of mangrove-derived carbon (whether organic or inorganic) is a very complex biogeochemical process depending on various factors. The hydrogeomorphic setting of mangrove habitat, forest structure, tidal inundation frequency, topography, soil hydraulic properties (Ho et al.,2017), the presence and absence of herbivorous and burrowing crabs and other geological factors may influence the export mechanism in mangroves (Robertson et al.,1986; Smith et al., 1991).

The lateral exchange of organic carbon as DOC and POC was reported more from mangrove habitats compared to recent DIC export studies (Ayukai

et al., 1998; Dittmar and Lara, 2001a; Davis et al., 2003; Bouillon et al., 2007). However, the concept of DIC export together with total alkalinity, which was first hypothesised by Bouillon et al. (2008) is nowadays major research accounting the carbon budget of mangrove ecosystems. This lateral exchange was later quantified by Maher et al. (2013) and Ray et al. (2018). Most recently Maher et al., 2018 revealed that lateral export of carbon as DIC together with total alkalinity contributed ~ 63 % of a total mangrove carbon budget and acted as the highest sink of atmospheric greenhouse gases.

Therefore carbon flux studies are very important in mangrove ecosystems and adjacent estuaries. The flux studies should always be accompanied by source characterisation in order to understand the origin of organic/inorganic matter. The influence of the mangrove ecosystem to the adjacent estuary through lateral export could be understood through the stable isotope study using the isotope ratio of carbon ($^{13}C/^{12}C = \delta^{13}C$) and nitrogen ($^{15}N/^{14}N = \delta^{15}$ N). The C_3 plants, including mangroves, are having a typical $\delta^{13}C$ ratio (-32 ‰ to - 22 ‰) and δ^{15} N (3 ‰ to 7 ‰) (Kendal, 1997) whereas marine phytoplankton has $\delta^{13}C$ (-20 ‰ to – 23 ‰) and δ^{15} N (6 ‰ -11 ‰) which is used to evaluate the source of organic matter (Gearing et al., 1977; Meyers, 1997; Bianchi et al., 2002). The understanding of the source of carbon and nitrogen will add scientific strength to the carbon dynamics studies rather than merely reporting the concentration of each carbon fractions.

6.2 Literature Review

The global mangrove export studies, mainly based on the organic matter, were reported by Twilley, 1992; Duarte and Cebrian, 1996; Jennerjahn and Ittekkot, 2002 and Dittmar et al., 2006. The global export of organic matter from mangroves to the coastal ocean was reported to be 46 x 10^{12}g C per year

by Jennerjahn and Ittekkot (2002); which accounted for 11 % of the total terrestrial carbon input to the ocean. Dittmar et al. (2006) also assessed the organic carbon export of mangroves (~10,000 km^2) to the open ocean off northern Brazil based on stable isotope analysis and proton nuclear magnetic resonance spectroscopy and confirmed the origin of organic carbon in the ocean as mangrove origin. Similar to Jennerjahn and Ittekkot (2002), they also estimated the global mangrove carbon export contribution as >10% of terrestrial input of carbon to the ocean.

The outwelling of organic matter from mangroves to adjacent coastal bodies as food for the higher trophic levels was first noticed by Odum (1968) and Odum and Heald (1975). Lee (1995) summarised the major research works on the export of organic matter to adjacent estuaries. Only a few studies were reported on export studies during earlier times. However, the major works of Gong and Ong (1990) and Twilley (1992) made the concept that mangroves are major exporters of nutrients and carbon. The other research works (Boto and Bunt, 1981; Twilley,1983; Clark,1985; Robertson, 1986; Lee,1990) which discussed on the flux of materials from mangroves to the estuary during those decades confirmed the concept of Twilley as well as Gong and Ong. Robertson (1986) reported 12523 t C y^{-1} as organic carbon export from mangroves of Great Barrier Reef, Australia. Many researchers reported that around 50% of net primary production of mangroves was exported to the ocean as organic matter (Robertson et al., 1992; Dittmar and Lara, 2001a, 2001b; Jennerjahn and Ittekkot, 2002). Among these works, Dittmar and Lara (2001b) reported the importance of sediment pore water-mediated export of organic matter through the tidal action in mangroves. Davis et al. (2003) studied the concentration and flux of various nutrients such as carbon, nitrogen and phosphorus in Florida mangroves. Young et al. (2005) reported the export of POC and DOC from a

lagoon in Mexico dominated by mangrove forest. They measured the concentration of POC, DOC and used the available literature for water budget and calculated the flux. They found out that mangroves of Celestun Lagoon, Mexico act as a source of organic carbon to the adjacent oceanic water body and also reported 92 % of the total carbon export as DOC. They also checked the groundwater export of carbon and nitrogen and found out that groundwater act as a significant source of nitrogen to the Lagoon, however insignificant to carbon. However, nowadays, DIC export through groundwater exchange is a hot topic of scientific research.

The export studies are always coupled with stable isotope study in order to confirm the presence of mangrove-derived carbon. Haines (1977, 1979) was the first to use this technique to derive the origin of organic matter in Georgia estuary. Later Rodelli et al. (1984) used stable carbon isotopes to study outwelling effects of Malaysian mangroves. However, the studies by Gearing et al. (1988) and Moran et al. (1991) revealed that the effect of mangrove-derived carbon export was limited to only 1-2 km. Lignin profile was also used by many researchers to find out the mangrove-derived carbon in estuarine water bodies (Meyers-Schulte and Hedges, 1986). Dittmar and Lara (2001c) used this technique to characterise the organic matter source in Brazilian coastal waters. Bouillon et al. (2003b) did a breakthrough study in carbon export through stable isotope analysis in Godavari estuary, India. They used $\delta^{13}C$ DIC Profile, and their results indicated that mineralisation of mangrove-derived dissolved organic carbon (DOC) and its emission as CO_2 to the atmosphere might act as an important fate for mangrove carbon. After this study, many stable isotope characterisation was done for both DOC and DIC of mangrove origin and its fate in the estuary and adjacent coastal waters.

As mentioned earlier, the export studies based on DIC together with total alkalinity was first hypothesised by Bouillon et al. (2008) in their global mangrove carbon budget. They estimated the global primary production of mangroves and found out that the >50 % of the fate of mangrove primary productivity was unaccounted. They reported that mineralisation was severely underestimated and a significant portion of carbon from mangroves may be exported to adjacent waters as dissolved inorganic carbon (DIC). However, this hypothesis originated from the results obtained while studying the mangrove dominated oligo-mesohaline Indian estuary, Godavari (Bouillon et al., 2003b). They mentioned about the carbonate dissolution process by measuring the total alkalinity, DIC and δ^{13}C DIC profile in the estuary. In the same year, Koneand Borges (2008) studied in detail about the lateral transport of Dissolved inorganic carbon from interstitial waters in mangroves of the Ca Mau Province, Vietnam to adjacent coastal ocean mediated by tidal pumping. They measured DIC, total alkalinity, pCO_2, and oxygen saturation levels (% O_2) in the mangroves and surrounding coastal habitats and found out the importance of this pathway in carbon export study. Miyajima et al. (2009) did the same kind of work together with stable isotope measurement to confirm the inorganic carbon source of mangroves in the coastal ocean in two Southeast Asian mangrove forests. Later Maher et al. (2013) tested the hypothesis of 'export of DIC through subsurface respiration and groundwater exchange mediated by tidal pumping' by measuring concentrations of DIC its stable isotope ratio (δ^{13}C DIC) and radon in groundwater throughout a tidal cycle from a mangrove tidal creek:, Moreton Bay, on the east coast of Australia. They accounted for the missing carbon sink in the total carbon budget and found out this pathway as a major sink. Sippo et al., 2016 also confirmed the

DIC export together with insights from total alkalinity and reported the importance of mangroves in buffering against coastal acidification.

However, these studies have only been estimated for short periods for a small study area and did not account the fate of this carbon once exported to the ocean. Ho et al. (2017) tried to fill this gap by an in-depth study by additional measurements of the quantity and fate of mangrove carbon export at the river basin, estuarine and coastal ocean cycles. They studied for a year on source-sink dynamics of dissolved carbon source in Shark and Harney rivers in Florida Everglades using SF6 tracer release experiments. It was found that ~ 80% of dissolved carbon was in the form of DIC and 42-48 % of mangrove-derived DIC flux into the rivers was emitted back to the atmosphere while the remaining part is discharged into the ocean. According to their estimates, less than 10 % was the contribution of mangrove-derived dissolved carbon to the coastal ocean. This contribution was comparatively low estimates within the previous reports from Shark river and also from other reports. The study by Ray et al. (2018) in Sundarban mangroves also quantified the DIC export together with total alkalinity to the Bay of Bengal through Hoogly river/estuary. They quantified the river originated dissolved and particulate carbon and also assessed the world's largest mangrove forest, Sundarbans derived carbon dynamics. They revealed that the major source of DIC and DOC in the Hooghly estuary was mangrove plant-derived organic matter and its subsequent degradation. However, POC was related to soil erosion. The quantification of export of this DIC pathway exceeds the missing carbon sink for Sundarbans mangroves. Maher et al. (2018) quantified mangrove-derived DIC export together with total alkalinity and also found out the flux of GHG from the water column and exposed sediments. An extensive field study was conducted in the mangroves of Southern Moreton Bay, on the East Coast of

Australia. The field data, together with already published data for those mangroves, especially burial rate, was used for budgeting the carbon. The study revealed that the export of carbon (DIC) and alkalinity was approximately 1.7 times higher than the burial rate as a long-term carbon sink in that mangrove habitat.

In India, carbon export studies were reported by Bouillon et al., 2003 in Godavari estuary as described in detail in fourth paragraph of review. Prasad and Ramanathan, 2008 reported the seasonal change in DOC, POC concentration in mangroves of Pichavaram and its contribution to the adjacent estuary. Mukherjee and Ray (2012) modelled the carbon cycling of Sundarbans mangroves. They studied the dynamics of litter carbon and its influence to the adjacent Hooghly estuary through sediment and water carbon flux together with environmental parameters. They quantified DOC, POC and DIC of water samples and also proved the influence of pH in the conversion of DIC to DCO_2 and dissolved bicarbonate. The study by Sarma et al. (2014) was an important study which described the source of organic carbon source in 27 estuaries of India and characterised the influence of both autochthonous and allochthonous origin of organic matter. Kathiresan (2014) mentioned about the interconnection of coastal ecosystems through mangroves. Bhavya et al. (2016) studied the stable isotope ratio of the suspended particular matter and DIC in Cochin estuary and reported the source of terrestrial source of carbon in the southern part of the estuary and mixed signal of marine and terrestrial source of carbon in the northern part of the estuary. Recently, Ray and Shahraki (2017) compared the organic matter source characterisation of Sundarban mangroves with Iranian mangroves and reported high input of riverine source (50-58%) to DOC in mangroves of Sundarban and POC source was characterised by mangrove litter and freshwater phytoplankton. Most recently, the study by Ray

et al. (2018) quantified the missing carbon through DIC export was also reported from Sundarban mangroves.

The literature suggests that current mangrove researche around the globe focuses on mangrove carbon export and its fate to the ocean. However, at the regional level, little attention is reported on this mangrove carbon export. Therefore, this study documents the different carbon fractions (DOC, POC, DIC) in mangroves of Cochin together with organic matter source characterisation of mangroves and mangrove- derived organic matter that influences the adjacent Cochin estuary by stable isotope analysis of $\delta^{13}C$ and $\delta^{15}N$.

6.3Materials and Methods

6.3.1 Carbon dynamics study in mangrove intertidal water

Sampling was conducted during 2014 March to 2015 August period on a bimonthly basis. However, October 2015-January 2016 post-monsoon samples were not analysed due to technical problems. Three stations (St.1 Aroor, St.2 Malippuram, Vypin Island, St.3 Mangalavanam Bird sanctuary) as described in chapter 2 were selected for regular monitoring for carbon flux study. Triplicate samples were taken from each station for carbon fractionation study and preservation was done according to standard protocols for carbon analysis (Reckhow, 2012). The intertidal water samples (depth <0.5m) inside the mangrove habitats were taken in pre-cleaned BOD bottles without any air bubble. Prior to analysis, DOC samples were collected in a syringe and filtered through sterilised syringe filters (Whatman GF/F filter 0.7µm) and transferred to glass vials for analysis (Bouillon et al.,2003b). Carbon and Nitrogen fractions like TC, TOC, DOC, POC, TIC, DIC, TN and DN were analysed using Analytik Jena MULTI NYC 2100 S TOC/TN_B Analyser. The autosampler of the instrument did the acidification of the sample using 2N HCl

before analysis. The instrument directly measured the total carbon and inorganic carbon. Dissolved carbon was measured using the same technique after syringe filtration. The POC was calculated by subtracting the TOC values with DOC.

The statistical analysis was done using SPSS 16.0v, as described in chapter 2. Since only one set of post-monsoon samples were obtained, statistical analysis (ANOVA) included only two seasons for checking the significant variation. The mean carbon and nitrogen variations were calculated using the entire data of the study period.

6.3.2 Carbon source characterisation and its fate

The carbon fractionation study is usually accompanied by stable isotope analysis in which stable isotopic ratios, $\delta^{13}C$ and δ^{15} N are widely used for indicating the source of organic matter. This organic carbon source characterization was conducted for POM samples from the mangrove stations of Cochin (St.1, St.2 and St.3 as described in Chapter 2) during 2017. The stable isotope study was also conducted in the adjoining Cochin estuary in order to understand the source of organic matter and also the export or import of organic matter from the mangrove habitat to the estuary. For which, five stations including the stations near to mangrove patches were selected in the Cochin estuary during 2017 June (Fig.6.1). The stations in Cochin estuary are include **St.1 Barmouth**: located at 9^{o} 55' 8.80" N, 76^{o} 19' 43.68" E and is the permanent opening between the Cochin estuary and Lakshadweep sea. The depth of the station is 5.56 m, and the station is affected by strong tidal flux. It is the ship channel for national and international vessels. Therefore dredging is a common practice in this area for the maintenance of the ship channel. It is a major area for stake net and Chinese dip nets operation. The LNG Terminal is located near to this station.**St.2 Vallarpadam-Barmouth:** this station is

located at 9° 58' 30" N, 76° 15' 17" E in between barmouth of the Cochin estuary and Vallarpadam Island. The depth of the area is 3 m. Since this station is closer to barmouth area, the tidal fluctuation is prevalent in the station. The International Container Trans-shipment Terminal (ICTT) is located on the coast of this station. The station was affected by many construction and reclamation activities. **St.3 Vallarpadam Island:** this station is a part of Cochin estuary, near to a mangrove habitat, and located at 9° 59' 26" N, 76° 15' 29" E with a depth of 2 m. The mangrove habitat is dominated by structurally developed *R. mucronata* trees. Vembanad bridge for ICTT is passing near to this station. **St.4 Bolgatty:** located at 9° 58' 57" N, 76° 16' 09" E and is one of the Gosree Island after Vallarpadam Island from barmouth area. The station is more close to Cochin city with a depth of 3 m. **St.5 Feeder canal to Mangalavanam:** is located at 9° 59' 09" N, 76° 16' 16" E in the Cochin estuary and it feeds a mangrove site, Mangalavanam Bird Sanctuary. This station is shallow with a depth of 1.5 m compared to other stations. Sampling was done during low tide to high tide period and the vice versa. Water, sediment, POM samples, mangrove leaf samples and water hyacinth samples were collected. A portion of the water sample was used for carbon fractionation analysis, and 1 L sample was filtered using pre-combustion Whatman GF/F filter paper for POM measurement and stable isotope analysis. The filter paper was acidified with 2N HCl and dried to remove moisture content. Sediment and plant samples were dried, ground and acidified with 2N HCl and again dried. The dried samples were packaged in tin capsules for mass spectrometry and analysed using a PyroCube-IRMS (Serial No.JC 455) for $^{15}N/^{14}N$ and $^{13}C/^{12}C$ ratios. Measurements are reported in δ notation [per mille (‰) units], and ovalbumin was used as a routine standard. Precision for $\delta^{13}C$ and $\delta^{15}N$ was generally ± 0.2‰ and ± 0.4 ‰ (Jim et al., 2011).

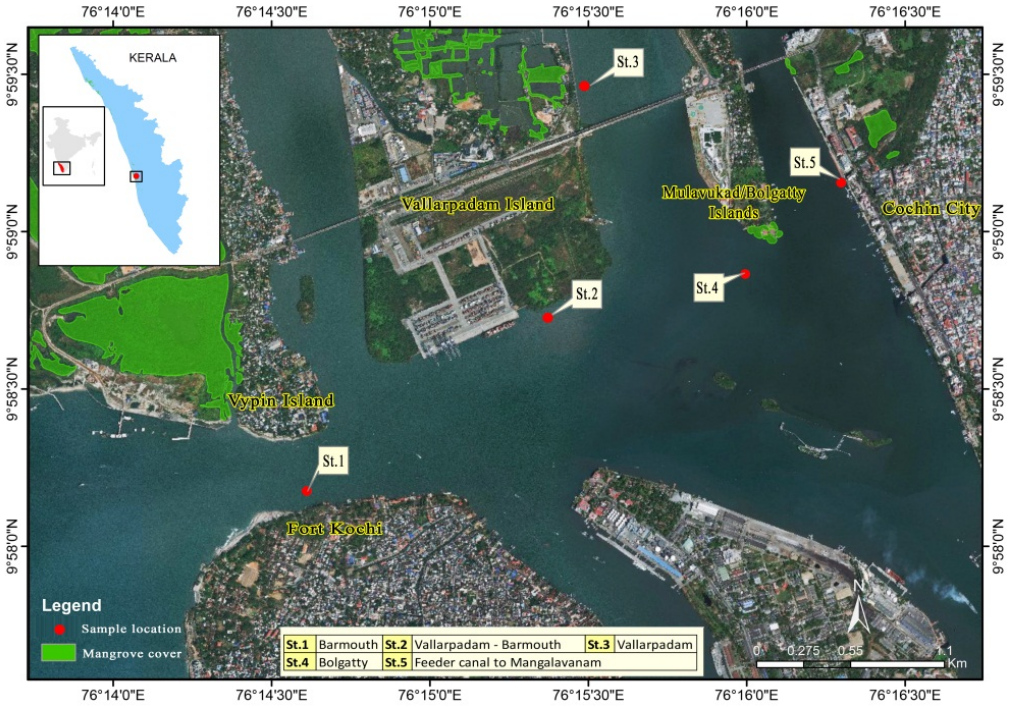

Figure 6.1 Location map of stations for carbon source characterisation in the Cochin estuary

6.4 Results

6.4.1 Carbon and Nitrogen dynamics

I. Total Carbon

High carbon content was obtained from different sampling stations of the Cochin mangroves. Total carbon (n = 90) ranged from 7.22 (St.1, MON 1; monsoon) to 128.9 mg L^{-1}(St.3, MON2) (Fig.6.2). The mean total carbon was highest during MON 2 (62.3 ± 17.3 mg L^{-1}). TC did not vary significantly with stations and seasons during the study period. However significant variation was observed annually (ANOVA $F_{1,67} = 33.83$, p =0.000, n = 72). The mean TC was higher in Year 2 (2015-16) compared to Year 1(2014-2015, omitting of postmonsoon values of Year 1 did not change the trend). The highest mean was observed in St.2 (32.73 ± 22.24 mg L^{-1}) compared to St.1 (28.70 ± 18.49

mgL^{-1}) and St.3 (26.85 ± 11.72 mg L^{-1}) in the first year. In the second year, St.3 was having slightly higher TC (57.51 ± 29.40 mg L^{-1}) compared to St.2 (56.88 ± 26.02mgL^{-1}) and St.1 (46.48 ± 10.91 mg L^{-1}). The annual variation in TC in different stations and different seasons is shown in Fig.6.3.

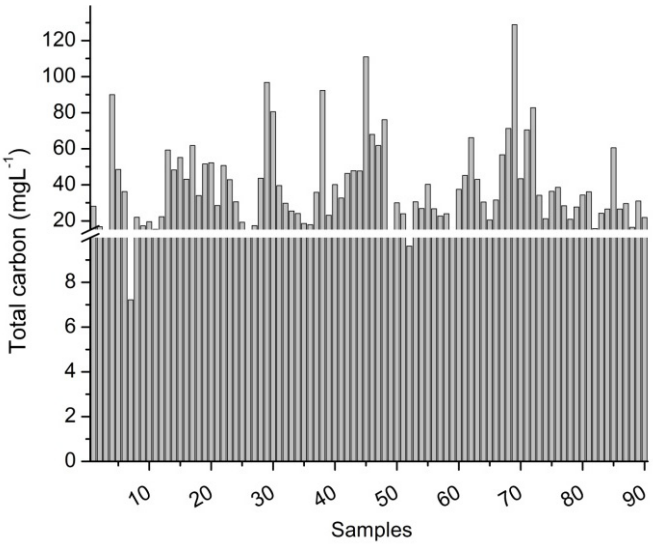

Figure 6.2 Distribution of total carbon content in intertidal water of Cochin mangroves during 2014-2015 period

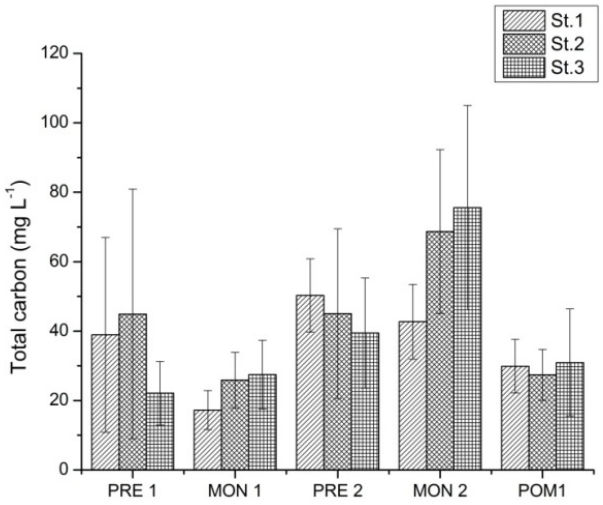

Figure 6.3 Spatio-temporal variation of total carbon content in intertidal waters of the Cochin mangroves during 2014-2015 period

II. Total Organic Carbon

Total organic carbon (n = 90) ranged from 1.35 (St.1, POM 1) to 85 mgL^{-1} (St.3, MON2). The mean TOC was maximum during MON 2 (32.31 ± 16.65 mgL^{-1}). There was no significant spatial and temporal variation of TOC during the study period. However, significant yearly variation was observed (ANOVA $F_{1,67} = 20.496$, $p = 0.000$, n = 72) during the study period. The mean TOC was higher in Year 2 compared to Year 1. The highest mean was observed in St.3 (27.49 ± 20.26 mg L^{-1}) in the second year. St.2 had 26.28 ± 15.85 mg L^{-1} TOC compared to St.1 (17.83 ± 12.16 mg L^{-1}) in the second year. In the first year, St.2 was having slightly higher TOC (15.58 ± 22.69 mg L^{-1}) compared to St.3 (10.56 ± 7.96 mg L^{-1}) and St.1 (7.56 ± 6.31 mg L^{-1}). The annual change in TOC in different stations and the different season is shown in Fig.6.4.

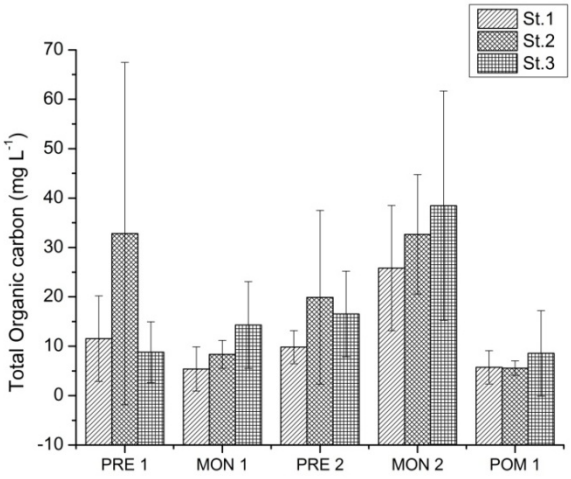

Figure 6.4 Spatio-temporal variation of total organic carbon content in the intertidal water of Cochin mangroves during 2014-2015 period

III. Dissolved Organic Carbon

Dissolved organic carbon (n=90) ranged from 1.2 (St.3, POM 1) to 78.2mg L^{-1}(St.2, PRE1). The mean DOC was maximum during MON 2 (20.9

± 3.3 mg L^{-1}). There was no significant spatial and temporal variation for DOC during the study period. However significant yearly variation was observed (ANOVA $F_{1,67} = 9.51$, $p = 0.003$, n = 72). The second year showed the highest mean DOC compared to the first year, and it was in St.2 (17.01± 10.39 mg L^{-1}). The mean DOC in St. 1 was 11.57 ± 8.28 mg L^{-1}, and in St.3, it was 14.93 ± 7.13 mg L^{-1} during the second year. In the first year also, St.2 was having higher DOC (13.23 ± 22.74 mg L^{-1}) compared to St.1 (6.34 ± 6.05 mg L^{-1}) and St.3 (6.99 ± 6.16 mg L^{-1}). The variation in DOC in different stations and the different seasons are shown in Fig.6.5.

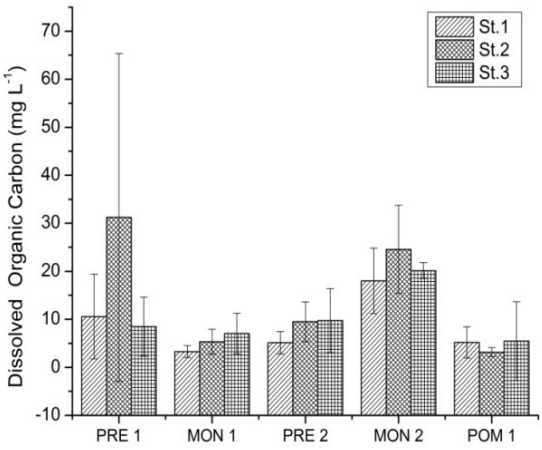

Figure 6.5 Spatio-temporal variation of dissolved organic carbon content in the intertidal water of Cochin mangroves during 2014-2015 period

IV. Particulate Organic Carbon

The particulate organic carbon (n=90) ranged from 0.09 (St.1, MON 1) to 40.05 mg L^{-1}(St.2, PRE 2) during the entire study period. The mean POC was maximum during MON 2 (11.41± 14.55 mg L^{-1}) and minimum during PRE 1(0.95 ± 0.74 mgL^{-1}). DOC did not vary significantly with stations. However significant seasonal and yearly variation was observed (ANOVA $F_{1,67} = 11.884$, $p = 0.001$, and ANOVA $F_{1,67} = 40.6882$, $p = 0.000$ respectively,

n = 72) during the study period. The mean POC was higher in Year 2 compared to Year 1. The highest mean was observed in St.3 (12.56 ± 16.99 mg L^{-1}) in the second year, followed by St.2 (9.27 ± 10.72 mg L^{-1}) and St.1 (6.26 ± 6.60mg L^{-1}). In the first year also St.3 was having slightly higher POC (3.57 ± 5.19 mg L^{-1}) compared to St.2 (2.32 ± 1.37 mg L^{-1}) and St.1 (1.22 ± 1.99 mgL^{-1}). The annual change in POC in different stations and the different seasons are shown in Fig.6.6.

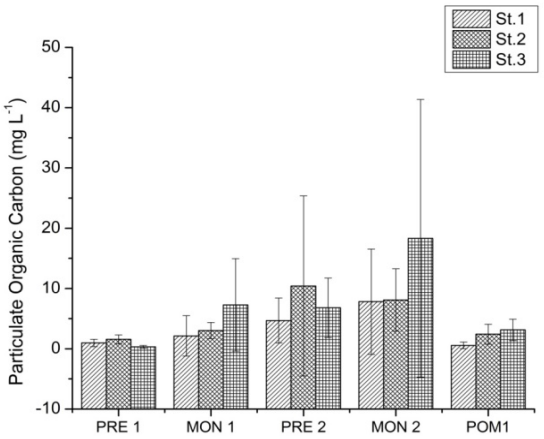

Figure 6.6 Spatio-temporal variation of particulate organic carbon content in intertidal water of Cochin mangroves during 2014-2015 period

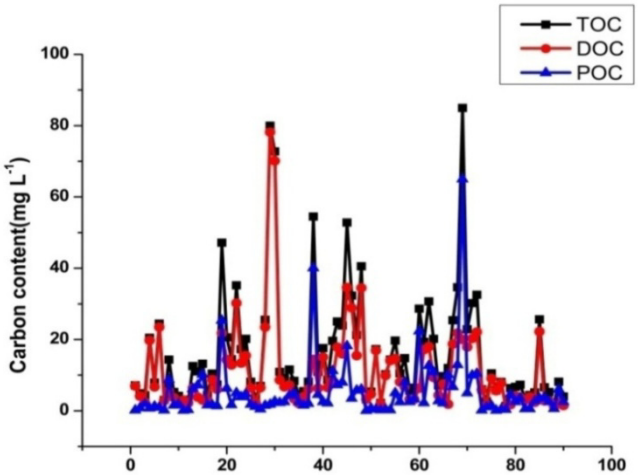

Figure 6.7 The variation in TOC, POC and DOC content in the intertidal water of Cochin mangroves during 2014-2015 period

The contribution of DOC was high compared to POC in total organic carbon fragment of the water present in the mangrove surface water in the study area (Fig.6.7).

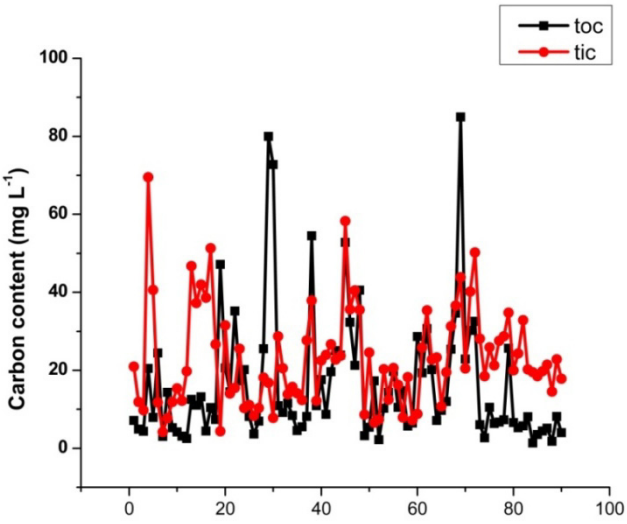

Figure 6.8 Comparison of concentration of TIC and TOC in the tidal surface water of mangroves of the study area

V. Total Inorganic Carbon

Total inorganic carbon (n = 90) ranged from 4.18 (St.1, MON 1) to 69.50 mg L^{-1}(St.1, PRE1) during the study period. The carbon dynamics showed that inorganic carbon contributed more to the total carbon content in mangrove tidal creek water compared to organic carbon (Fig.6.8). The mean TIC was maximum during MON 2 (30.02 ± 14.22 mg L^{-1}) followed by pre-monsoon season 2 (29.5 ± 11.18 mg L^{-1}), and the minimum was observed during MON1 (14.19 ± 6.03 mg L^{-1}). TIC showed significant variation only with the year (ANOVA $F_{1,67} = 27.54$, $p = 0.000$, n = 72) during the study period. The mean TIC was higher in year 2 compared to year 1 that was similar to organic carbon. The highest mean was observed in St.2 and St.3 (30.60 ± 11.87mg L^{-1}

and 30.02 ± 11.54 mg L^{-1} respectively) with a slightly low value in St.1 (28.65 ± 15.15 mgL^{-1}). In the first year also St.1 was having higher TIC (21.15 ± 15.16 mg L^{-1}) compared to St.2 (17.15 ± 6.63 mg L^{-1}) and St.3 (16.29 ± 7.79 mgL^{-1}). The annual change in TIC in different stations and different seasons is shown in Fig.6.9.

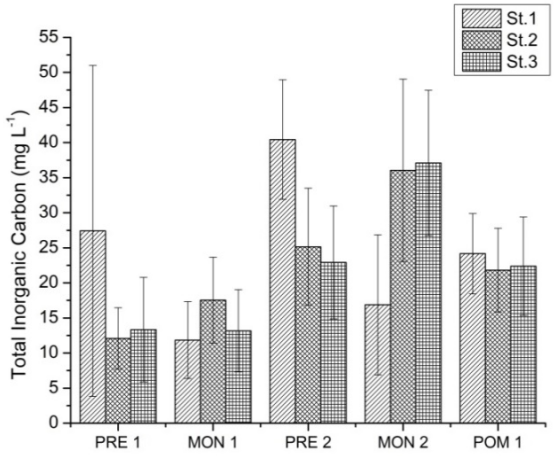

Figure 6.9 Spatio-temporal variation of total inorganic carbon content intertidal water of Cochin mangroves during 2014-2015 period

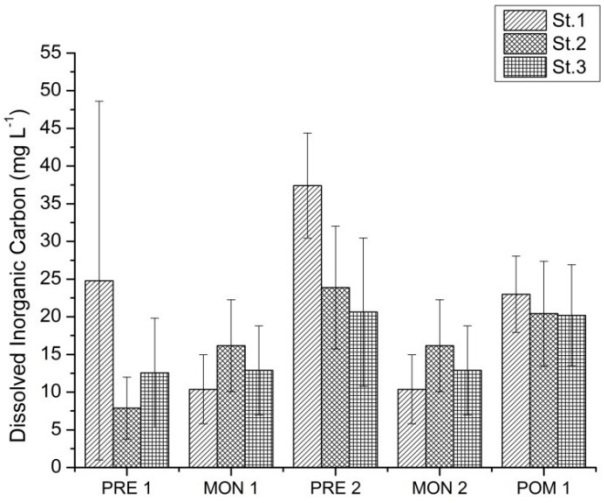

Figure 6.10 Spatio-temporal variation of dissolved inorganic carbon content in intertidal water of Cochin mangroves during 2014-2015 period

VI. Dissolved Inorganic Carbon

The dissolved inorganic carbon (n = 90) ranged from 3.2 (St.1, MON 1) to 67.18 mg L^{-1}(St.1, PRE1) during the study period. The mean DIC was maximum during MON 2 (29.12 ± 14.88 mg L^{-1}) and pre-monsoon season 2 (27.3 ± 10.87 mg L^{-1}) and the minimum was observed during MON1 (13.14 ± 5.77 mg L^{-1}). DIC varied significantly only with the year (ANOVA $F_{1, 67}$ = 26.38, p = 0.000, n = 72) during the study period. The second year showed higher DIC compared to the first year. The highest mean was observed in St.2 (30.26 ± 12.80 mg L^{-1}) followed by St.3 (28.12 ± 12.35 mg L^{-1}) with a slightly low value in St.1 (26.26 ± 14.23 mgL^{-1}). In the first year, St.1 was having higher DIC (19.39 ± 14.96 mg L^{-1}) compared to St.2 (14.81 ± 7.67 mg L^{-1}) and St.3 (15.21 ± 7.23 mgL^{-1}). The annual change in DIC in different stations and the different season is shown in Fig.6.10. Among the dissolved carbon fractionation, dissolved inorganic carbon was more compared to DOC in mangrove surface water.

VII. Total Nitrogen

The total nitrogen (n = 90) ranged from 0.15 (St.3, POM 1) to 32.1mgL^{-1}(St.2, MON 2) during the study period. The mean TN was maximum during MON 2 (11.47 ± 7.36 mg L^{-1}) and the minimum during PRE1 (1.76 ± 1.05 mgL^{-1}). Total nitrogen significantly varied with year (ANOVA $F_{1,67}$=83.697, p = 0.000, n = 72) and season (ANOVA $F_{1,67}$ = 30.66, p = 0.000, n = 72) during the study period. The second year showed higher TN compared to the first year. The highest mean was observed in St.2 (10.09 ± 8.90 mg L^{-1}) followed by St.3 (9.63 ± 5.22 mg L^{-1}) and St.1 (5.37 ± 2.52 mg L^{-1}). In the first year, there was no much variation for nitrogen concentration between stations. In St.1, it was 2.58 ± 0.92 mg L^{-1}, St.2 = 2.58 ± 0.95 mg L^{-1} and in St.3 it was 2.32 ±

1.25mg L^{-1}. The annual change in TN in different stations and the different seasons was shown in Fig.6.11.

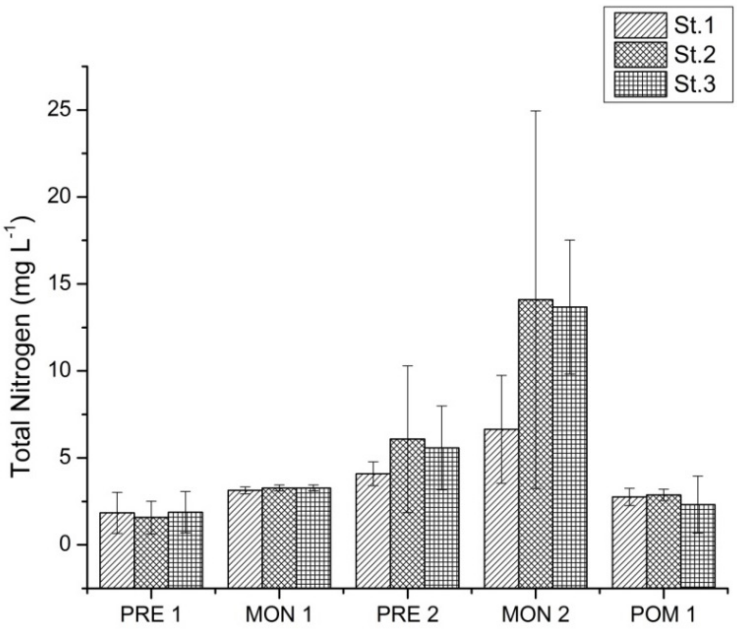

Figure 6.11 Spatio-temporal variation of total nitrogen content in intertidal water of Cochin mangroves during 2014-2015 period

VIII. Dissolved Nitrogen

The dissolved nitrogen (n = 90) ranged from 0.07 (St.3, POM 1) to 23.25mg L^{-1}(St.2, MON 2) during the study period. The mean DN was maximum during MON 2 (6.02 ± 5.60 mg L^{-1}), and the minimum was observed during PRE1 (1.10 ± 0.989 mgL^{-1}). Dissolved nitrogen significantly varied with year ($\chi^2(1) = 16.258$, $p = 0.000$, n = 72) and season ($\chi^2(2) = 8.908$, $p = 0.003$, n = 72) during the study period. The second year showed higher dissolved nitrogen compared to the first year. The highest mean was observed in St.2 (6.16 ± 6.63mg L^{-1}) followed by St.3 (5.04 ± 2.47 mg L^{-1}) and St.1 (2.90 ± 1.18 mg L^{-1}). In the first year, there was no much variation in nitrogen concentration between stations. In St.1, it was 2.35 ± 0.91 mg L^{-1}, St.2 = 2.33 ±

1.00 mgL^{-1} and in St.3 it was 1.44 ± 1.32mg L^{-1}. The annual change in DN in different stations and the different seasons is shown in Fig.6.12.

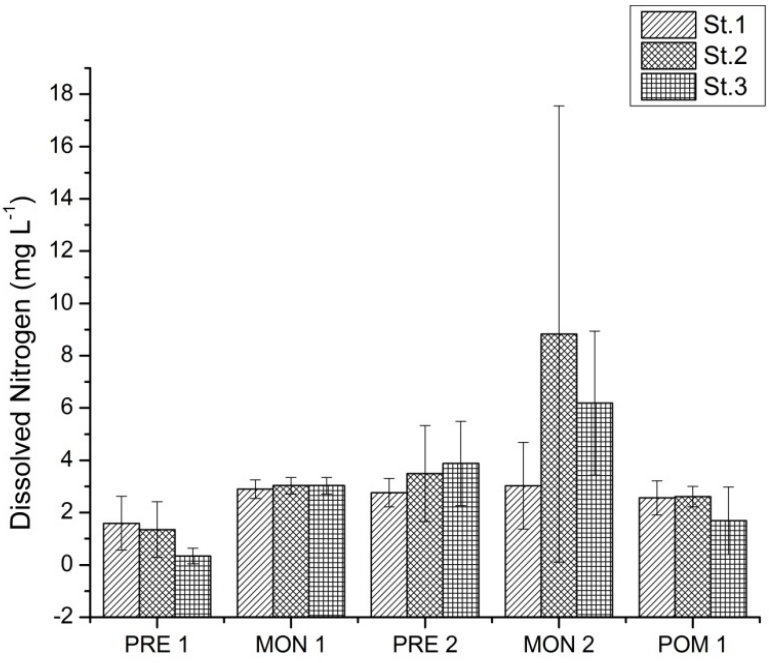

Figure 6.12 Spatio-temporal variation of dissolved nitrogen content in in intertidal water of Cochin mangroves during 2014-2015 period

6.4.2 Organic matter source characterisation

I. Mangrove intertidal water

The stable isotope analysis of water samples from the mangrove habitats of the study area revealed that in St.1 carbon and nitrogen have depleted values (-26.76 ± 0.20 ‰ for $\delta^{13}C$ and 6.07 ± 0.24 ‰ for $\delta^{15}N$). In St.2, even though carbon showed depleted value (-26.68 ± 0.26 ‰ for $\delta^{13}C$), $\delta^{15}N$ was slightly enriched with a mean of 8.85 ± 0.23 ‰. The St.3 showed depleting values for carbon and nitrogen inside the mangrove habitats (-28.80 ± 0.15 ‰ for $\delta^{13}C$ and 8.05 ± 0.21 ‰ for $\delta^{15}N$) while it showed enriched values (-21.73 ± 0.58 ‰ for $\delta^{13}C$ and 7.21 ± 0.42 ‰ for $\delta^{15}N$) near the opening of feeder canal (St.5)

from the Cochin estuary to the mangrove habitat. The other stations did not show any variability in stable isotope ratio within the station (Fig 6.13).

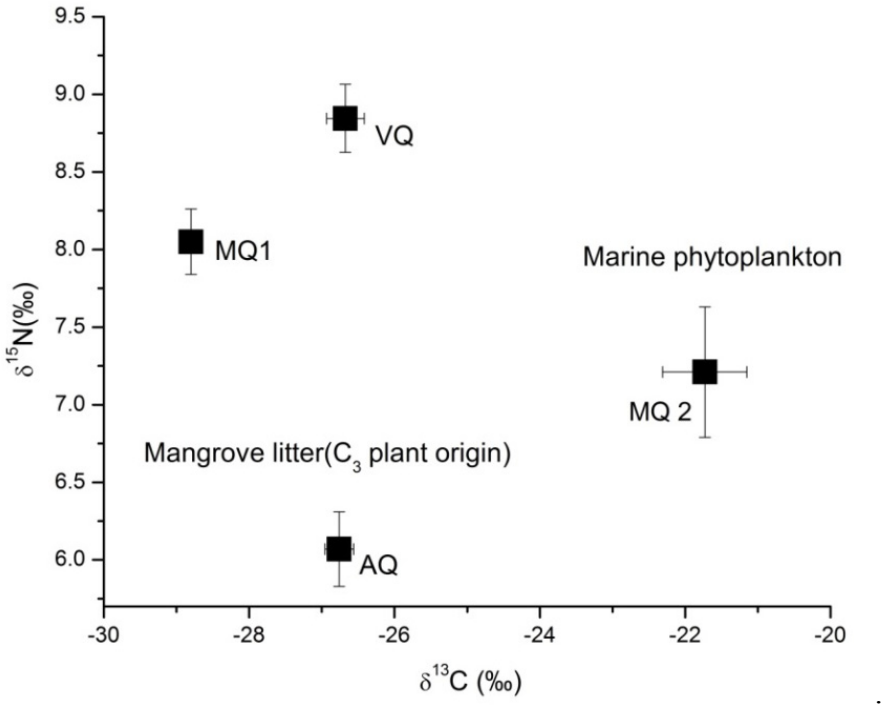

Figure 6.13 Stable isotope ratio of carbon and nitrogen in the POM samples of Cochin mangroves during June 2017

II. Stable isotope analysis of estuarine samples

The POM samples from Barmouth of the Cochin estuary to a station near to mangrove habitat showed a decrease in $\delta^{13}C$ and $\delta^{15}N$. The Barmouth station (St.1) was having a mean $\delta^{13}C$ of -23.64 ± 0.87 ‰ and mean $\delta^{15}N$ of 5.28 ± 0.23 ‰ during low tide and -20.93 ± 0.26 ‰, 6.84 ± 0.09 ‰ for respectively during high tide. The station near to mangrove habitat showed more depleting values for carbon and nitrogen $\delta^{13}C$ and $\delta^{15}N$ (Table 6.1). The St.5 have shown more depleted $\delta^{13}C$ (-24.77 ± 1.06 ‰ in low to high tide and -25.24 ± 0.81 ‰ during high to low tide) and $\delta^{15}N$ (4.46 ± 0.21 ‰ in low to high tide and 3.85 ± 0.22 ‰ during high to low tide).

Table 6.1 Stable isotope ratio of POM samples from the Cochin estuary during at a tidal cycle during June 2017

Stations	Tide	$\delta^{13}C$	$\delta^{15}N$
St.1	low	-23.64±0.87	5.28±0.23
	high	-20.93 ±0.26	6.84±0.09
St.2	low-high	-23.68±1.34	5.60±0.14
	high-low	-19.78±0.96	7.26±0.26
St.3	low-high	-24.32±0.32	6.25±0.21
	high-low	-25.74±0.78	7.23±0.17
St.4	low-high	-25.33±0.74	4.97±0.18
	high-low	-23.44±1.67	2.74±0.20
St.5	low-high	-24.77±1.06	4.46±0.21
	high-low	-25.24±0.81	3.85±0.22

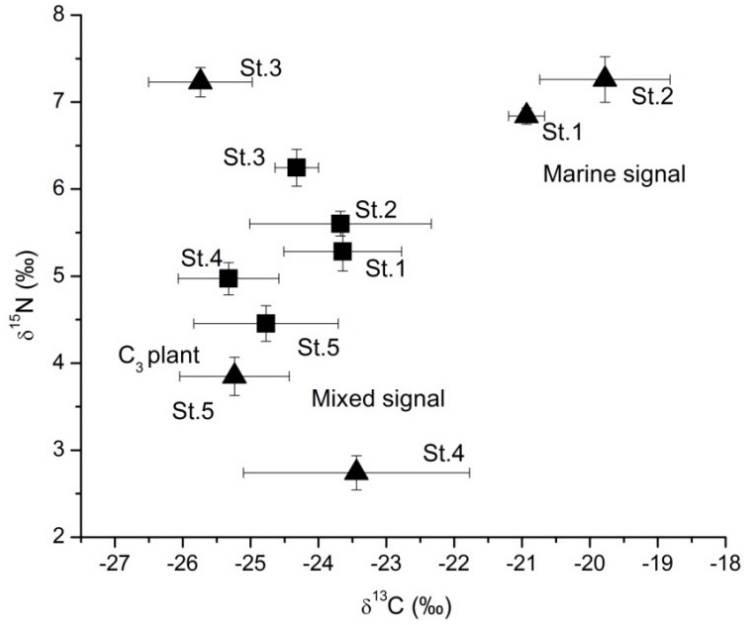

Figure 6.14 Stable isotope ratio comparison for detecting organic matter source in the sampling stations of Cochin estuary during June 2017

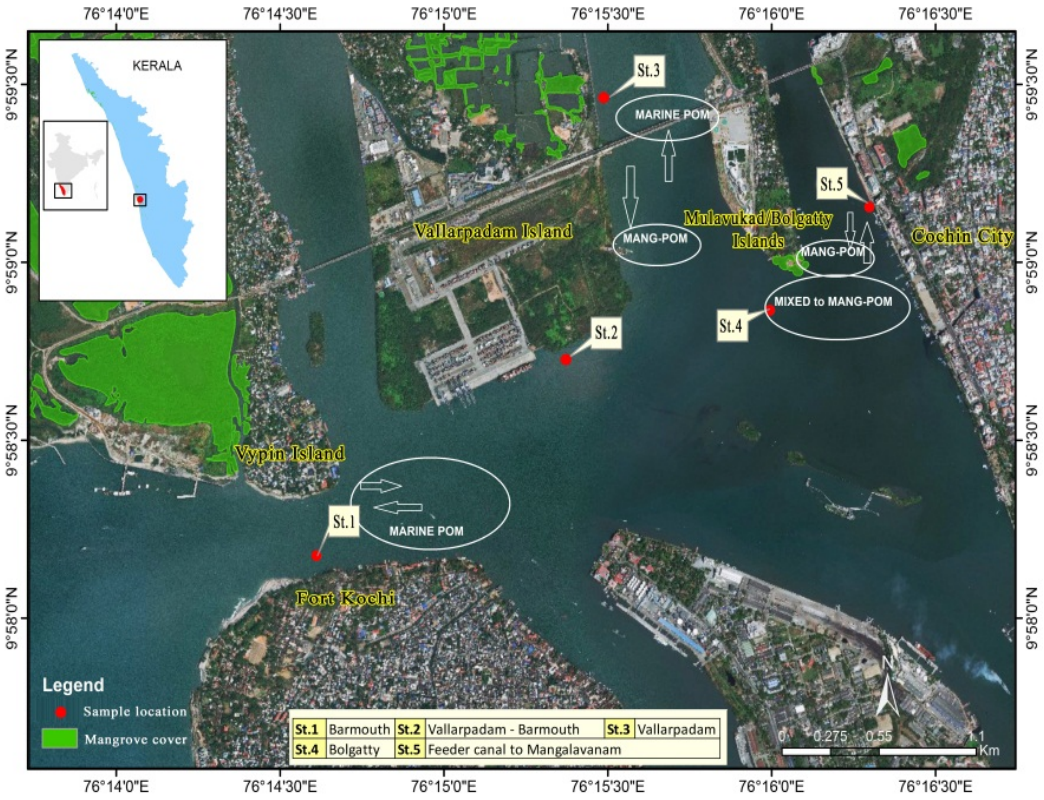

Figure 6.15 Pictorial representation of carbon source characterisation in the Cochin estuary

⟶ Low tide to high tide
⟵ High tide to low tide
Mang-POM: mangrove -derived POM

The stable isotope ratio of sediment samples in the same stations also corroborated with the POM results and was more depleted in St.5 feeder canal to Mangalavanam mangrove habitat ($\delta^{13}C$ of -25.72 ‰ and $\delta^{15}N$ of 6.82 ‰). The St.4, which is located nearer to St.5, was also showing depleting nature ($\delta^{13}C$ of ‰ and $\delta^{15}N$ of 6.82 ‰). The sediment samples in other three stations showed purely marine origin, in which St.1 was having $\delta^{13}C$ of -23.88 ‰ and $\delta^{15}N$ of 7.41 ‰, St.2 = - 23.68 ‰ for $\delta^{13}C$ and $\delta^{15}N$ of 7.44 ‰ a and St.3 showed $\delta^{13}C$ of -23.7 ‰ and $\delta^{15}N$ of 7.19 ‰. The C/N ratio was very less in

these samples ranging from 10.22 to 12.13. High nitrogen concentration was obtained in stations nearer to mangrove habitat (2.5 g kg^{-1} in St.4 and 2.1 g kg^{-1} in St.5). The $\delta^{13}C$ and $\delta^{15}N$ of POM samples were plotted together in a graph for better comparison with standard ranges for marine and C_3 plant source signal (Fig.6.14. Fig.6.15).The average $\delta^{13}C$ and $\delta^{15}N$ for mangrove leaves in the study area was -28.42 ± 1.1 ‰ and 5.86 ± 1.0 ‰ respectively.

6.5 Discussion

6.5.1 Carbon variants in intertidal water of mangrove habitats

High carbon pool was obtained in the water samples from the mangrove habitats of the present study, compared to various studies. The range of POC, DOC and DIC was very high compared to Machiwa,1999; Bouillon et al., 2003b; Dittmar et al., 2006; Liu et al., 2016; Ray et al., 2018. However, the mean DOC and POC is comparable to Godavari estuary and surrounding mangroves by Bouillon et al., 2003b. It was higher than Sundarban mangroves (Ray et al., 2015; Ray and Shakkari, 2016) and Amazonian mangroves (Dittmar and Lara, 2001a).The range of POC in the present study was 0.09 - 12.88 mg L^{-1}. This range was higher than Iranian mangroves (4–5 mg L^{-1}) and Sundarbans (0.3–0.6 mg L^{-1}) reported by Ray and Shahraki, 2016; African mangroves (0.3–4.06 mg L^{-1}, Bouillon et al., 2007); southeast Brazilian mangroves (0.8–3.29 mg L^{-1}, Rezende et al., 2007) and Australian mangroves (2.4–4.8 mg L^{-1}, Maher et al., 2013). However, high POC range was observed along Southwest Florida Everglades (14–18 mg L^{-1}; Twilley, 1985). One of the reasons for such higher DOC, POC ranges for the Cochin mangroves could be the high water residence time inside the mangrove habitat. It could be seen that most of the studies reported DOC, POC and other carbon variants was for tidal creek water.

However, the current study represents the carbon dynamics in the intertidal water inside the mangrove habitat. The depth of the study area was below 0.5 m, and in St1 and St.3 the depth was not more than 0.30 m. Therefore more solutes, and particulate matter may dissolve or suspended in the surface water due to tidal mixing. However, in Sundarbans with high river flow together with low water residence time mediated low carbon pool in tidal creek waters and increased the export of DOC, POC to the Bay of Bengal.

Among different forms of carbon, POC exhibited high seasonality and was high during the monsoon season. Except for DIC, all the carbon fractions were high during monsoon season. This high carbon concentration during monsoon season may be due to resuspension of mangrove sediment with the tidal creek water during the monsoon season. The high mangrove litter, together with an assemblage of phytoplankton and resuspended sediment, could contribute to the high POC pool in the mangrove habitats of the study area. Similar observations were reported by Ray and Shahkari, 2016 in Iranian mangroves and Sundarbans. Of the total organic carbon in the mangroves of the study area, 68.23 % was DOC, and 31.73% was POC. However, a slightly higher contribution (72.9 ± 10.6% of the TOC pool) of DOC to TOC was obtained for Godavari mangroves by Bouillon et al., 2003.It was found that more DOC was present in mangrove tidal water than POC. It is expected that more DOC is exported than POC in the present mangrove area similar to reports of Twilley (1985) or it may be efficiently recycled within the forest (Boto et al., 1990; Robertson et al., 1992).

Among the total carbon, 58.35 % was contributed by inorganic carbon, and 41.64 % was contributed by organic carbon. The DIC was also high in the present study (3.2 to 67.18 mg L^{-1}) compared to many literatures (Bouillon et al., 2003; Miyajima et al., 2009). However, it was comparable with the DIC

concentration obtained for intertidal groundwater (45.2 mg L^{-1} to 77.11 mg L^{-1}) in the mangroves of southern Moreton Bay, on the east coast of Australia (Maher et al., 2013) and also with Sippo et al., 2016. Maher et al.(2013) detected the submarine groundwater discharge (SGD) through ^{222}Rn, a tracer for natural submarine groundwater discharge in the mangrove creek water and revealed that the high concentration of DIC in the intertidal groundwater in the mangroves of Moreton Bay was contributed by this SGD discharge and helped in export and import of organic and inorganic carbon. The comparable range of DIC concentration in the intertidal water of Cochin mangroves with other mangrove habitats with SGD indicated that there might be a possibility for the SGD or groundwater source in the present study area.

Inorganic carbon was high (especially DIC) during the pre-monsoon season. The high evaporation rate and high salinity favoured higher DIC (Kone et al., 2009). The pore-water DIC, derived from anaerobic organic matter degradation through the sulfate reduction pathway, could also add to a significant amount of DIC to the total DIC pool (Kone and Borges, 2008).

6.5.2 Organic matter characterisation in POM samples of mangrove stations

The analysis of $\delta^{13}C$ and $\delta^{15}N$ of POM samples in intertidal water of mangroves in flooded condition revealed that the organic carbon in the intertidal water of mangrove habitats was well within the standard range for stable isotope ratio for mangrove plant and similar to the range of $\delta^{13}C$ of mangrove leaf (-28.42±1.1‰) obtained from the study area. Therefore confirmed the origin of organic carbon as POM in intertidal water of the mangrove habitats as mangrove plant. However in St.3, near to the feeder canal from Cochin estuary showed a value of -21.73 ± 0.58 ‰, which purely

signalled towards marine phytoplankton. The $\delta^{15}N$ range (6.91-7.90 ‰) obtained in this station also confirmed the marine organic matter source as POM in St.3. This result indicated that St.3 was receiving a portion of its organic carbon as POM through marine phytoplankton and major nitrogen source as marine phytoplankton. In St.2 also $\delta^{15}N$ was enriched and may be signalling to marine source. However, the carbon source was purely mangrove litter origin in St.2. The $\delta^{15}N$ of POM samples revealed that nitrogen source in St.1 was mangrove plant origin and comparable with standard range and the average $\delta^{15}N$ for mangrove leaf (5.86 ± 1.0 ‰) of the study area from the present study. Thus in St.1, both carbon and nitrogen source as POM is purely based on mangrove litter origin.

6.5.3 Organic matter characterisation in POM samples in estuarine samples

The stable isotope results, and carbon variants analysis revealed that there is a probability for export of this mangrove-derived organic matter to adjacent coastal waters mainly as DOC or DIC rather than POM since DOC and DIC concentration was very high in mangrove tidal water. The tidal cycle analysis for stable isotope $\delta^{13}C$ and $\delta^{15}N$ in Cochin estuary including two sites adjacent to the mangrove patches revealed that the values $\delta^{13}C$ and $\delta^{15}N$ for POM displayed ranges that are most characteristic of marine POC (marine phytoplankton origin). However, stations near to mangrove patches showed organic matter source for C_3 plants (mangroves). The station near to mangrove patch (St.5) showed more depleted $\delta^{13}C$ and $\delta^{15}N$ (-25.24 ± 0.81‰ and 3.85 ± 0.22 ‰) and during high tide to low tide period with a $\delta^{13}C$ = -25.72 ‰, $\delta^{15}N$ = 6.82 ‰ in sediment samples. This stable isotope ratio during the tidal cycle indicated that considerable export of mangrove-derived organic carbon was taking place from mangrove habitat to the estuary during the tidal cycle. The

Vallarpadam region (St.3) also nearer to mangrove habitat signaling towards export of mangrove organic carbon to the estuary during high tide to low tide period with its mangrove plant range for $\delta^{13}C$ and $\delta^{15}N$ in POM samples and sediment samples ($\delta^{13}C$ = -25.74 ±0.76‰ ‰, $\delta^{15}N$= 7.23 ±0.17‰ in POM samples and $\delta^{13}C$ =-23.68 ‰, $\delta^{15}N$= 7.44 ‰ in sediment samples). The mangrove source origin for organic carbon was diminishing, and marine phytoplankton source was found increasing towards Barmouth region of the estuary. It indicated that Cochin estuary was mainly depending on phytoplankton-derived organic matter and the influence of mangrove patches as organic matter source was limited to only a few kilometres. The reason may be the degradation of mangrove areas in and around Cochin estuary decreased its outwelling capacity to the estuary.

A further detailed study is required to confirm the source of organic carbon by analysing the $\delta^{13}C$ of all the possible source materials in that area by applying suitable mixing models. However, the stable isotope ratio for DIC was not accounted for in the present study. The literature showed that DIC export was high from mangroves compared to DOC export, which acts as a major missing carbon sink from the mangrove-derived blue carbon paradigm (Bouillon et al., 2008; Maher et al., 2013; Ray et al., 2018; Maher et al., 2018). Therefore future research should account for detailed ground water-mediated DIC export and its source characterisation through stable isotope analysis. The fate of this mangrove-derived DIC in the ocean through the estuary should also be accompanied by greenhouse gas emission studies in the mangrove ecosystem and the estuary.

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Chapter 7

CARBON STOCK ASSESSMENT IN MANGROVE SOIL

7.1 Introduction

The carbon which is received in the mangrove ecosystem as litterfall may be stored in the soil as soil carbon stock, which is the amount of carbon in the soil for a particular area. The litter from mangroves is decomposed within weeks by the leaf-eating herbivorous crabs (Nordhaus et al., 2006) and is stored in the soil pool. According to IPCC (2006) soil carbon pool is defined as "Carbon in mineral soils to a specified depth chosen and applied consistently through a time series. Live and dead fine roots within the soil (of less than the suggested minimum for belowground biomass) are included wherever they cannot be empirically distinguished from the soil organic matter". This carbon includes both organic and inorganic carbon, which may be mangrove origin or marine origin. An ecosystem with most of its organic carbon in nonreactive, recalcitrant pools will store carbon for longer periods than an ecosystem with a major portion of its organic carbon in active pools like microbial biomass (Buyanovsky et al., 1994). Some studies have revealed that 90 % of mangrove primary productivity are stored in their substrate (Donato et al., 2011; Kauffman et al., 2011; Stringer et al., 2015). According to recent estimates by Hamilton and Friess (2018) 2.96 ± 0.53 Pg of carbon is stored globally in

mangrove soil, which is equivalent to 70.65 % of total ecosystem carbon stock of global mangroves. Therefore, soil carbon stock or soil carbon pool assessment is very relevant for total ecosystem carbon stock assessment in a mangrove ecosystem. The long term soil carbon burial thus depends on the soil carbon stock of mangrove ecosystem (Kristensen et al., 2008).

The source characterisation of organic carbon in the soil carbon stock is also essential in determining the importance of mangrove-derived carbon in the regional and global level. Only through the organic carbon source analysis, quantifying the carbon sequestration potential of mangroves or its ability to reduce CO_2 from the atmosphere will be more meaningful. In the past, the C/N ratio was used as a proxy to determine the carbon source in a system. Nowadays the application of chemical tracers (stable isotopes) to identify the source and fate of organic matter in coastal environments is attaining more scientific interest (Kuramoto and Minagawa, 2001; Gonneea et al.,2004; Tremblay et al., 2007; Kristensen et al.,2008; Weiss et al., 2016). The stable isotopes of carbon ($\delta^{13}C$), together with nitrogen ($\delta^{15}N$), are used to characterize organic matter source and cycling in coastal environments and mangrove ecosystems.

7.2 Literature Review

The mangrove soil carbon and its dynamics related to litterfall decomposition is always a topic of research in mangrove ecosystems since ancient times. Many studies are reported on organic matter cycling and mineralization process in the mangrove soil (Lacerda et al., 1995; Alongi, 1996; Jennerjahn and Ittekkot, 1997; Alongi et al., 1999; 2000; Kristensen, 2000; Jennerjahn and Ittekkot, 2002; Alongi et al., 2005b). Lacerda et al. (1995) studied the organic carbon stock in different monospecific stand of mangroves and found out that there is a difference in the biogeochemistry of

organic matter in the mangrove soil depending upon the mangrove species. According to their study, nitrogen and organic carbon content are high in *Avicennia* zone compared to *Rhizophora* zone.

Mineralisation of organic matter in mangrove sediments of Australia and Thailand was studied by Alongi et al., 1999 and Kristensen, 2000. Chen and Twilley, 1999 formulated a simulation model for nutrient and organic matter accumulation in mangrove soils. Later Alongi et al., 2001 studied in detail about the metabolic pathways which controlled the organic carbon accumulation in mangrove soil. In 2002, Jennerjahn and Ittekkot reviewed all the available data on mangrove production, sedimentation of organic matter and export data and highlighted the importance of mangroves in the deposition of organic matter along tropical continental margins. The source characterization of organic carbon in mangrove sediments was another breakthrough study which actually confirmed the mangrove plant origin of organic carbon buried in the mangrove environment (Bouillon et al., 2003a).

The studies, particularly on soil carbon stock, were done both in global and regional levels. The ecosystem carbon stock assessment of global mangroves by many researchers is always accompanied with soil carbon stock (Duarte et al., 2013; Alongi, 2012 and 2014; Hamilton and Friess, 2018). The global soil carbon has decreased from 9.4 -10.4 Pg C (Duarte et al., 2013) to 2.96 ± 0.53 Pg of carbon (Hamilton and Friess, 2018). The fast degradation of mangroves and conversion of mangroves to aquaculture farms triggered the loss of carbon stock in mangrove soil. The soil carbon stock in different mangroves habitats of the world was studied in detail by many researchers. Matsui (1998) estimated organic carbon stocks of mangrove roots and sediments in Hinchinbrook Channel, Australia. The estimated mean soil carbon stock was 296 t C ha^{-1} contributes nearly 64 % to the ecosystem carbon stock

in that area. Khan et al., 2007 studied carbon as well as nitrogen stock in monospecific pioneer stands of *Kandelia obovata* in Japan and found low organic carbon stock of 57.3 t C ha^{-1} in the soil. From 2010 to the present, there have been numerous studies reported on soil carbon stock and ecosystem carbon stock of mangroves. Kauffman et al., 2011 studied ecosystem carbon stock in Micronesian mangroves and found out that ~70% of ecosystem carbon stock was pooled in soil. Zhang et al., 2012 checked whether restoration of mangroves resulted in any change in sedimentary organic carbon content in Southern China. They checked the carbon stock in barren, plantation and natural mangrove forests in the study area and found out that restoration of mangroves improved soil carbon stock compared to barren sites. Later, in Southern China, Wang et al., 2013 assessed the ecosystem carbon stock of mangroves along the tidal gradient and found out an increase in carbon stock in biomass as well as in soil carbon stock from low intertidal region to the high intertidal zone. Carbon stocks of Mexican Caribbean mangroves were studied by Adame et al., 2013 and found out that soil carbon stock contributed 78-99% of ecosystem carbon stock. They also concluded that environmental variables such as salinity and phosphorus limited the carbon stock in their study area. Lunstrum and Chen (2014) studied the carbon stock and accumulation in sediments of young mangrove forest of South-East China. Later many studies were conducted on mangrove soil carbon stock around the world by; Sitoe et al. (2014) in Sofala bay mangroves, Tue et al.(2014) in Vietnam mangroves, Abino et al. (2014) in Philippines mangroves, Adame et al. (2015) in Mexican mangroves, Bhomia et al. (2016b) in the Pacific and Caribbean coasts of Honduras, MacKenzie et al. (2016) in Vietnam mangroves, Eid and Shaltout (2016) in Egyptian mangroves while Bulmer et al. (2016) studied carbon and nitrogen stocks in a temperate mangroves in New Zealand.

The difference in soil organic carbon (SOC) stock of marine mangroves, estuarine mangroves and degraded mangroves of Indonesia was studied by Weiss et al., 2016 and reported high SOC stock for marine mangroves followed by estuarine mangroves and degrading mangroves. The soil carbon stock and the reduction in the carbon stock of mangroves due to the conversion of land use as cattle pastures in Mexican mangroves was studied by Kauffman et al., 2016. Recently, Marchand, 2017 reported the SOC stock in mangroves of French Guiana and found out that SOC stock increased with age of mangrove stand. A low carbon sink of mangrove habitat in the Red Sea was studied recently by Almahasheer et al., 2017. They reported very low organic carbon stock in the soil as well as low burial rate compared to humid regions of the world. They concluded that low rainfall and extreme weather conditions decreased mangrove plant growth rate and increased respiration rate resulting in low sink capacity of these mangroves.

In Indian mangroves, the soil carbon studies were initially focused either on organic carbon content and C/N ratio related to biodiversity studies (Pravinkumar et al., 2013 in Pichavaram mangroves) or on chemical characterization (Sebastian and Chacko, 2006 and Geetha et al., 2008 in Cochin mangroves; Thilagavathi et al., 2011 in Muthupettai mangroves). The organic matter source characterization using stable isotopes and lignin phenols in the mangrove habitats of Pichavaram, Tamil Nadu was done by Prasad and Ramanathan (2009). They reported the influence of mangrove litter in sedimentary organic carbon. Ranjan et al. (2010) studied in detail on the characterization of organic matter in the Pichavaram mangroves, Tamil Nadu. They reported the organic matter in core sediment samples of mangroves and two estuarine complexes near this mangrove habitat and linked the pore water salinity, DOC, C/N ratio and chlorophyll pigments in order to characterize the

sediment biogeochemistry of estuarine complex. Mukherjee et al. (2014) reported the effect of various environmental factors on organic carbon stock of Sagar Island of the Hooghly-Malta estuarine ecosystem in Sundarban forest.

Recently some research works were reported on mangrove soil carbon stocks and sequestration potential. Ray et al. (2011) studied the carbon sequestration by biomass increment and also reported the annual soil carbon storage in the Sundarban mangroves. The carbon stocks of Mahanadi Mangrove forest (natural and planted), East Coast of India was studied by Sahu et al. (2016). They found out a positive correlation between vegetation biomass and soil organic carbon, which indicated the contribution of vegetation in building surface sediment organic carbon. The effect of land use change on carbon stocks of mangroves in Bhitarkanika was studied in detail by Bhomia et al. (2016a). They assessed dense mangrove forests, scrub mangroves, restored/planted mangroves and abandoned aquaculture ponds for ecosystem carbon stocks. The aquaculture farms were having to low soil carbon stocks compared to other mangrove habitats in their study. In the regional level, studies on mangrove carbon are limited. Sebastian and Chacko (2006) reported the soil texture and organic matter content in Cochin mangroves. Geetha et al. (2008) studied the source of organic matter in Cochin mangroves based on the C/N ratio. Later Joseph et al. (2012) reported the source of organic matter in mangroves of Cochin based on C/N ratio, $\delta^{13}C$ and fatty acid profile. The soil carbon stock studies in Kerala mangroves are very scanty, and a recent report came from Kadalundi mangrove forest by Vinod et al. (2018). They estimated ecosystem carbon stock, its CO_2 equivalent and also assessed its economic valuation.

The literature indicated a gap in research on soil carbon stock at the regional level. The assessment of global carbon stocks of mangroves need

more regional data for estimation of accurate CO_2 equivalent for conservation practices, carbon economy and ultimately for regulating climate change problems. Therefore an attempt was taken in order to study the soil carbon stock of selected mangroves of Cochin estuary.

7.3 Materials and Methods

The collection of sediment sample and methodology for the analysis of various physicochemical parameters, carbon and nitrogen are discussed in Chapter 2.2. The pH, Eh, moisture content and sediment temperature of the samples are noted on monthly basis. The carbon and nitrogen analysis was done on a bi-monthly basis. The particle size analysis and bulk density measurement was taken seasonally during the three years of the study (2013-2015). The study area is also described in Chapter 2.2. The bulk density measurement is taken by drying a known volume of sample at 105 ^{o}C in hot air oven to constant weight. The calculation of bulk density is as follows:

Bulk density (g cm^{-3}) = Dry soil weight (g) / Soil volume (cm^3).

Soil carbon stock is calculated from total carbon (TC), soil organic carbon (SOC) and soil inorganic carbon (SIC) by substituting corresponding TC, SOC and SIC values in the equation:

Carbon pool (t C ha^{-1}) = C con (%) x Bulk density (g cm^{-3}) x depth (cm)

Carbon stock (t) = carbon pool x mangrove area

The mangrove area of the three stations was estimated through remote sensing and GIS (Geographic Information System) method. Arc GIS.10.2 software was used for image processing and area estimation. Multi-temporal medium resolution IRS P6 LISS III imagery was used to extract the mangrove vegetation cover. Extracted data was cross checked with Google satellite

images. GIS tools were used to classify the landuse/land cover of the study area. GPS (Global Positioning System) location of the preset study area was used to create digital signatures to extract the pixel values of the mangrove cover. All those GPS sample location were also used for ground truthing. Identified pixel values were vectorised after the resampling and reclassification processes using GIS technique. Vectorised data was used to calculate the area of mangrove cover. The same methodology was adopted for estimating mangrove cover for entire Kerala.

The stable isotope analysis

Isotope Ratio Mass Spectrometry (IRMS) is a specialised technique used to understand the information about the chemical, geographic, and biological origins of substances. It is derived by analyzing the relative isotopic abundances of the elements which comprise the material. The stable isotope ratios of elements such as carbon and nitrogen may locally be enriched or depleted by different kinetic and thermodynamic factors.

Representative dried sediment samples (in each year three seasonal samples) are taken from carbon stock assessment sample collection (from mangrove stations St.1, St.2 and St.3) from the entire study period (2013-2015) for organic carbon and nitrogen source characterisation (Cole et al., 2011). The air-dried samples were treated with 2 N HCl for removing inorganic carbon, after which it was again dried. The dried samples were packaged in tin capsules for mass spectrometry and analyzed using a PyroCube-IRMS (Serial No.JC 455) for $^{15}N/^{14}N$ and $^{13}C/^{12}C$ ratios. Measurements are reported in [per mil (‰) units], and ovalbumin was used as a routine standard. Precision for $\delta\ ^{13}C$ and $\delta\ ^{15}N$ was generally ± 0.2 ‰ and ± 0.4 ‰.

7.4 Results

7.4.1 Physico-chemical characterisation of sediment

The major physicochemical characters of the sediment samples in the mangrove habitat is described in Chapter 2.4.3.2 The sediment temperature was high during the pre-monsoon season and low during the post-monsoon season. The sediment pH was slightly acidic in St.1 and St.3 while neutral to alkaline pH was observed in St.2. The redox potential of sediment showed reducing nature of the environment in three stations, however more reduced condition was observed in St.2 and St.1. The moisture content was high in St.1 compared to the other two stations. Sediment texture also varied significantly with stations and St.1 was dominated with silt content followed by clay and could be considered as silty-clay loam according to USDA particle size classification. The other two stations could be considered as loamy sand forms since the sand was dominating in sediment texture. The seasonal pattern of sediment texture in three stations showed that the monsoon season was having higher silt content (Fig. 7.1 a-c). The mean bulk density in St.1 was 0.370 ± 0.05 g cm^{-3}, which is very low compared to sand dominated stations at St.2 and St.3. However, St.2 was having a mean bulk density of 0.565 ± 0.32 g cm^{-3} and St.3 showed a mean of 0.793 ± 0.14 g cm^{-3} in dry soil bulk density.

I. Sediment (Soil) Total carbon (STC)

The total carbon in the core sediment samples of the study area significantly varied with the station (ANOVA $F_{2,175} = 48.83$, $p = 0.000$, n = 190) however there was no significant seasonal and annual variation in total carbon content during the entire study period. The total carbon content in the sediment samples of three stations during the study period is shown in Fig.7.2. The mean total carbon in the core sediment samples of St.3 was 74.69± 41.40 g kg^{-1} and had the highest mean among stations followed by St.1 (74.00± 12.03

g kg^{-1}). The lowest total carbon content was observed in St.2 with a mean of 41.0 ± 24.68 g kg^{-1}. However, the mean TC in St.2 was further low (25.47 ± 10.94 g kg^{-1}) when considering only the quadrats (Q1, Q2, Q3) within the aquaculture farm. In this station, total carbon significantly varied with quadrats (One Way -ANOVA $F_{4,35} = 18.02$, $p = 0.000$, n = 40) and the post hoc results (Tukey HSD) also revealed that this significant variation was due to carbon stock in quadrat 4 and 5(Q4, Q5).

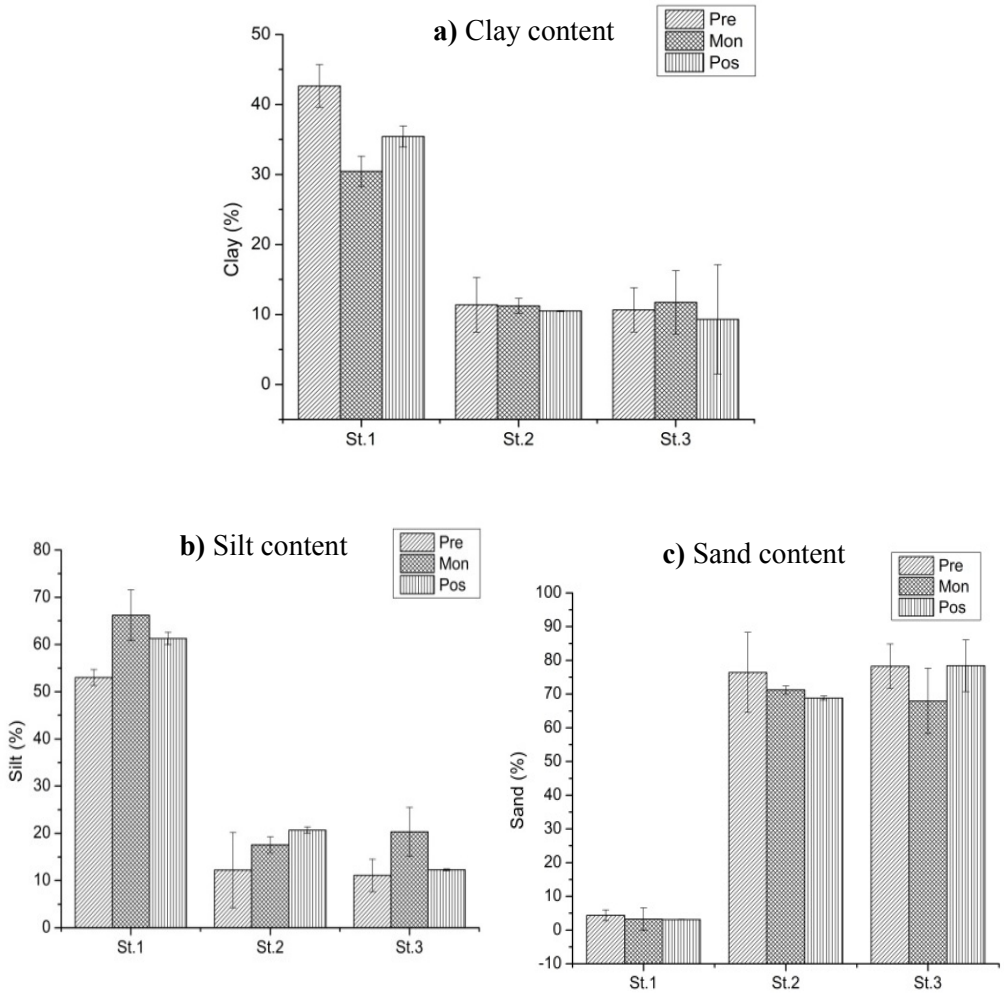

Figure 7.1 a-c Temporal variation of sediment texture in the Cochin mangroves during 2013-2015 period

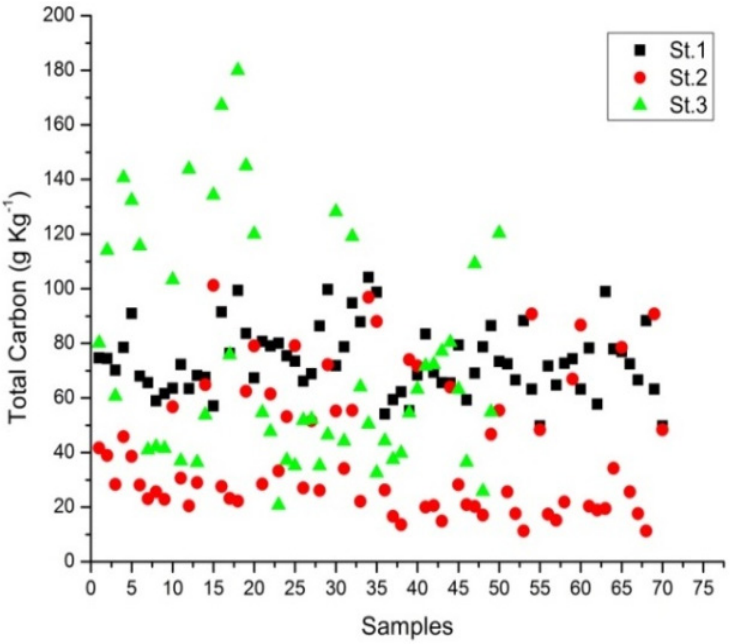

Figure 7.2 Distribution of total carbon content in the sediment samples of Cochin mangroves during 2013-2015 period

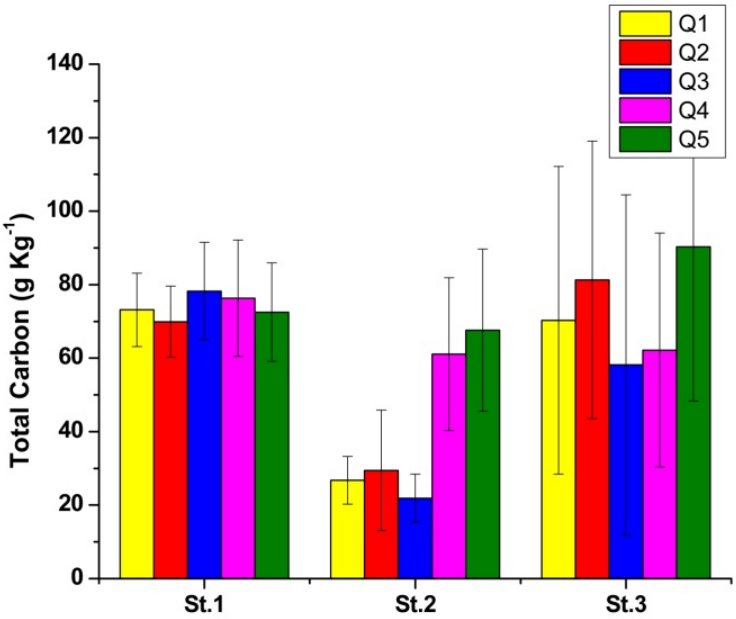

Figure.7.3 Spatial variation in mean total carbon content in the sediment samples of Cochin mangroves during 2013-2015 period

The range of total carbon in St.1 was 54.07(Q1) to 104.1 g kg^{-1} (Q4); in St.2 it was 13.5(Q3) to 101.2 g kg^{-1} (Q5) and in St.3 it ranged from 20.78(Q3) to 180.0 g k^{-1}(Q3). The variation in total carbon content in different quadrats within different stations is shown in Fig.7.3.

II. Sediment (soil) organic carbon (SOC)

The SOC content in the core sediment samples of the study area significantly varied with stations (ANOVA $F_{2, 97} = 55.93$, $p = 0.000$, n =115) but there was no significant seasonal and annual variation during the entire study period. The SOC content in the sediment samples of three stations during the study period is shown in Fig.7.4. The mean SOC in the core sediment samples was highest at St.1 (61.23 ± 11.62 g kg^{-1}) followed by St.3 (59.30± 32.34 g kg^{-1}).

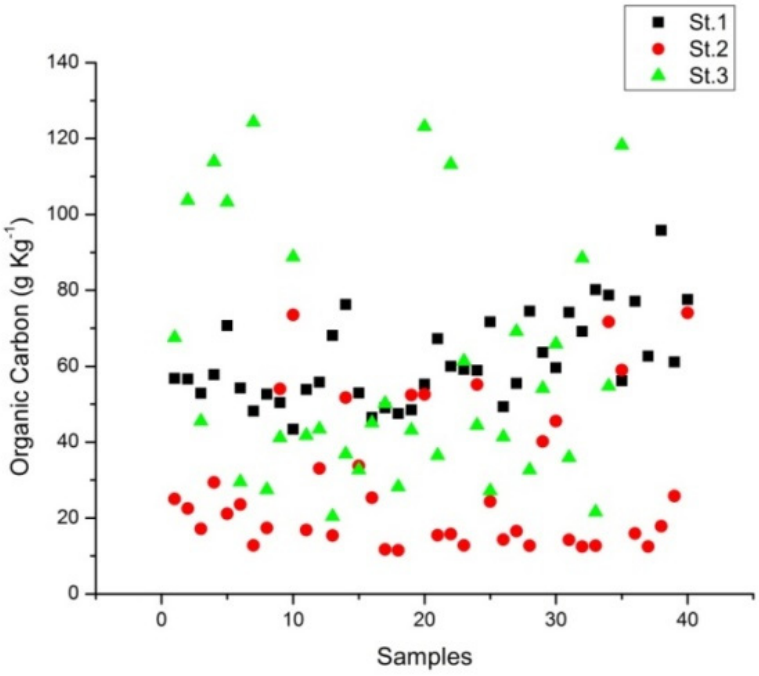

Figure 7.4 Distribution of organic carbon content in the sediment samples of Cochin mangroves during 2013-2015 period

The lowest total carbon content was observed in St.2 with a mean of 29.23 ± 19.18 g kg^{-1}. SOC content was also very low in St.2 while considering only the quadrats (Q1, Q2, Q3) within the aquaculture farm. In St.3 and St.1, a significant portion of the total carbon is contributed by organic carbon. In St.1, 85.27 % of the total carbon is organic carbon, and in St.3, 89.15 % is organic carbon. In St.2, comparatively lower (75.30 %) organic carbon contribution was observed.

The range of SOC in St.1 was 43.34 (Q5) to 95.79 g kg^{-1}(Q3); in St.2 it was 11.46 (Q3) to 74.05 g kg^{-1} (Q 5), and in St.3 it ranged from 20.44 (Q3) to 124.30 g kg^{-1}(Q2). The variation in SOC content in different quadrats within different stations is shown in Fig.7.5

III. Sediment (soil) inorganic carbon (SIC)

The SIC content in the core sediment samples of the study area did not vary significantly between stations and seasons. However, significant annual variation was observed (ANOVA $F_{2,97}$= 28.94, p = 0.000, n=115) in SIC content during the entire study period. In the first year (2013), the mean SIC concentration of the three stations was 16.79 ± 7.07g kg^{-1} that showed a decrease in the next two years (7.36 ± 5.38 g kg^{-1} in year 2 and 4.66 ± 3.95 g kg^{-1} in year 3). The mean SIC in the core sediment samples of St.1 was 11.19 ± 6.74 g kg^{-1}, St.2, 9.41± 6.71 g kg^{-1} and in St.3 it was 9.10 ± 9.49 g kg^{-1}. The range of SIC in the study area was 0.06 to 29.12 g kg^{-1} during the study period. The variation in SIC content in different quadrats within different stations is depicted in Fig.7.6.

IV. Total Nitrogen

The total Kjeldahl nitrogen content in the sediment samples significantly varied between stations (ANOVA $F_{2, 104}$ = 21.88, p =0.000,

n=115) and quadrats within the stations (ANOVA $F_{4,104}$= 4.44, p =0.002, n=115).

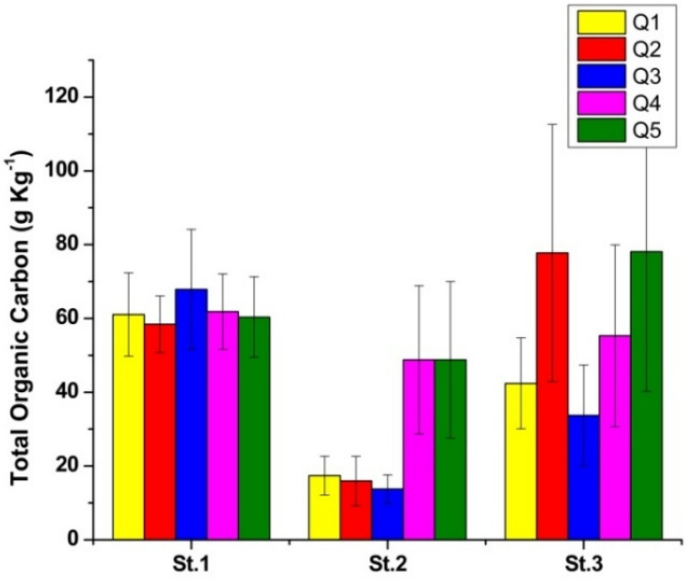

Figure 7.5 Spatial variation in mean organic carbon content in the sediment samples of Cochin mangroves during 2013-2015 period

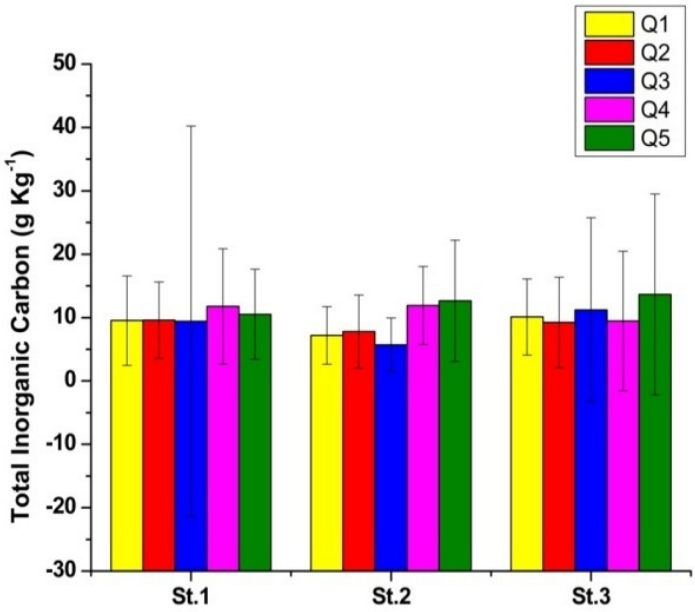

Figure 7.6 Spatial variation in mean inorganic carbon content in the sediment samples of Cochin mangroves during 2013-2015 period

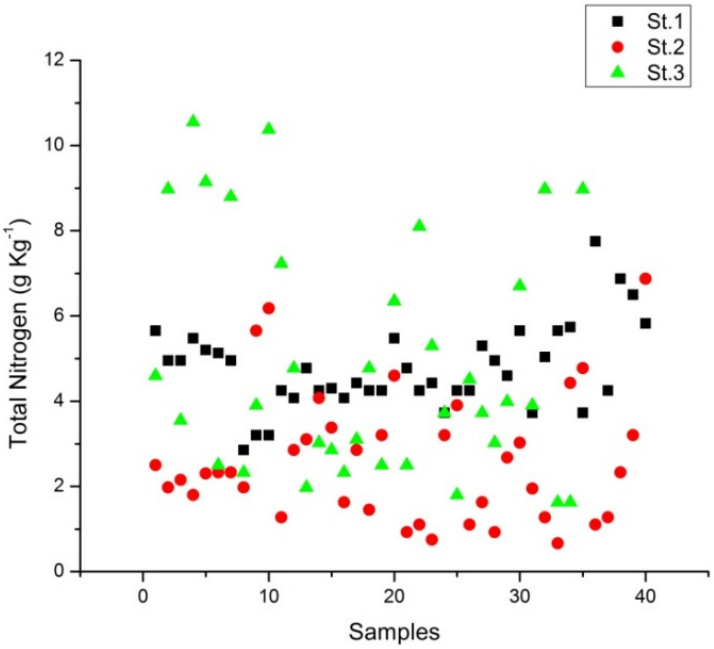

Figure 7.7 Distribution of total nitrogen content in sediment samples of Cochin mangroves during 2013-2015 period

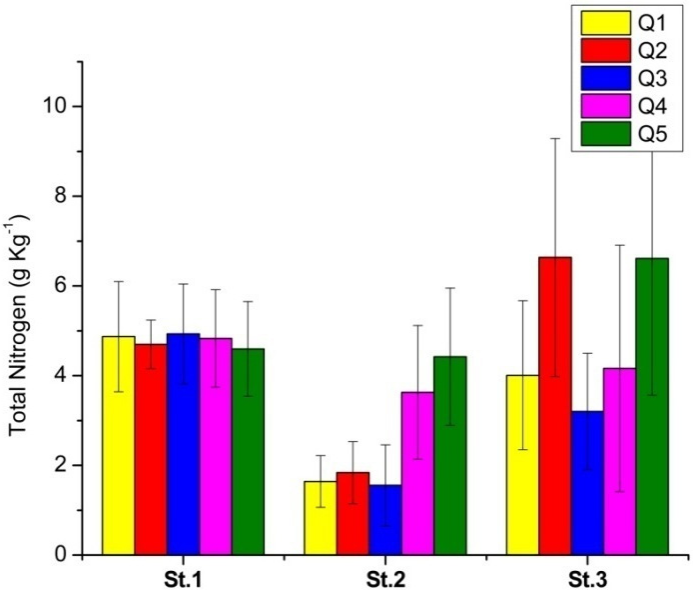

Figure 7.8 Spatial variation in mean total nitrogen content in the sediment samples of Cochin mangroves during 2013-2015 period

There was no significant variation of TN with seasons and years. The nitrogen content in the sediment samples of three stations during the study period is shown in Fig.7.7. The mean nitrogen concentration in the core sediment samples of St.1 and St.3 (4.77± 0.99 g kg^{-1} and 4.92 ± 2.76 g kg^{-1} respectively) was slightly higher compared to St.2 which had a mean nitrogen concentration of 2.62± 1.5 g kg^{-1}. The nitrogen concentration ranged from 0.66 (St.2) to 10.44g kg^{-1} (St.3) during the study period. The variation in nitrogen concentration between stations and quadrats is shown in Fig.7.8.

V. C/N Ratio

The C/N ratio (OC/N) in the sediment samples did not exhibit significant variation with the station, quadrat, year and season. The C/N ratio in the sediment samples of three stations during the study period is shown in Fig.7.9 a-c. The mean C/N ratio in the core sediment samples of St.1 was 13.11 ± 2.53 with the highest C/N ratio 19.1 and lowest as 9.41. In St.2, the maximum C/N ratio was 19.22 and minimum was 4.11 with a mean C/N ratio of 11.57 ± 3.76. The St.3 was having a mean C/N ratio of 12.96 ± 4.87 with a minimum C/N ratio of 5.78 and maximum of 33.73.

7.4.2 Organic matter source characterisation

The results of stable isotope study ($\delta^{13}C$, $\delta^{15}N$) of the sediment is shown in Fig. 7.10 and Table 7.1. In St.1, $\delta^{13}C$ of sediment samples ranged from -29.38 to -26.76 ‰ with an exceptionally depleted value of -40.11 (this value was not taken for the mean). The $\delta^{15}N$ values ranged from 4.94 -7.00 ‰ in St.1. In St.2, $\delta^{13}C$ of sediment samples ranged from -28.25 to -26.06‰ with 3.95 to 5.74‰. The carbon and nitrogen stable isotope ratio in St.3 ranged from -29.86 to -28.90‰ and 9.90 to 11.09 ‰, respectively.

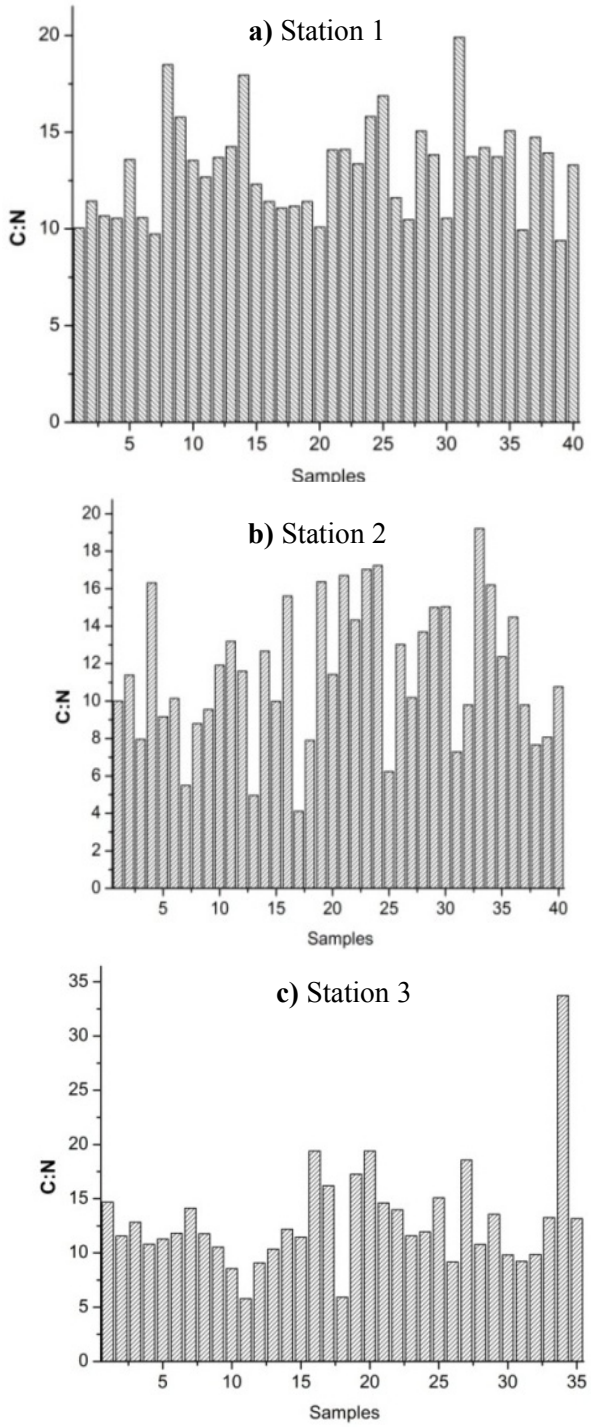

Figure 7.9 a-c Distribution of C/N ratio in the sediment samples of Cochin mangroves during 2013-2015 period

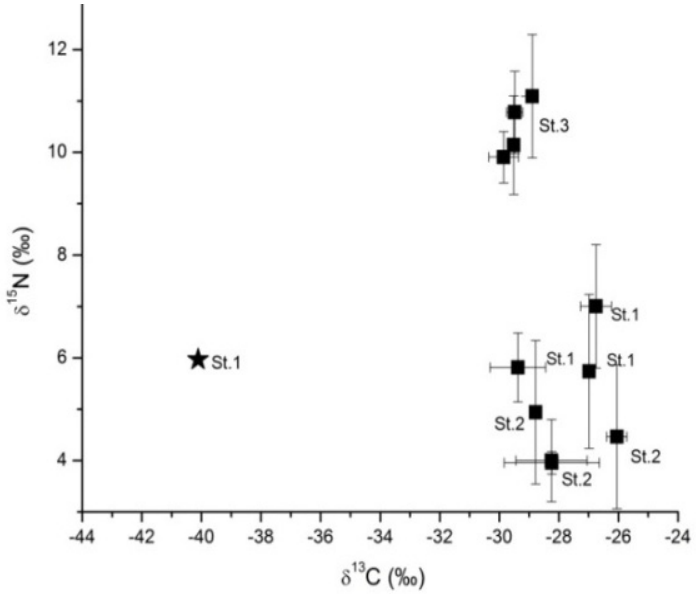

Figure 7.10 Stable isotope ratio of sediment samples from Cochin mangroves during 2013-2015 period

Table 7.1 Mean stable isotope ratio and C/N ratio of sediment samples of Cochin mangroves during 2013-2015 period

Stations	δ^{13}C (‰)	δ^{15}N (‰)	C (%)	N (%)	C:N
St.1	-28.31±1.4 (Mangrove origin)	5.93 ±.85 (Mangrove origin)	5.63±1.7	0.43±.12	13.1± .51 (Mixed signal)
St.2	-27.4±1.06 (Mangrove origin)	4.54±0.83 (Mangrove origin, Slightly depleting)	2.66 ±.51	0.19 ±.03	14.44 ±2.7 (Mixed signal)
St.3	-29.44 ± 0.40 (Mangrove origin)	10.48 ±0.6 (Slightly enriched, Marine source mixing)	4.69 ± 0.38	0.38 ± .04	12.24±.51 (Mixed signal)

7.4.3 Soil carbon pool and carbon stock assessment of the study area

The average soil carbon pool in Cochin mangroves, which was calculated from the three-year data (2013-2015) using bulk density, soil depth and carbon content was estimated at 73.22 ± 39.40 t C ha^{-1}. The highest soil carbon pool was in St.3, around 118.45 t C ha^{-1} followed by St.1 (54.83 t C ha^{-1}) and lowest

in St.2 (46.36 t C ha^{-1}). Soil organic carbon pool (SOC) was also highest in St.3 (94.05 t C ha^{-1}) followed by St.1 (45.37 t C ha^{-1}) and St.2 (33.05 t C ha^{-1}). Similarly, high soil inorganic carbon pool was in St.3 and was 14.43 t C ha^{-1} followed by St.2 (10.64 t C ha^{-1}) and St.1 (8.82 t C ha^{-1}). Among the three mangrove habitats, St.2 was having low soil carbon pool or carbon stock/ha. While considering only the three quadrats in aquaculture farm, the carbon stock again decreased and reached a soil carbon pool of 28.80 t C ha^{-1} with soil organic carbon pool of 19.10 t C ha^{-1} and inorganic carbon pool of 8.06 t C ha^{-1}. Therefore, the slight increase in soil carbon pool in St.2 was due to the presence of undisturbed mangrove plants outside the aquaculture farm.

The mangrove area in St.1 was 15.13 ha, followed by St.2 (10.74 ha) and St.3 (4 ha). Therefore the soil carbon stock in St.1 was higher (829.58 t C) followed by St.2 (497.94 t C) and St.3 (473.81 t C). The corresponding soil organic carbon stock in St.1 was 686.42 t C followed by St.3 (376.18 t C) and St.2 (355.0 t C). The inorganic carbon stock was high in St.1 (133.26 t C) followed by St.2 (114.28 t C) and St.3 (57.73 t C).

7.5 Discussion

7.5.1 Sediment geochemistry and carbon stock

The physicochemical parameters of sediment are directly linked to habitat topography, mangrove species composition and presence or absence of important benthic community in the region which will, in turn, affect the carbon and nitrogen biogeochemistry. The relationship between various physicochemical characters on carbon and nitrogen in the sediment sample was shown in Table 7.2. The sediment pH was significantly negatively correlated to redox potential (r = - 0.307, $p < 0.01$) of the sediment. The redox potential was more reducing in St.2 with more negative values; thus almost an alkaline pH prevailed in this habitat. The open nature of the mangrove habitat at St.2 (three

quadrats), limited the decaying of litterfall within the ecosystem due to the probability of high export rate of litter in open mangroves, thereby decreased the leaching of acids from mangrove litter leading to alkaline pH. The high density of *E. agallocha* species in the station, which is having strong alkaloids also facilitate the alkaline nature of the sediment in St.2. However, St. 1 and St.2 was partially closed in nature, and the litterfall was retained within the station due to higher crab density leading to the decay and leaching of organic acids from mangrove leaves (Liao,1990) thereby resulting in slightly acidic sediment condition in these stations.

The sediment texture in the study area differed according to the stations with St.1 had silty-clay loam with the highest contribution from silt content 60.01 ± 9.09 % and a mean clay content of 36.26 ± 7.96 %. Loamy sand form of sediment was observed in the other two stations. Most of the mangrove habitats showed a clay loam sediment texture. The silty clay loam type of sediment in the mangroves was reported by other researchers like Sah et al. (1989) and Khan et al. (1993). However, sand dominated mangrove habitats were reported by Moreno and Calderon (2011). The bulk density of the sediment samples in the present study could also be related to sediment texture, and sand dominated stations had high bulk density compared to silt and clay dominated site (St.1). The bulk density in mangroves usually ranged from 0.73 g cm^{-3} to 1.42 g cm^{-3} (Sah et al., 1989; Ukpong, 1997; Stringer et al., 2016). However, in the present study it showed lower values due to the differences in soil core sample depth of the present study with other studies. The present study has focused only on the upper 20 cm depth profile of the sediment compared to other studies having a depth profile of 1 m. However the bulk density of the present study was comparable with surface depth profile studies such as a bulk density of < 0.30 g cm^{-3} was

reported from Florida mangroves (Breithaupt et al., 2014) and 60 cm depth profile study reported a high range of 0.18 to 0.96 g cm^{-3} of bulk density by MacKenzie et al., 2016 in Vietnam and Palau mangroves, The Republic of Palau, an Island in Western Pacific ocean.

The moisture content in the sediment samples was high in St.1 and St.3 compared to sand dominated sediments of St.2. It was strongly positively correlated to carbon content (r =0.688, $p < 0.01$ for TOC). Even though St.3 was also sand dominated site, there was high surface layer organic matter deposition, which may be related to the high moisture content in this station. The nitrogen concentration in the sediments of the study area was high (0.093 to 1.1 %) compared to many mangroves of the world (Matsui et al., 2015; Gandaseca et al., 2016; Guo et al., 2018). Matsui et al., 2015 reported 0.001 to 0.873 % of total nitrogen from Thailand mangroves and Gandaseca et al., 2016 reported 0.112 to 0.403 % as TN in Lawas, Malaysian mangroves. Total nitrogen of 0.046 to 0.097 % was recorded from Sundarban (Bangladesh) by Hossain et al., 2016. In Indian Sundarbans it was 0.043 -0.15% (Prasad et al., 2017) while Pichavaram mangrove forest recorded 0.023 to .123 % by Ranjan et al., 2008. Kathiresan, 2000 also reported low values for nitrogen in Pichavaram mangroves. However, TN concentrations were comparable with other studies in and around Cochin estuary, including the present study area (0.16-9.39 g kg^{-1}, Geetha et al., 2008). The high nitrogen content may be due to increased anthropogenic activities in the present study area. C/N ratio was low compared to peaty mangroves, but comparable with mangroves of mineral sediment (Coringa, Bouillon et al., 2003a). The low OC/TN ratios indicate the fact that anthropogenic N loadings are altering the OC/TN stoichiometry (Prasad and Ramanathan 2009). The increasing nitrogen loading in mangrove habitats and its impact should be studied in detail in a future perspective, and

recent global studies have reported on this topic (Reis et al., 2017). The organic carbon content and C/N ratio of the present study was compared with different mangroves of the world and Indian mangroves is presented in Table 7.3. It could be seen that, Cochin mangroves had high organic carbon content compared to mangrove sediments having very high C/N ratio. Therefore it is evident that anthropogenic nitrogen concentration decreased the C/N ratio in Cochin mangroves.

Table 7.2 Correlation analysis showing the relationship between various physico-chemical parameters of the sediment in Cochin mangroves during 2013-2015 period

	TOC	TIC	TC	TN	Sand	Clay	Silt	pH	Eh	Moist	Temp
TOC	1										
TIC	.228*	1									
TC	.802**	.341**	1								
TN	.858**	.315**	.774**	1							
Sand	-.608**	-.277**	-.510**	-.566**	1						
Clay	.542**	.189*	.471**	.490**	-.880**	1					
Silt	.589**	.260**	.482**	.540**	-.961**	.785**	1				
pH	-.284**	-.278**	-.438**	-.339**	.234*	-.223*	-.194*	1			
Eh	.107	.243**	.242**	.205*	-.01	-.01	-.03	-.307**	1		
Moist	.688**	.214*	.588**	.649**	-.512**	.519**	.477**	-.188*	.022	1	
Temp	-.366**	.075	-.17	-.259**	144	-.03	-.209*	.034	.081	-.244**	1

*. Correlation is significant at the 0.05 level (2-tailed).
**. Correlation is significant at the 0.01 level (2-tailed).

7.5.2 Organic matter source characterisation

Organic matter of C_3 plants typically possess $\delta^{13}C$ values of -32‰ to -22‰ that for δ^{15} N having 3 ‰ -7 ‰ (Kendal, 1997) where as marine phytoplankton have -20 ‰ to - 23‰ for $\delta^{13}C$ and 6 ‰ -11 ‰ for δ^{15} N was commonly used to evaluate the sources of organic matter in estuarine sediments (Gearing et al., 1977; Meyers, 1997; Bianchi et al., 2002). Organic matter having a planktonic origin has a C/N ratio of 6 to 9 whereas those

originating from terrestrial vascular plants and their derivatives in sediments has a C/N ratio of 15 or higher (Bordowskiy, 1965a; Bordowskiy, 1965b; Prahl et al., 1980; Biggs et al., 1983; Ertel and Hedges, Ertel et al., 1986; 1984; Post et al., 1985; Hedges et al., 1986; Orem et al., 1991). Thus according to the stable isotope range and C/N ratio range, the source characterisation of organic carbon and nitrogen was analysed in the present study. The stable isotope study ($\delta^{13}C$, $\delta^{15}N$) of the sediment confirmed that carbon source in the t mangrove sites was of mangrove litter origin and not from marine POC (Table 7.1). In St.1, $\delta^{13}C$ and $\delta^{15}N$ of sediment samples gave a clear signal of pure mangrove origin of organic matter ($\delta^{13}C$ = -28.31 ± 1.4 ‰, $\delta^{15}N$ = 5.93 ± .85 ‰). However, St.2 and St.3 exhibited a mixed signal of nitrogen source. Joseph et al., 2012 also revealed the source of organic carbon in mangrove sediments of Mangalavanam and Vypin region as mangrove litter origin. However, they got high values (- 26.71 to - 25.53 ‰) compared to the present study results, which were more near to mangrove plant $\delta^{13}C$ values indicating the mangrove litter composition in the mangrove sediment. Only an extremely depleted $\delta^{13}C$ value (- 40.11 ‰) was recorded in post monsoon, 2015 sample of St.1. This low $\delta^{13}C$ value could potentially be explained by a much depleted source like coal, petroleum or methane.

Since there was no point source for coal/petroleum at this site, the most likely explanation could be methane production by methanogenesis (Golding et al., 2013). However, from that single data, it could not be able to say that methane production is always happening in that area. The stable isotope analysis in the same year and other years of the present study did not match with this exceptionally depleted value at St.1. Therefore, it was not considered in taking the average of $\delta^{13}C$ values for St.1.The comparison of stable isotope ratio of the present study with other mangroves of the world and India is given

in Table 7.3. The Sundarban mangroves showed a wide range for organic carbon source from marine to mangrove plant origin (-26.8 to-10.96 ‰) by Prasad et al., 2017. However, the source characterisation of organic carbon from Pichavaram mangroves, Tamil Nadu was slightly more depleted than Sundarban mangroves, West Bengal (-28.92 to -25.34 ‰ by Prasad and Ramanathan, 2009 and - 27.5 to - 18.9 ‰ by Ranjan et al., 2011) and comparable to the present study.

The mangrove plants have low nitrogen and are not a good source of nitrogen for the organisms in higher trophic level. The stable isotope signature also showed that except in St.1, the source of nitrogen was not signalling purely to mangrove plant. Rather, it showed a mixed signal. In St.2, slightly depleted values for δ^{15} N (3.95 to 4.46 ‰) could be explained through the fertilizer application or feed application in the aquaculture pond in that station. The marine input as the nitrogen source in St.3 was clearly understood from the enriched δ^{15}N values from the station. However, the values were not much enriched like Sundarban mangroves, which recorded very high (05-17.55 ‰) δ^{15} N range which in turn indicated the loading of anthropogenic nitrogen to mangrove habitats (Prasad et al., 2017). The location of St.3 that was nearer to Barmouth of the Cochin estuary, was connected to the estuary through a feeder canal. This feeder canal may be acting as a source of marine phytoplankton that derived PON to mangrove sediments. Also this condition may facilitate the growth of nitrogen-fixing cyanobacteria which is considered as a major source of nitrogen in mangrove environments (Mannand Steinke,1989; Lee and Joye, 2006; Alfaro-Espinoza and Ullrich, 2015; Reis et al.,2017) that could also be act as a source of nitrogen in St.3. Further, St.3 being a major nesting place of migratory birds received allochthonous source of nitrogen through the droppings of migratory birds that could be signalling to the marine source of

nitrogen in the station. However, more point source study and application of mixing models may give a clear picture of the sedimentary nitrogen source of St.3.

7.5.3 Carbon stock

The drivers on soil carbon stocks are different in different mangrove habitats around the world and generalization will be a difficult task. However, some major drivers could be derived from global studies. It was reported that high mangrove productivity might not have resulted in high soil carbon stock in the upper layer due to high sedimentation load. Sundarbans mangrove forest (Banerjee et al., 2012) and Zambezi river delta in Mozambique (Stringer et al., 2016), is an example to this process and these areas reported only a very low percentage of organic carbon in the soil profile. In contrast to this, some low productive mangrove habitats showed high soil carbon density due to its hydrogeomorphic setting (Ezcurra et al., 2016). However, the role of the biological pump through crabs or microbial biomass was not checked in these habitats. A significant difference in soil carbon was observed within the mangrove habitats of the study by many researchers due to the difference in hydrogeomorphic gradient (open mangrove, closed mangrove, fringe mangroves, riverine mangrove etc.) which resulted in zonation (Kauffman et al., 2011; Ouyang et al., 2017; Lewis et al., 2018). However, in this study, such significant differences were not observed between quadrats except in St.2 where three quadrats were located inside the aquaculture farm and two outside the farm. This slight variation in carbon content observed in the quadrat within the station 2 of the present study may be related to the mangrove species diversity in that particular quadrat.

The carbon content in the mangrove sediment gets directly affected by sediment texture (Bijoy Nandan et al., 2015; Gireeshkumar et al., 2012;

Kauffman et al., 2017, 2018) which was clearly observed in St.1 and St.2 except that in St.3. However the carbon was negatively correlated to sand (r = - 0.608, $p < 0.01$ for TOC; r = - 0.510, $p < 0.01$ for TC) and positively correlated to silt (r = - 0.589, $p < 0.01$ and r = - 0.482, $p < 0.01$ for TC) and clay particles (r = - 0.589, $p < 0.01$ and r = - 0.471, $p < 0.01$ for TC) in the sediment. In St.1 and St.2, the inverse relation of sand and organic carbon was evident. However, in St.3, which is also a sand-dominated site, was having higher carbon content. Therefore, it is evident that rather than geological influence, the mangrove habitats in the study area were majorly controlled by the biological pump.

The higher diversity of mangrove plants and corresponding litterfall may be one of the reasons for the significant difference in carbon content. Litterfall was positively correlated to TC (r_s=0.251, p=0.017). The age of mangrove stands and biomass was also strongly influencing the sediment carbon and nitrogen biogeochemistry in mangrove ecosystems (Lunstrum and Chen, 2014; Kauffman, 2011, 2014; Marchand, 2017). Marchand (2017) got a strong linear relationship for organic carbon stock with mangrove stand age. The age and biomass carbon stock were also high in St.3 and St.1, which reflected well in the high soil carbon stock in these stations. Moreover, the crab density played a major role in changing the biogeochemistry of mangrove habitats and thereby resulting in high carbon stock/ha in the study area. St.1 and St.3 had high crab density, which altered the sediment biogeochemistry and also helped in retaining the mangrove litter within the ecosystem. However, in St.2, which was observed with very low mangrove crab density, was having the lowest carbon content. Therefore mangrove crab driven biological pump significantly helped in the storage of carbon in the soil pool of the study area.

The soil organic carbon stock in the present study was compared with different mangrove habitats around the globe (Table 7.4). The results were comparable with Kadalundi mangroves in Kerala, which reported a similar range of (17.70 -122.47 with a mean of 63.87±8.67 tC ha^{-1}) soil carbon stock in surface layer up to 30 cm depth (Vinod et al., 2018). It is also comparable with SOC stock in 20 cm depth in Southeast Australia (57.3- 94.2 t C ha^{-1}, Howe et al., 2009) and SOC stock in mangroves of Mahanadi delta, India (Sahu et al., 2016).

Table 7.3 Comparison of carbon, nitrogen and stable isotope ratio of sediment samples of Cochin mangrove during 2013-2015 period

Location	OC%	CN	$\delta^{13}C$ (‰)	$\delta^{15}N$(‰)	Reference
Sundarbans	0.76-5.22	10.56-48	-10.96 -26.8	0.05-17.55	Prasad et al.,2017
Indonesia Estuarine Marine:	1.07-8.51 17.26-26.24	9-28 29-64;	-25.68-27.96 -27.60-27.96	2.5 - 7.2 -0.6 - 0.7	Weiss et al., 2016
Eastern Brazil	0.26 -4.82	4.4- 11.7	-	-	Jennerjahn andIttekkot,1997
Vietnam	-	-	-23.43-24.81	-	Tue et al.,2011
Mexico	5.88 1.67 3.33	57.9 53.8 53.4	-28.79 -26.55 -28.93	6.80 7.89 4.31	Gonneea et al., 2004
Coringa mangroves	0.6- 31.7%	7.0 - 27.3	-29.4 and -20.6	-	Bouillon et al.,2003a
Pichavaram	-	12.99-14.22	-28.92 to -25.34	5.64-8.12	Prasad and Ramanathan, 2009
Pichavaram,	0.06-1.97	5.25-27.3	-27.5 to -18.9	0.69-6.2	Ranjan et al., 2011
Mangalavanam Vypin	-	10.67- 15.97 10.15-13.5	-	-	Zeena, 2005
Mangalavanam, Vypin	-	8.2 -12.6	-25.53 -26.71	-	Joseph et al., 2012
Cochin Mangroves	1.14-12.43	4.11-33.73	-29.52 to-26.06	3.95-11.09	Present Study

Table 7.4 Comparison of SOC stock in different mangroves of the world with the present study

Location	Depth of study(cm)	SOC Stock t ha^{-1}	Reference
Hinchinbrook Channel, Australia	50	296	Matsui,1998
Japan	100	57.3	Khan et al.,2007
Micronesian mangroves Palau	89,101,160	315, 428 and 818 (seaward, interior, landward) 614, 530, and 1,042 (seaward, interior, landward) (noted as carbon stock)	Kauffman et al.,2011
Micronesian mangroves Yap	148,159,231		
Southern China	100	237.68 (mean of different mangrove zones)	Wang et al.,2013
Mexican Caribbean	>100	95-1106	Adame et al., 2013
Sofala Bay mangroves	100cm	160	Sitoe et al., 2014
Philippines	30 cm	173.75	Abino et al., 2014
Indonesia	>100	marine mangroves (271-572) estuarine mangroves (100-315) degraded (80-132)	Weiss et al., 2016
Pacific and Caribbean coasts of Honduras	>100	347-1600	Bhomia et al., 2016 a
Venezuelan Caribbean coast	Most of the samples in 10 cm	11.30 to 59.84	Barreto et al., 2016
French Guiana	45	4.8-107.5	Marchand, 2017
Indian Mangroves			
Mahanadi Mangrove Wetland, East Coast of India	30 cm	54.3± 3.0 (mean) in natural stands 60.9 ±5.6(mean) in plantations	Sahu et al., 2016
Bhitarkanika		61 ± 8 (aquaculture ponds) 92 ± 20 (plantations) 177 ± 14 (scrub mangroves) 134 ± 17 dense mangroves)	Bhomia et al.,2016 a
Kadalundi	30	63.87±8.67 (mean)	Vinod et al.,2018
Cochin Mangroves	20	45.37, 33.05, 94.05 57.49 ± 32.25 (mean)	Present Study

However, the result of the soil organic carbon stock of the present study was higher (33.05 - 94.05 t C ha^{-1}) compared to the same surface depth profile (20cm) soil carbon stock studies in other mangroves of the world like by Barreto et al., 2016 that reported 11.30 to 59.84 tC ha^{-1} in surface soil. Moreover, results of this study are considerably higher compared to SOC stock

recorded for 1 m sediment depth in Okinawa, Japan (57.3 t C ha^{-1}, Khan et al., 2007) and Northern Vietnam (68.5 t C ha^{-1}, Nguyen et al., 2009).

The carbon stock assessment in the present study revealed that soil carbon stock was significantly varied according to stations and this significant variation was due to sediment physical characters like particle size and moisture content. However, the major driving force in this carbon stock variation is due to the difference in crab density in the stations which act as a significant biological pump in the mangrove ecosystem. The total carbon and organic carbon is comparatively very low in St.2 and high in the other two stations. While comparing with the results of the present study with other mangrove soil carbon stock studies around the world, it depicts a substantial low stock in the present study. However, while looking into the depth of the soil core taken in the other studies, it is understood that the present study values are comparable. The high SOC stocks were reported in the studies where entire soil depth was taken for the stock assessment (most often >100 cm, Kauffman, 2011; Wang et al.,2013; Adame et al.,2013; Weiss et al., 2016; Bhomia et al., 2016 b). Therefore, the comparison of SOC stock of the present study with SOC stock profile for different soil depth profile studies in the literature indicated that the SOC stock for the entire soil depth of Cochin mangroves might have the potential to have a very high soil carbon stock. Future studies can be focused on profiling the entire soil depth of the study area.

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Chapter 8

TOTAL ECOSYSTEM STOCK ASSESSMENT AND SOIL CARBON SEQUESTRATION

8.1 Introduction

Mangrove forests, their potential for carbon sequestration and relationship to climate change are a heavily debated topic in the scientific community and policy making. The increasing CO_2 concentration in the atmosphere and related climate change are threatening biodiversity. In this scenario, reducing emissions from deforestation and forest degradation in developing countries (REDD+) is emphasised among international climate agreements for mitigating climate change and for reducing CO_2 concentration in the atmosphere. It is considered as the most cost-effective method, and it will help in reducing the CO_2 concentrations in the atmosphere through financial support as carbon credits to developing countries for reforestation programmes. Therefore, regular and in-depth carbon monitoring of each forest ecosystems are needed (carbon stock assessment) to calculate the carbon credit of each forest. Many studies related to carbon sequestration of mangrove forests revealed that they have more carbon sequestration capacity than tropical rain forests (Donato et al., 2011). Thus carbon stock assessment of mangrove forests and quantifying their sequestration potential around the globe is essential. Carbon stock assessment includes measurement of different carbon

pools over recent years (2-3 years), and it is reported that 50% of mangrove carbon stocks are sequestered in the soil (Donato et al., 2011). Considering the amount of carbon sequestered in mangrove forest soils, measurement of the historical burial rate (millennium, centennial and decadal scales) is also essential to assess longer-term trends and to provide context for recent burial rates (natural vs anthropogenic settings). Thus the soil carbon burial rate is otherwise known as soil carbon sequestration. Therefore hereafter the soil carbon sequestration will be termed as carbon burial. The assessment of ecosystem carbon stock and burial rate of organic and inorganic carbon is essential for understanding the sink and source capacity of the mangrove ecosystem.

8.2. Literature Review

8.2.1 Carbon burial

Mangrove ecosystems are considered a sink of carbon through their long term storage of primary production into the deep soil (Twilley, 1992; Ong, 1993; Matsui, 1998; Fujimoto et al., 1999; Boullion, 2008b). The age of the soil with respect to depth will vary in different mangrove environments depending upon its sedimentation rate and topography. It is reported that 400-700 years old sediment was deposited in the upper 1.5 m of sediment core in the mangroves of Brazil (Dittmar and Lara, 2001b). The estimate of the percentage of the burial of mangrove primary production differs in various studies depending on the topography, environmental conditions and also on the influence of biological pump. Duarte and Cebrian (1996), estimated that ~10 % of mangrove primary production is buried in mangrove soil. Alongi et al. (2004) reported that primary production and burial increases with age of mangrove stands.

In general, organic carbon (OC) burial rates are estimated by measuring the concentration of OC in the section of soil or sediment and pairing those concentrations with an age model for the section of sediment in question. OC burial rates are dependent on the dating methods used to measure linear accumulation rate or mass accumulation rate (MAR) of the sediment. The mass accumulation rate is otherwise known as sedimentation rate only with a difference that the former is the amount of sediment remaining in the system and latter is the amount of sediment coming into a system over time. ^{14}C is a commonly used dating method for millennial characterisation that has been proven effective for estimating OC burial rate in peaty mangroves (Scholl et al., 1969; Woodroffe, 1981; Twilley et al., 1992; Ong, 1993; Jennerjahn and Ittekkot, 2002 and Bird et al., 2004).

Another method is repeated measurements of sediment accumulation by using marker horizons or Surface Elevation Tables (SETs), which are effective for sub-annual carbon burial rates (Cahoon and Lynch, 1997). However, OC in the surface layer will be very high (lack of degradation), and it will not be representative of the deep soil carbon profile since 97 % of carbon is lost due to diagenetic processes within the first year of deposition (Duarte and Cebrián, 1996). Therefore burial rates estimated through surface markers may overestimate the real burial rate.^{210}Pb and^{137}Cs are effective short-lived radioisotopes for characterizing OC burial rates on the centennial time scale. The ^{210}Pb dating method was first introduced by Goldberg (1963) and subsequently used by Crozaz et al. (1964) for studying the accumulation history of Antarctic snow. This method was first used in coastal sediments by Koide et al. (1972 and 1973). Later this technique was evolved as a powerful tool for dating recent sediments and used for multiple applications in

oceanography and limnology (Mabit et al., 2014; Sanchez-Cabeza and Ruiz-Fernandez, 2012).

^{210}Pb is a radionuclide with a half-life of 22.3 years and is a product of ^{238}U decay series.^{226}Ra ($t_{1/2}$ = 1,600 years), which is found in the atmosphere, decays to ^{222}Rn ($t_{1/2}$ = 3.8 days) and escapes from the crust of the lithosphere and ultimately decays to ^{210}Pb (Eisenbud and Gesell, 1997).^{210}Pb is deposited by wet atmospheric fallout (precipitation) and adsorbs to clays and organic compounds. Due to this physical process, the ^{210}Pb accumulates over time in organic matter accumulated in peaty or clayey sediment. The difference between the ^{210}Pb produced naturally in the soils (supported ^{210}Pb), and the ^{210}Pb that is deposited from the atmosphere or water column (unsupported or excess ^{210}Pb) can then be used to date the sediment column as each layer of sediment is deposited, and the excess ^{210}Pb begins to decay. Fallout of ^{137}Cs, a short-lived radioisotope thermonuclear byproduct (half life 30.2 years) has been extensively used to date recent sediments from flood plain, lacustrine, wetland and other environments (Pennington et al., 1976; Delaune et al.,1978) on the principle that the input of fallout has a defined temporal pattern. Therefore the vertical distribution of ^{137}Cs in a sediment profile can be related to the known record of ^{137}Cs fallout in that region. Thus, the deepest occurrence of ^{137}Cs in the profile can be approximately equated with the onset of ^{137}Cs fallout in the early 1950s, while peaks in activity can be equated with peaks in fallout in 1963 which is used as a marker. ^{137}Cs activity profiles are commonly used as a corroborative record for age models produced using^{210}Pb activity.

A mass balance approach together with available estimates of primary production, litterfall, export and remineralization were used for estimating global carbon burial rate by Jennerjahn and Ittekkot (2002). Without directly

measuring burial data, they estimated that 25% of mangrove litterfall or primary productivity was sequestered in the sediment annually. However, Twilley et al. (1992) and Chmura et al. (2003) used primary burial rate values from the literature and reported mean global annual burial rates as 210 g OC $m^{-2}yr^{-1}$. Using the data set of Chmura et al. (2003), which included skewness, Duarte et al. (2005) corrected it and reproduced the global mean rate of burial as 139 g OC m^{-2} yr^{-1}. The values of global burial rate were upgraded by Alongi et al. (2004) and Mcleod et al. (2011). Due to the difference in area of mangroves over different time scales from various studies, Breithaupt et al. (2012) standardised the mangrove carbon burial rate into a common global mangrove areal extent to 160000 km^2 and reported each global burial rate in the literature. They reported the global carbon burial rate as 24.9 Tg C yr^{-1} by using the mangrove area, according to Spalding et al. (2010).

The major burial studies in the mangrove ecosystem before 2005 were Lynch et al. (1989) in mangroves of South-West Florida, Belize and Terminos lagoons (used both ^{210}Pb and^{137}Cs technique for MAR calculation);Twilley Alongi et al. (2001) and Alongi et al. (2004) in Thailand and Matang mangrove forests respectively. The carbon burial rate in mangrove sediments of Mexico for the past 160 years using ^{210}Pb was assessed by Gonneea et al. (2004). Later Sanders et al., 2008, 2010a, 2010b and 2010c studied in detail on the carbon burial rate of different Brazilian mangroves using ^{210}Pb radioisotope technique for sediment accumulation rate estimation. Then Breithaupt et al. (2012) compiled all the regional studies on carbon burial estimates and reviewed the global carbon burial rate. The sediment carbon burial rate and accretion rate was related to storm events and also to sea level rise by Smoak et al. (2013). The temporal variability in sedimentation rate, accretion rate and burial rate of different nutrients, including carbon in the mangrove forest of Florida was

assessed by Breithaupt et al. (2014). The carbon stock assessment in soil together with burial rate in the mangrove forest of French Guiana was recently assessed by Marchand (2017). Another recent work was carbon stock, its source assessment and accumulation rate analysis in Indonesian mangroves using ^{210}Pb dating method by Kusumaningtyas et al. (2019). Now the current research focuses are on beyond burial (Maher et al., 2018) and carbonate burial (Saderne et al., 2019) in mangrove ecosystems.

There were no published studies on carbon sequestration through carbon burial in sediment pool in any Indian mangroves. Only Ray et al. (2011) in Sundarban mangroves attempted to quantify the burial rate through empirical formulae. Therefore, to understand the total ecosystem carbon stock assessment and carbon burial or carbon sequestration in sediment pool is a very significant study in the Indian scenario.

8.2.2 Total ecosystem carbon stock

Mangroves are the most carbon-rich ecosystem, containing an average carbon stock of 937 t C ha^{-1}, with a carbon burial rate of 174 g C m^{-2} year^{-1} (Alongi, 2012). The total ecosystem carbon stock of mangrove forest includes biomass pool and soil carbon pool. The biomass pool includes living biomass and dead biomass. The dead biomass contains downed wood and dead non-tree plants as well as leaf litter. Many stock assessment studies are focused on only one or two carbon pools. However, some studies focused on overall ecosystem carbon stock assessment in a particular mangrove area. There were some global estimates of total ecosystem carbon stock (Duarte et al., 2013; Alongi et al., 2012, 2014). Alongi (2014) reported a global average of total ecosystem carbon stock as 956 t C ha^{-1}, which is very much above than the carbon stock in rain forests (241 t C ha^{-1}), peat swamps (408 t C ha^{-1}), salt marshes (593 t C

ha^{-1}) and seagrasses (142.2 t C ha^{-1}). Recently Hamilton and Friess (2018) reported global carbon stocks from the mangrove ecosystem and carbon emissions due to mangrove deforestation. The major countries which contributed more than 50% of global carbon stock are Indonesia, Brazil, Malaysia and Papua New Guinea. They reported 4.19 Pg of carbon in 2012 as global ecosystem carbon stock and in which 2.96 Pg of carbon stock is stored in the soil and 1.23 Pg in the living biomass. The work highlighted that 2% of global mangrove carbon was lost between 2000 and 2012, which is equivalent to 316,996,250 t of CO_2 emissions.

There were many carbon stock studies in mangrove ecosystem either confined to biomass or soil pool. Studies on total ecosystem carbon stock for a particular mangrove ecosystem are scanty. However, many recent studies were focused on the total ecosystem carbon stock assessment. Kauffman et al., 2011 studied ecosystem carbon stock in Micronesian mangroves by measuring biomass and soil carbon pool. In Southern China, Chen et al. (2012) assessed total carbon stock and biomass increment and its carbon sequestration potential through biomass in monoculture stands and mixed stands of *S. caseolaris* and *S.apetala*. Total ecosystem carbon stock of different mangrove stands like *Avicennia marina*, *Sonneratia apetala*, *Aegiceras corniculatum* + *Kandelia obovata*, *Rhizophora stylosa* and *Bruguier*a *gymnorrhiza* of Southern China was reported by Wang et al. (2013). These studied did not include litterfall data to their carbon stock. The ecosystem carbon stock and the possible CO_2 emission due to the conversion of mangroves to aquaculture farm or deforestation were assessed in few studies. In the Dominican Republic, it was studied by Kauffman et al. (2014) and the same type of research was done by Bhomia et al. (2016b) in mangroves of Pacific and Caribbean coasts of Honduras. They reported that conversion of mangroves into aquaculture ponds

or any other agriculture land would release the stored carbon inside the deep soil due to mineralization and oxidation. A detailed ecosystem carbon stock assessment along the Atlantic coast of West-Central Africa, including 33 different mangrove forests were studied by Kauffman and Bhomia (2017). They reported downed wood biomass also as carbon stock. The ecosystem carbon stock in the Amazon region, Brazil, was assessed by Kauffman et al. (2018). They found out that soil carbon stock of mangroves was low even though the biomass carbon stock was very high in that region.

In India, mangrove carbon stock assessment was very scanty. Most of the studies focused on either biomass or soil carbon stock; however; some recent total ecosystem carbon estimates are available in the literature. Rahman et al. (2015) studied ecosystem carbon stock in Sundarban mangroves and analysed variation in carbon stock according to vegetation type and also based on salinity gradient. Total ecosystem carbon stock of Bhitarkanika mangroves was done by Bhomia et al. (2016a). They estimated carbon stock in different types of mangroves in that area mainly aquaculture, planted, scrub and dense mangroves and found out that mangroves converted to aquaculture stock were having low carbon stock compared to other types of mangroves. Sahu et al. (2016) studied the Mahanadi delta mangroves, East coast of India. In the West coast, Vinod et al. (2018) studied the total ecosystem carbon stock and equivalent CO_2 emission in Kadalundi mangroves, Kerala.

8.3 Materials and Methods

8.3.1 Soil carbon burial

Soil carbon burial rate was assessed according to Anderson et al., 1988. Sequestration rate was calculated by multiplying mass accumulation rate with carbon concentration (%). Three individual soil cores (4.6 cm diameter) were

sampled from each mangrove environment (St.1, St.2, St.3, study area details are described in chapter 2). The core sample taken from St.1 is denoted as Core I, from St.2 as Core II and from St.3 as Core III. Depth of the core taken were upto 30 cm, 45 cm and 50 cm from St.1, St.2 and St.3.Each core was subsampled (2cm interval up to 10 cm, 5 cm interval up to 50 cm). A portion of the core soil sample was dried and used to determine dry bulk density, as mentioned in Chapter 7.2. The other environmental characters such as pH, Eh, moisture content and sediment texture analysis were also done using standard procedures as mentioned in Chapter 2.3.

Short-lived radioisotope geochronologies, based on excess ^{210}Pb ($^{210}Pb_{xs}$) were used to establish mass accumulation rates following methods described in Brooks et al. (2015), Schwing et al. (2017) and Larson et al. (2018). As with any geochronological tool, $^{210}Pb_{xs}$ dating must be corroborated. This was effectively accomplished by using ^{137}Cs (Livingston and Povinec, 2000).

Freeze-dried bulk sediment samples were counted on Canberra HPGe (high-purity germanium) coaxial well photon detectors (Model # GCW3023) to determine $^{210}Pb_{xs}$ and ^{137}Cs activity. Activities were corrected for counting time, detector efficiency and self-absorption while the accuracy of measurements were evaluated using the IAEA-447 certified reference material. The constant rate of supply (CRS) model was used to establish a chronology and mass accumulation rates (MARs) for each core (Robbins, 1978: Appleby and Oldfield, 1978; Sanchez-Cabeza and Ruiz-Fernández, 2012). The use of MARs corrects for differential sediment compaction down the core, thereby enabling a direct comparison of $^{210}Pb_{xs}$ accumulation rates throughout the core. MARs were calculated as follows:

$$MAR\ (g/cm^2/yr) = DBD \times LAR \quad (1)$$

DBD = Dry bulk density (g/cm^3) = dry weight / sample volume (2)

Sample volume = sample interval (i.e. 2cm, 5 cm) x area of core barrel (inner diameter) (3)

LAR (cm/yr) = linear accumulation rate (4)

The ^{137}Cs activity was checked for the confirmation of MAR results obtained from ^{210}Pb activity. ^{137}Cs activity was used alone for the linear accumulation rate calculation only when a continuous vertical profile for ^{210}Pb activity was not observed. In that case, only a peak in ^{137}Cs was measured, and this peak was assumed to indicate the year 1963. A linear accumulation rate (equation 4) was then calculated for the portion of the core above the ^{137}Cs peak by dividing the peak activity depth with the difference in years between 1963 and the year of collection.

A portion of the core sediment samples were then analysed for total carbon, TIC, TOC were measured using Analytikjena TOC analyser multi N/C 2100 S HT 1300 Solid module. The carbon source in each interval of the core was analysed on PyroCube-IRMS (Serial No.JC 455) for $\delta^{13}C$ and $\delta^{15}N$ stable isotope ratio. The carbon and nitrogen source in each interval of the core was analysed for $\delta^{13}C$ and $\delta^{15}N$ stable isotope ratio. Samples were packaged in tin capsules for mass spectrometry and analyzed using a Costech (Valencia, CA USA) elemental analyzer interfaced with a continuous flow Micromass (Manchester, UK) Isoprime isotope ratio mass spectrometer (EA-IRMS) for $^{15}N/^{14}N$ and $^{13}C/^{12}C$ ratios. Measurements are recorded in δ notation [per mil (‰) units], and ovalbumin was used as a routine standard. Precision for $\delta^{13}C$ and $\delta^{15}N$ was generally ± 0.2‰ and ± 0.4 ‰. The relationship between the physico- chemical characters of the core sediment sample with carbon was analysed using correlation matrix. The Pearson correlation was done for

normally distributed data and Spearman's rank correlation was done for non-normal data using SPSS 16.0v

8.3.2 Total ecosystem carbon stock and economic valuation

Total ecosystem carbon pool was estimated by adding all carbon stocks together as given below, where as carbon stock of the study area was calculated by multiplying the carbon pool with an areal extent of the study area. The mangrove area estimation was done using remote sensing and GIS method and detailed methodology was described in Chapter 7.

Total Carbon pool of Mangroves = C_{AGB}+ C_{BGB}+ $C_{litterfall}$+ C_{Soil}

Where

C_{AGB} = Carbon stock in above ground biomass

C_{BGB} = Carbon stock in belowground biomass

$C_{litterfall}$ = Carbon stock as dead biomass, litterfall

C_{Soil} = Carbon stock in soil pool

Total Ecosystem Carbon stock of Mangroves = Carbon pool x study area

Greenhouse gas inventories (and emissions) are often reported in units of carbon dioxide (CO_2) equivalents, or CO_2e (multiplying the carbon stock with a factor value of 3.6; IPCC, 2007). The carbon dioxide (CO_2) equivalents mean, how much CO_2 can be fixed as carbon stock otherwise how much CO_2 may be released into the atmosphere when these stocks are disturbed. This will help to understand the value of mangrove ecosystem in terms of climate change. The economic valuation of carbon was also calculated, according to Moore and Diaz (2015). They computed the social cost of carbon (SCC) as the US $ 220 per ton of CO_2, which is equivalent to ~ ₹15400 per ton. These values were adopted for the conversion of mangrove carbon to SCC.

8.4 Results

8.4.1 Soil carbon burial

I. Sediment core physico - chemical characteristics

Each core from the stations was examined for physico-chemical characteristics. The mean pH in the sediment core of St.1 was acidic (5.95 ± 0.62) with a minimum pH along the 4-6cm depth interval and maximum pH of 6.82 in the surface layer (Fig.8.1a). The range of redox potential in the sediment core of St.1 was -80 to -310 mV. The maximum reduced nature was observed in the surface layer, and the most oxygenated layer was 6-8 cm depth interval (Fig.8.1b). The moisture content did not differ along with the depth profile, and the mean moisture content in the sediment core of St.1 was 67.52 ± 4.28 % (Fig.8.1c). The sediment texture analysis revealed that in St.1 silt (66.26 ± 2.81 %) is the main component followed by clay (32.88 ± 2.96%) and the only negligible amount was contributed by sand (0.86 ± 0.53%) (Fig.8.1d).

The bulk density increased with downward vertical profile and carbon content decreased with increasing bulk density (Fig.8.2). The mean bulk density in Core 1 (St.1) for all depth intervals was 0.39 ± 0.06 g cm^{-3}. The minimum bulk density was in the surface layer (0-2cm) and was 0.27 g cm^{-3} that increased with depth and reached a maximum of 0.47 g cm^{-3} in 25-30 cm interval. The mean total carbon concentration in the sediment core of St.1 was 115.24 ± 31.56 g kg^{-1} with organic carbon 94.73 ± 32.10 g kg^{-1} and inorganic carbon 20.51 ± 4.64 g kg^{-1}(Table 8.1). The maximum total carbon was observed in 6-8 cm depth interval (162.5 g kg^{-1}) and the minimum was in 25-30 cm depth interval (77.41 g kg^{-1}). From 6-8 cm depth, the total carbon was showing low values compared to surface layers.

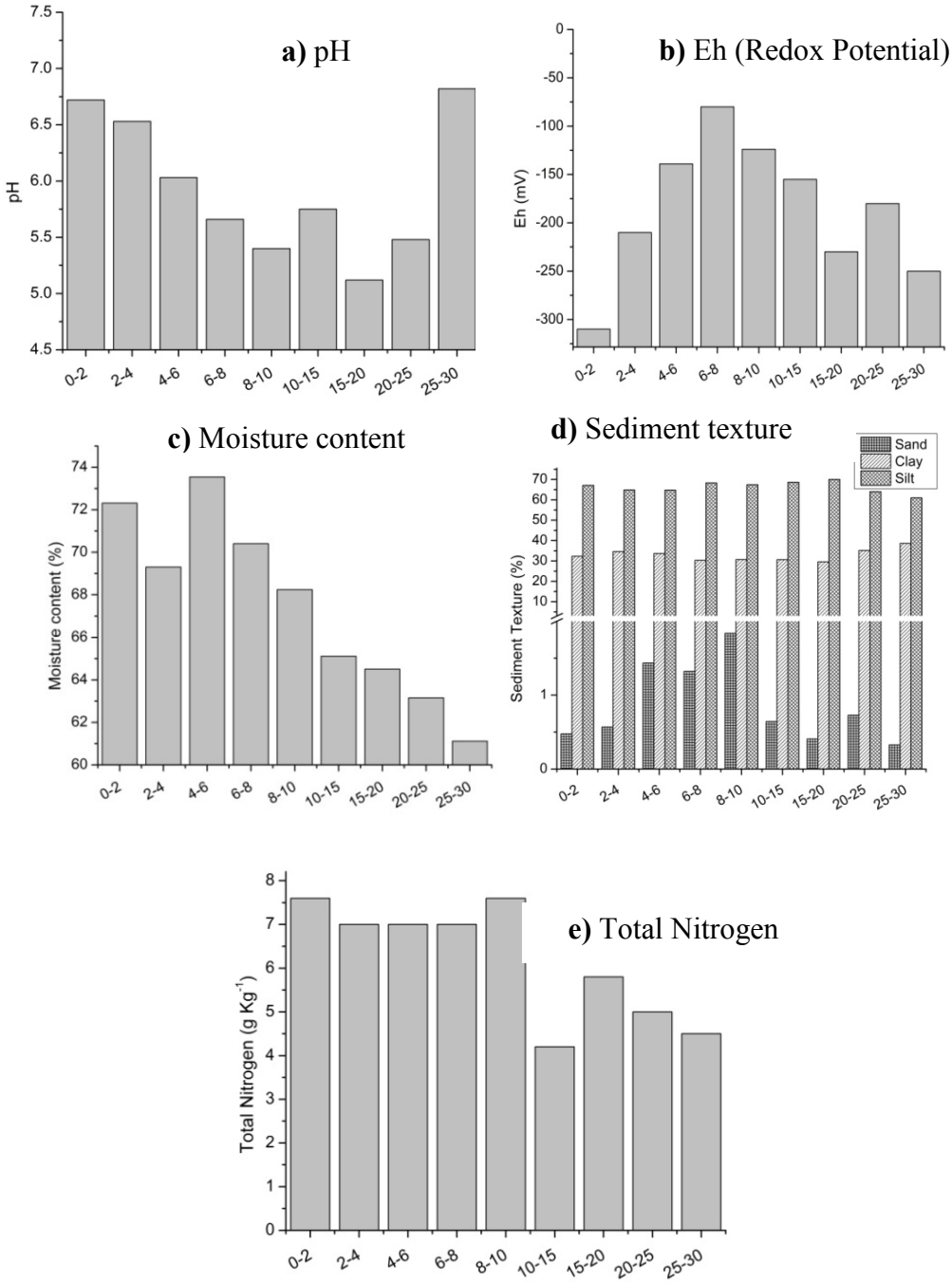

Figure 8.1 The variation in different physico-chemical parameters with depth interval (cm) of Core I

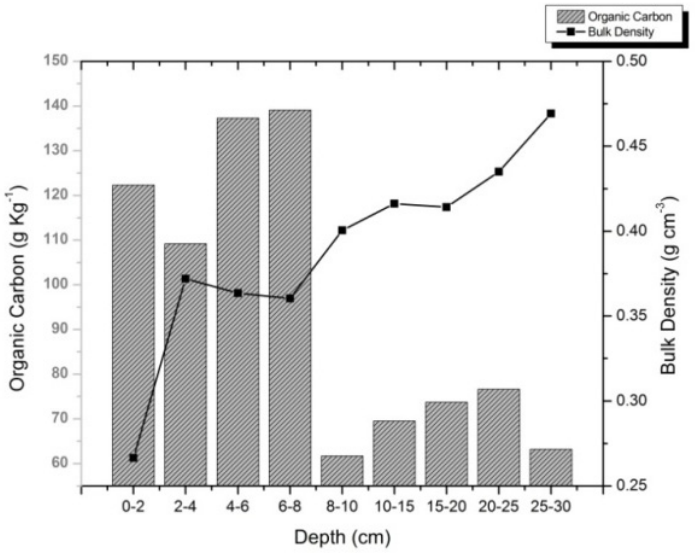

Figure 8.2 The bulk density vs organic carbon content according to the vertical profile of sediment Core I

Table 8.1 Carbon, Nitrogen, and stable isotope ratio of sediment in different depth intervals of sediment Core I

Depth (cm)	TOC (g kg^{-1})	TIC (g kg^{-1})	TC (g kg^{-1})	TN (g kg^{-1})	$\delta^{13}C$ (‰)	$\delta^{15}N$(‰)	C: N
0-2	122.3	15.6	137.9	7.6	-27.38	6.82	18.14
2-4	109.2	20.2	129.4	7	-28.57	7.73	18.49
4-6	137.3	16.7	154	7	-28.43	9.34	22
6-8	139.1	23.4	162.5	7	-29.30	8.25	23.21
8-10	61.7	20.2	81.9	7.6	-27.43	5.98	10.78
10-15	69.5	21.1	90.6	4.2	-30.50	3.14	21.57
15-20	73.7	28.98	102.68	5.8	-26.34	9.17	17.7
20-25	76.6	24.16	100.76	5	-26.44	8.53	20.15
25-30	63.2	14.21	77.41	4.5	-25.31	6.44	17.2

The nitrogen also followed the same trend, when the mean concentration in the sediment core at St.1 was 6.19 ± 1.34 g kg^{-1}(Fig.8.1 e). The maximum nitrogen concentration was observed in 0-2 cm depth interval and 8-10 cm

depth interval (7.6 g kg^{-1}) while the minimum was in 25-30 cm depth interval (4.5 g kg^{-1}). The mean stable isotope ratio of $\delta^{13}C$ and δ^{15} N and C/N ratio in the sediment core of St.1 was $\delta^{13}C$ = -27.74 ± 1.62 ‰, δ^{15} N = 7.27 ± 1.95 ‰, C: N=18.80 ± 3.60). The stable isotope ratio of carbon and nitrogen for each depth interval is given in Table 8.1.

The mean pH in sediment core of St.2 was neutral to slightly acidic (6.80 ± 0.40) with a minimum pH in 4-6 cm depth interval and maximum pH of 7.47 in 35-40 cm depth interval (Fig.8.3 a). The range of redox potential in the sediment core of St.2 was -420 to -150 mV. The maximum reduced nature was observed in 10-15 depth interval, and the most oxidised layer was 40-45 cm depth interval (Fig.8.3 b). The moisture content showed marked difference along with the depth profile, and the range of moisture content in the sediment core of St.2 was 20.47 % (15-20 cm depth) to 81.86% in surface layer (Fig.8.3c). The sediment texture analysis revealed that in St.2, sand (89.03 ± 6.97 %) was the main component followed by silt (5.81 ± 4.84 %) and clay (5.15 ± 2.47 %) (Fig. 8.3d).

An apparent increase in bulk density was observed in the sediment core of St.2 according to downward vertical profile (Fig.8.4). The mean bulk density in Core 2 (St.2) for all depth intervals was high compared to St.1 (0.81 ± 0.36 g cm^{-3}). The minimum bulk density was in the surface layer (0-2cm) and was 0.137 g cm^{-3}. It increased with depth and reached a maximum of 1.25 g cm^{-3} in 40-45 cm depth interval. The mean total carbon concentration in the sediment core of St.2 was comparatively low, having 37.81 ± 25.47 g kg^{-1}, organic carbon of 26.80 ± 18.37 g kg^{-1} and inorganic carbon of 11.01 ±7.46 g kg^{-1} (Table 8.2). The maximum total carbon was observed in the surface layer (91.5 g kg^{-1}), and the minimum (9.32 g kg^{-1}) at 40-45 cm depth interval. At this station, there was a clear decrease in carbon content downward the core.

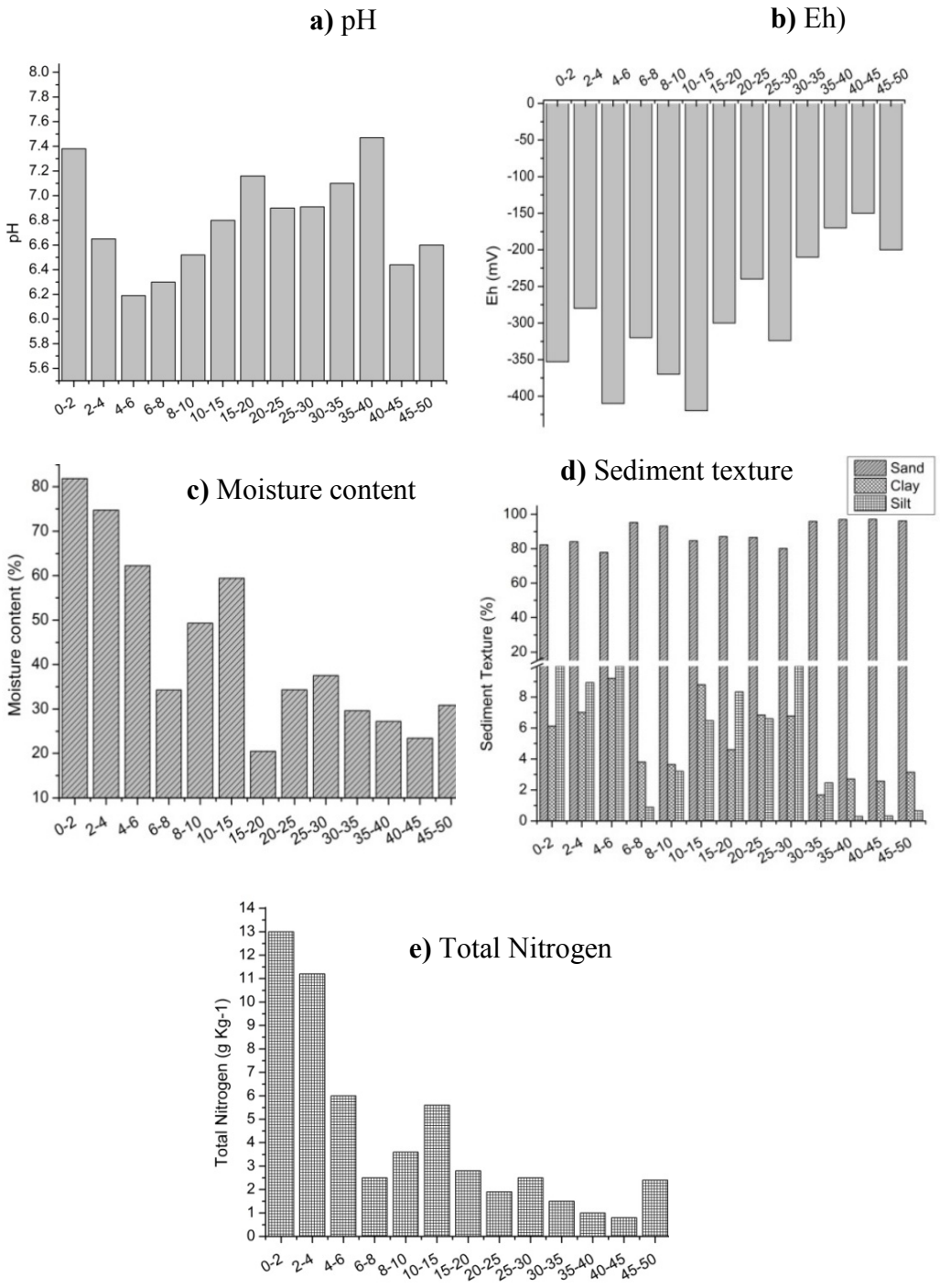

Figure 8.3 The variation in different physico-chemical parameters with depth interval (cm) of Core II

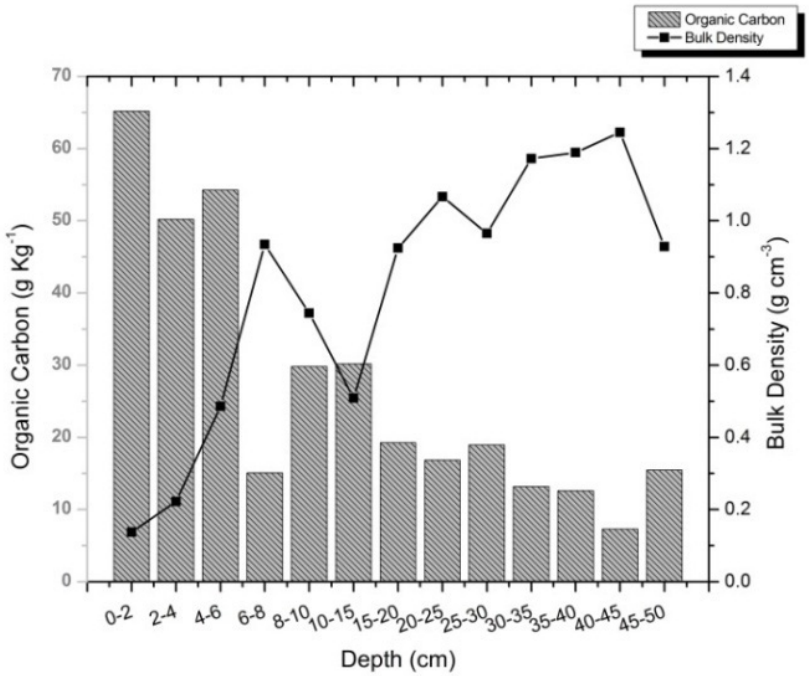

Figure 8.4 The bulk density vs organic carbon content according to the vertical profile of sediment Core II

The nitrogen also followed the same trend, and the mean nitrogen concentration was 4.22 ± 3.84 g kg^{-1} (Fig.8.3 e). The maximum nitrogen concentration was observed in 0-2 cm depth interval (13.0 g kg^{-1}) and the minimum (0.8 g kg^{-1}) at 40-45 cm depth interval. The mean stable isotope ratio of $\delta^{13}C$ and δ^{15} N was more depleted up to a depth interval of 8-10 cm with $\delta^{13}C$ = -26.59 ± 1.29 ‰ and δ^{15} N = 5.34 ±1.90 ‰; below which the values were enriched (-22.55 ± 0.74 ‰ and δ^{15} N = 8.78 ± 2.33 ‰) and depth started depleting again beyond 40-45 cm (-24.51 ± 0.30 ‰ and δ^{15} N = 8.18 ±1.82 ‰). The mean C/N ratio was low (10.63 ± 2.75) compared to the general trend of the C/N ratio in mangrove sediments. The depth wise profile of stable isotope ratio of carbon, nitrogen and C/N ratio are shown in Table 8.2.

Table 8.2 Carbon, Nitrogen, and stable isotope ratio of sediment in different depth intervals of sediment Core II

Depth(cm)	TOC	TIC	TC	TN	$\delta^{13}C$	$\delta^{15}N$	C: N
0-2	65.2	26.3	91.5	13	-27.52	4.65	7.04
2-4	50.2	25	75.2	11.2	-27.62	2.75	6.71
4-6	54.27	16.68	70.95	6	-26.87	5.07	11.83
6-8	15.1	8.38	23.48	2.5	-24.44	7.8	9.39
8-10	29.8	9.84	39.64	3.6	-26.51	6.41	11.01
10-15	30.2	10	40.2	5.6	-23.21	4.5	7.18
15-20	19.24	10.76	30	2.8	-21.73	10.39	10.71
20-25	16.84	6.48	23.32	1.9	-22.62	10.40	12.27
25-30	18.97	10.83	29.8	2.5	-22.04	9.81	11.92
30-35	13.19	4.48	17.67	1.5	-22.08	9.91	11.78
35-40	12.6	4.37	16.97	1	-23.62	7.64	16.97
40-45	7.3	2.02	9.32	0.8	-24.3	6.89	11.65
45-50	15.46	8.04	23.5	2.4	-24.72	9.47	9.79

An apparent increase in bulk density was observed in the sediment core of St.3 as proceeding downward the vertical profile (Fig.8.6). The mean bulk density in Core III (St.3) for all depth intervals were high compared to St.1 and St.2 (0.96 ± 0.24 g cm^{-3}). The minimum bulk density was in the surface layer (0-2cm) with 0.527 g cm^{-3} which gradually increased with depth and reached a maximum of 1.35 g cm^{-3} at 25-30 cm depth interval. The mean total carbon concentration in the sediment core of St.3 was 45.80 ± 27.77 g kg^{-1} with organic carbon 30.56 ± 16.87 g kg^{-1} and inorganic carbon 9.30 ± 5.21 g kg^{-1} (Table 8.3). The maximum total carbon was observed in the surface layer (91.2 g kg^{-1}), and the minimum was at 30-35cm depth interval (16.46 g kg^{-1}). There was a clear decrease in carbon content towards the bottom of the core.

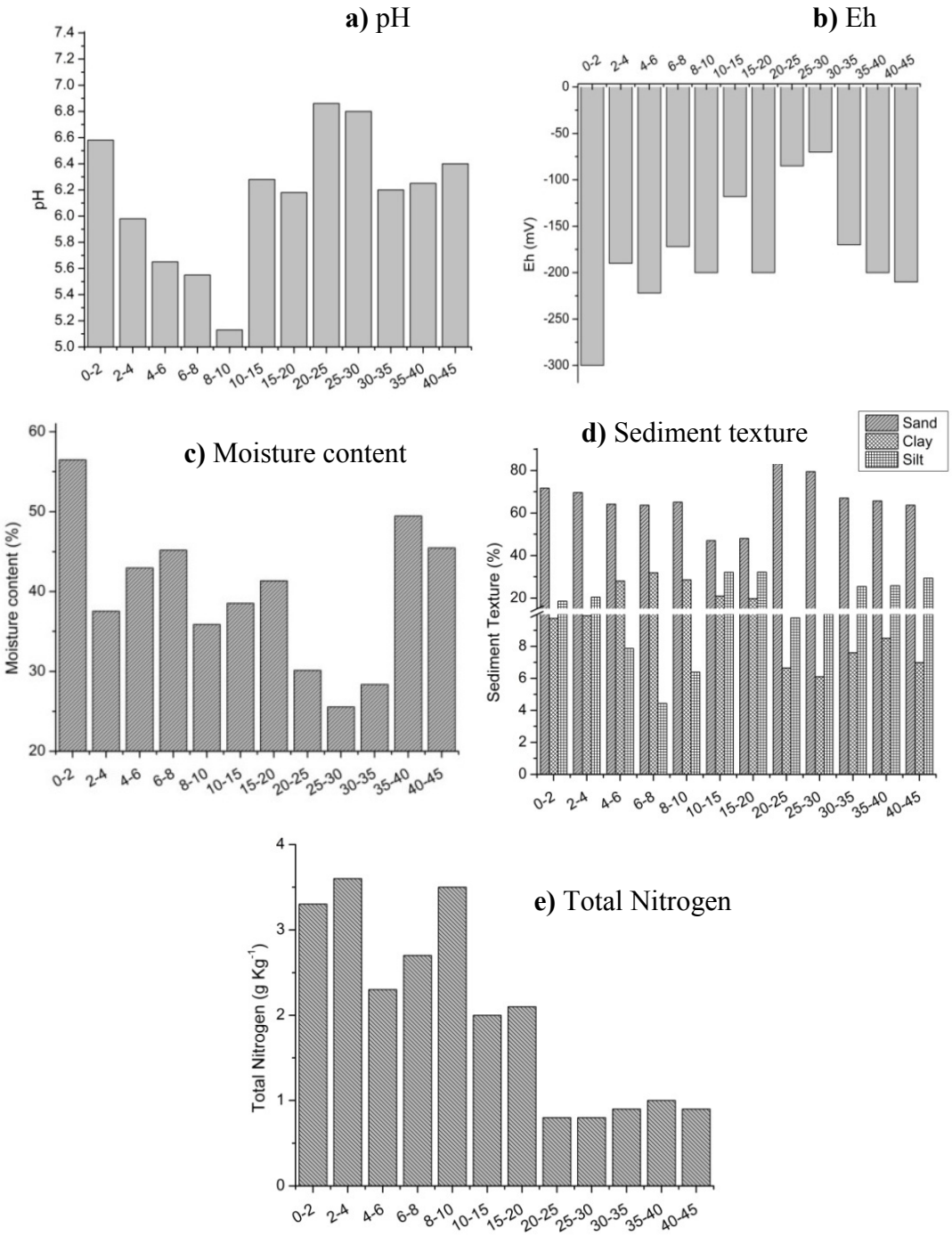

Figure 8.5 The variation in different physico-chemical parameters with depth interval (cm) of sediment Core III

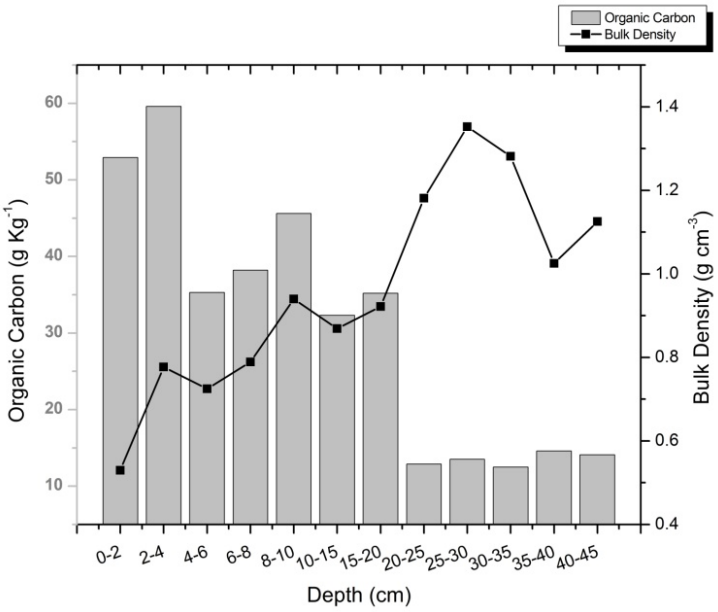

Figure 8.6 The bulk density vs organic carbon content according to the vertical profile of sediment Core III

Table 8.3 Carbon, Nitrogen, and stable isotope ratio of sediment in different depth intervals of sediment Core III

Depth (cm)	TOC	TIC	TC	TN	$\delta^{13}C$	$\delta^{15}N$	C:N
0-2	52.9	11.96	91.2	3.3	-27.84	9.07	19.65
2-4	59.6	14.55	85.5	3.6	-27.31	7.14	20.6
4-6	35.3	16.46	71.65	2.3	-27.58	8.08	22.5
6-8	38.2	18.11	56.31	2.7	-26.69	10.22	20.86
8-10	45.6	12.71	58.31	3.5	-26.37	11.83	16.66
10-15	32.3	7.22	53.2	2	-26.44	10.26	19.76
15-20	35.2	7.86	43.06	2.1	-26.48	9.73	20.5
20-25	12.9	6.02	18.92	0.8	-25.63	7.62	23.65
25-30	13.5	4.49	17.99	0.8	-25.05	8.28	22.49
30-35	12.5	3.96	16.46	0.9	-24.81	7.13	18.29
35-40	14.6	3.29	17.89	1	-24.82	5.29	17.89
40-45	14.1	5	19.1	0.9	-25.16	6.87	21.22

The nitrogen also followed the same trend with a mean nitrogen concentration of 1.99 ± 1.10 g kg^{-1} (Fig.8.5 e). The maximum nitrogen

concentration was observed in 2-4 cm depth interval (3.6 g kg^{-1}), and the minimum was in 20-25 cm and 25-30 cm depth interval (0.8 g kg^{-1}). The mean stable isotope ratio of $\delta^{13}C$ and C/N ratio was -26.18 ± 1.08 ‰ and 20.34 ± 2.04, respectively, which indicated a more depleting nature. However, δ^{15} N (8.46 ± 1.82 ‰) showed enriched values (Table 8.3).

II. ^{210}Pb and ^{137}Cs activities and CRS-Modeled historical data

From the soil carbon sequestration study, only two sites (St.2 and St.3) had continuous ^{210} Pb activity profiles for the calculation of mass accumulation rate (Table 8.4). Since St.1, did not showed a continous ^{210}Pb activity profiles only ^{137}Cs activity was used for the calculation of linear accumulation rate. The core samples from the two stations (St.2 and St.3) examined in the study have a typical exponential decrease in specific excess ^{210} Pb activity down core (Table 8.5) which is mandatory for assessing the age of that core profile and also MAR calculation. For St. 1, the peak in ^{137} Cs activity was observed at 10-15 cm depth interval. Detailed age models are presented in Table 8.5

III. Carbon Burial Rate

The mean mass accumulation rate (MAR) of sediment in St.1 according to peak ^{137}Cs activity was 0.08 ±0.01g cm^2 yr^{-1}. The sedimentation rate was low in the surface layer that increased down the sediment core (Fig.8.7). In St.2, the mean MAR was 0.09 ±0.03 g cm^2 yr^{-1}. Fig.8.7 provides a detailed record of MAR over time. A sharp increase in sedimentation rate was observed in St.2 from 2004-2010 period at 4-6 cm depth interval. The mean MAR of sediment in St.3 was very high compared to the other two stations and was 0.44±0.05 g cm^2 yr^{-1}. There was a continuous increase in mass accumulation rate down the core in St.3 (Fig.8.7).

Table 8.4 Short lived radionuclide ^{210}Pb and ^{137}Cs Activity in the sediment Core I

Depth	Excess ^{210}Pb Activity (dpm g^{-1})	Excess ^{210}Pb Uncertainty (dpm g^{-1})	^{137}Cs Activity (dpm g^{-1})
0	10.76	0.33	0.11
2	14.11	0.37	0.16
4	12.25	0.34	0.36
6	13.92	0.35	0.34
8	11.58	0.32	0.57
10	10.48	0.30	0.96
15	10.73	0.30	0.57
20	7.88	0.25	0.44

Table 8.5 Short lived radionuclide ^{210} Pb and ^{137}Cs activity in the sediment Core II and Core III

Depth (cm)	Excess ^{210} Pb Activity (dpm g^{-1})	Excess ^{210} Pb Uncertainty dpm g^{-1})	^{137}Cs Activity (dpm g^{-1})	Calendar Year (CE)	Calendar Year Uncertainty
Core II					
0	12.38	0.35	0.11	2017.5	2
2	8.78	0.27	0.09	2010.9	3
4	6.34	0.22	0.22	2004.6	3
6	4.58	0.20	0.86	1991.1	6
8	2.18	0.14	0.16	1949.7	6
10	-0.08	0.06	0.13		
Core III					
0	4.83	0.32	0.02	2017.5	2.4
2	6.35	0.37	0.03	2009.9	2.7
4	5.38	0.33	0.15	1995.0	3.5
6	2.64	0.30	0.34	1974.7	5.0
8	1.06	0.23	0.16	1954.3	6.3
10	0.62	0.20	0.11	1936.5	6.3

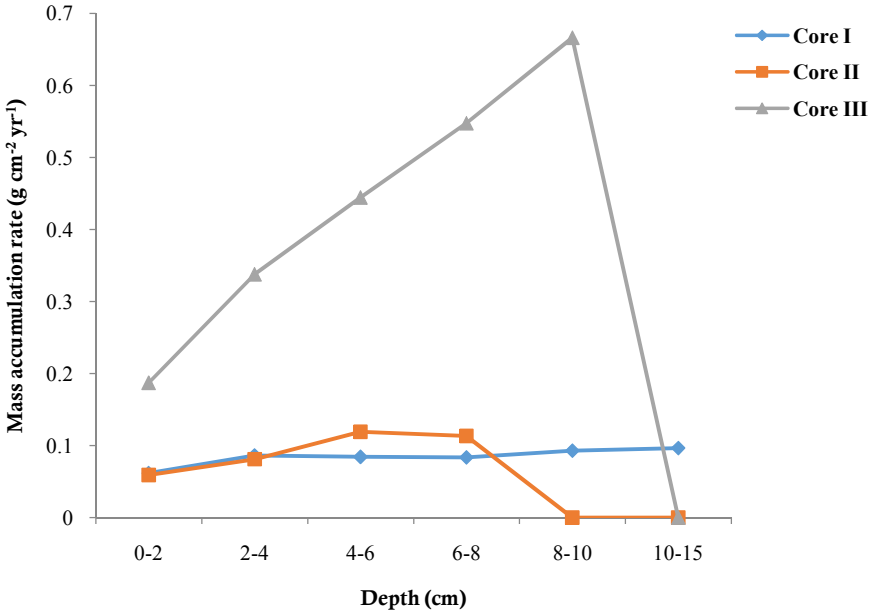

Figure 8.7 Mass accumulation rate of sediment for three sediment cores in the Cochin mangroves

The estimated mean total carbon burial rate in St.1 was 10.41 ± 2.50 t C $ha^{-1}yr^{-1}$(1041.43 ± 250.26 g C $m^{-2}yr^{-1}$), in which organic carbon burial rate was 8.75 ± 2.50 t C $ha^{-1}yr^{-1}$(875.35 ± 250.13 g C $m^{-2}yr^{-1}$), and inorganic carbon burial rate was 1.67 ± 0.41 t C $ha^{-1}yr^{-1}$(166.80 ± 40.68 g C $m^{-2}yr^{-1}$) respectively. In St.2, the total carbon burial rate was very low and was 0.57 ± 0.24t C ha^{-1} yr^{-1} (56.59 ± 23.84 g C $m^{-2}yr^{-1}$). The corresponding organic carbon burial rate in St.2 was 0.40 ± 0.19 t C $ha^{-1}yr^{-1}$ (40.28 ± 19.44 g C $m^{-2}yr^{-1}$) and inorganic carbon burial rate was 0.16 ±0.05 t C $ha^{-1}yr^{-1}$(16.31 ± 5.01 g C $m^{-2}yr^{-1}$). The total carbon burial rate, organic carbon burial rate and inorganic carbon burial rate in St.3 were 2.95 ± 0.79 t C $ha^{-1}yr^{-1}$(294.85 ± 79.00 g C $m^{-2}yr^{-1}$), 1.93 ± 0.75 t C $ha^{-1}yr^{-1}$(193.97 ± 75.41g C $m^{-2}yr^{-1}$) and 0.66 ± 0.30 t C $ha^{-1}yr^{-1}$(65.68 ± 30.34 g C $m^{-2}yr^{-1}$) respectively. The average (median) total carbon burial rate in mangroves of Cochin was estimated as 2.95 t C ha^{-1} yr^{-1} (294.85 g C m^{-2}

yr^{-1}), and the organic carbon burial rate was 1.93± 0.75tC $ha^{-1}yr^{-1}$ (193.97 g C $m^{-2}yr^{-1}$).

8.4.2 Ecosystem carbon stock

Total ecosystem carbon pool of the Cochin mangroves was estimated to 345.80 ± 202.04 t C ha^{-1}, in which above ground biomass was171.68 ± 104.42 t C ha^{-1}(according to Eq.2), the belowground biomass was 93.78 ± 59.52 t C ha^{-1}, soil carbon pool was 73.22 ± 39.40 t C ha^{-1} and litterfall carbon as dead biomass was 7.12 ± 2.81 t C ha^{-1}. The ecosystem carbon pool was high in St.3 (572.43 t C ha^{-1}) followed by St.1 (280.46 t C ha^{-1}) and St.2 (184.52 t C ha^{-1}). The contribution of each carbon stock to total ecosystem carbon stock in three stations is given in Fig.8.9. In St.1, aboveground living biomass was 142.35 t C ha^{-1} followed by BGB (72.91t C ha^{-1}), soil carbon pool (54.83 t C ha^{-1}) and litterfall production (10.37 t C ha^{-1}). In St.2, the AGB was low 85.08 t C ha^{-1} followed by BGB (4.50 t C ha^{-1}), soil pool (46.36 t C ha^{-1}) and litterfall (5.57 t C ha^{-1}). The carbon storage as AGB in St.3 was very high (287.63t C ha^{-1}) followed by 160.91 t C ha^{-1} BGB with high soil carbon stock (118.45 t C ha^{-1}) and litter fall production (5.43 t C ha^{-1}). The estimated mangrove area was high in St.1 (15.13 ha) followed by St.2 (10.74 ha) and St.3 (4 ha). Therefore the corresponding ecosystem carbon stocks in these areas were 4243.40 t in St.1 followed by 2289.71 t in St.3 and 1981.70 t in St.2.

The estimated mangrove areal extent surrounding the Cochin estuary was 411.13 ha, which includes the area in Ernakulam district along with Aroor. From this areal extent, the possible ecosystem carbon stock of Cochin mangroves was calculated to be 142168.75 t C. Therefore it accounts to an estimated amount of 521759.31 t CO_2 e. Even though Cochin mangroves are in a patchy distribution that has a potential to sequester and store substantial quantity of carbon dioxide from the atmosphere.

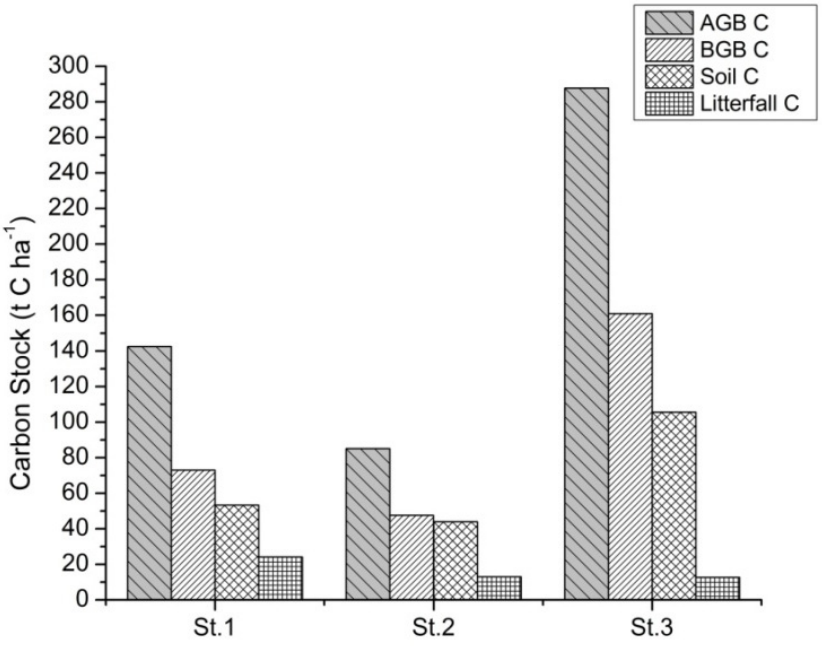

Figure 8.9 The spatial variation of different carbon pools in the Cochin mangroves during 2013-2015 period

8.4.3 Economic valuation of mangroves in terms of carbon stock

The Social cost of carbon (SCC) contributed by Cochin mangroves to ecosystem carbon stock in the present study was US $ 114787048.75, which is approximately equivalent to8035.09 million. Considering the soil carbon stock (since biomass carbon stock of mangroves will significantly vary in each district, only soil carbon stock was used instead of ecosystem carbon stock) of Cochin mangroves and the mangrove area estimated for each districts of Kerala, the possible SCC and CO_2 e of the corresponding mangrove habitats in the districts of the state was calculated (Table 8.6). The mangrove areal extent was higher in Kannur district (900 ha) followed by Ernakulam and Alappuzha. The least mangrove areal extent was observed in Thiruvananthapuram.

Table 8.6 Mangrove areal extent in different districts of Kerala and contribution to soil carbon stock, CO_2e and Social Cost of Carbon from Kerala mangroves

Districts	Mangrove area (ha)	Carbon Stock(t)	$C0_2$ e (t)	SCC(US $)
Kazaragodu	90	6589.8	24184.57	5320605
Kannur	900	65898	241845.7	53206045
Kozhikkode	74	5418.28	19885.09	4374719
Malappuram	38	2782.36	10211.26	2246477
Thrissur	89	6516.58	23915.85	5261487
Ernakulam	396	28993.25	106405.2	23409146
Kottayam	44	3221.68	11827.57	2601184
Alappuzha	110	8054.2	29558.91	6502961
Kollam	36	2635.92	9673.83	2128242
Trivandrum	5	366.1	1343.59	295589.1

8.5 Discussion

8.5.1 Sediment carbon burial

a. Physico-chemical characteristics of sediment core

Various physico-chemical parameters of the sediment influences the availability and storage of carbon in mangrove sediment. The correlation for physico- chemical parameters in the sediment Core I showed that when depth increased bulk density also increased and was significantly positively correlated (r =0.912, $p < 0.01$) and negatively correlated to TOC (r = -0.755, $p < 0.05$), TC (r = -0.727, $p < 0.05$), TN (r = -0.805, $p <0.01$), and moisture content (r = -0.925, $p < 0.01$). Even though there was only a negligible increase in dry bulk density of the sediment down the core in St.1, it negatively affected the organic matter content moving down the core (Table 8.7). The pH of the mangrove sediment ranged from acidic to alkaline conditions that varied with the availability of organic substances from mangrove flora and fauna as well as

contents of carbonates and bicarbonates (Williams, 1987). In St.1, it was almost acidic and exhibited a negative correlation to redox potential (Eh). A similar influence of redox potential on pH of the sediment was reported by Miao et al. (2006). The acidic nature of mangrove sediment was due to the decomposition of mangrove litter and release of various organic acids as a result of hydrolysis of tannin in mangrove plants and also oxidation of FeS_2 and FeS to H_2SO_4 (Liao,1990). The Eh of the sediment was positively correlated to sand content ($r = 0.784$, $p < 0.05$). Usually, sand dominated soil will have less organic matter having lower reducing properties resulting in more positive values for Eh (Pearson and Stanley, 1979). The primary source of organic carbon in mangrove sediment was from mangrove litter and in the present study it was significantly positively correlated to moisture content of the sediment ($r = 0.841$, $p < 0.01$) while negatively correlated to bulk density of the sediment ($r = - 0.736$, $p < 0.05$) which is a usual trend in sediment geochemistry. The same trend was seen in the case of total carbon and total nitrogen.

The organic matter is always bound to clay and silt particle of the sediment. In sediment Core I, there was no marked change in sediment texture (clayey silt) up to the maximum depth interval of the study. The stable isotope signature of carbon and nitrogen in the core sediment of St.1 confirmed the origin of mangrove-derived organic matter in the sediment. The stable isotope ranges for mangroves for $\delta^{13}C$ was -32 to -24 ‰ and that for $\delta^{15}N$ was 3 to 7 ‰ whereas for marine phytoplankton it has $\delta^{13}C$ of - 20 ‰ to - 23 ‰ and $\delta^{15}N$ of 6 ‰ to 11 ‰ (Rodelli et al.,1984; Bouillon et al., 2003; Kendal, 1997; Gearing et al., 1977; Meyers, 1997; Bianchi et al., 2002). The stable isotope ratio of different mangrove plants were studied by Rodelli et al., 1984; Bouillon et al., 2003a, 2008 and Tue et al., 2011. The values of $\delta^{13}C$, δ^{15} N and

C/N ratio of mangrove sediment in the core sample in the present investigation was more adjacent to the stable isotope range of global mangrove plant compared to sediment samples of Sundarban and Coringa mangroves (Prasad et al., 2017; Bouillon et al., 2003a). However, $\delta^{15}N$ varied slightly and indicated the presence of marine phytoplankton nitrogen source in the sediment in 4-6, 6-8, 15-20 and 20-25 cm depth intervals.

Table 8.7 Correlation analysis of physico-chemical parameters of sediment Core I

	Depth	**pH**	**Eh**	**TOC**	**TIC**	**TC**	**TN**	**CN**	**Bulk.de**	**Moist**	**Sand**	**Clay**
Depth	1											
pH	.332	1										
Eh	.047	-.714*	1									
TOC	-.755*	-.241	.162	1								
TIC	.281	-.158	.302	-.188	1							
TC	-.727*	-.268	.209	.990**	-.044	1						
TN	-.805**	-.335	.097	.604	-.131	.595	1					
CN	-.112	-.050	.218	.587	.101	.612	-.262	1				
Bulk. de	.912**	.016	.211	-.736*	.236	-.713*	-.755*	-.137	1			
Moist	-.925**	-.458	.180	.841**	-.261	.817**	.840**	.187	-.859**	1		
Sand	-.243	-.670*	.784*	.233	-.013	.235	.542	-.194	-.124	.492	1	
Clay	.294	.408	-.373	-.124	-.596	-.214	-.338	.002	.356	-.348	-.360	1
Silt	-.264	-.302	.244	.087	.630	.181	.253	.035	-.352	.272	.189	-.984**1

*. Correlation is significant at the 0.05 level (2-tailed)
**. Correlation is significant at the 0.01 level (2-tailed)

In St.2, bulk density (Bulk.de) and sand increases with depth that was significant and positively correlated ($r = 0.845$, $p < 0.01$ for bulk density and

r =0.622, $p < 0.05$ for sand) with depth (Table 8.8). There was an inverse relation of organic matter with depth that was negatively correlated to TOC (r = - 0.810, $p < 0.01$), TC (r = - 0.839, $p < 0.01$), TN (r = - 0.804, $p < 0.01$) and moisture content (r = - 0.815, $p < 0.01$). When the depth increases, more sand content was observed in the sediment core, which correspondingly increases with g dry bulk density. The organic matter has less affinity to sand component compared to clay and silts and therefore results in a decrease in organic matter downward the core. St.2 was neutral in pH compared to acidic soil in St.1 as described earlier. The Eh of the sediment was positively correlated to sand content (r = 0.703, $p < 0.01$) and bulk density (r = 0.691, $p < 0.01$) similar to Core I. It was negatively correlated to organic matter, clay content and moisture content of the sediment resulting in more negative values for Eh when more organic matter gets reduced leading to anoxic conditions. Similar observations were reported from retting areas of the backwaters of Kerala (Bijoy Nandan and Abdul Azis, 1995)

The organic carbon in Core II was positively correlated to moisture content, TN and silt content. However, it was negatively correlated to sand and bulk density (Table 8.8). Similar trend was noticed in the case of total carbon and total nitrogen. In Core II, there was marked change in sediment texture compared to Core I. Organic matter is always bound to clay and silt particle of the sediment. Therefore, TC, TOC and TN showed significant correlation with sediment texture in the sediment Core II. The sand was negatively correlated to organic matter (TOC, TN) where as clay and silt positively correlated to organic matter (Table 8.8).The stable isotope signature of carbon and nitrogen in Core II confirmed the origin of mangrove-derived organic matter only in the surface layer of the sediment. The mean stable isotope ratio of $\delta^{13}C$ and δ^{15} N up to a depth interval of 8-10 cm was showing mangrove litter source and

below that depth showed marine signal (-22.55 ± 0.74 ‰ and δ^{15} N = 8.78 ± 2.33 ‰) which beyond 40-45 cm depth started showing a mixed signal (-24.51± 0.30 ‰ and δ^{15} N = 8.18 ± 1.82 ‰). The mean C/N ratio was low (10.63 ± 2.75) compared to the general trend of the C/N ratio in mangrove sediments. Since this station was near to seashore, it may indicate a transition from a beach setting to a mangrove forest setting. This is supported by the fact that the mangroves in this station were quite younger (according to local survey and structural characters). Many historical topographical changes may have happened in this area and may be the reason for the marine signal in the deeper sections of this core.

Table 8.8 Correlation analysis of physico-chemical parameters in sediment Core II

	Depth	pH	Eh	TOC	TIC	TC	TN	CN	Bulk.d	Moist	Sand	Clay	Silt
Depth	1												
pH	.143	1											
Eh	.753**	.249	1										
TOC	-.810**	-.127	-.708**	1									
TIC	-.823**	.051	-.535	.857**	1								
TC	-.839**	-.076	-.677*	.987**	.928**	1							
TN	-.804**	.091	-.503	.807**	.965**	.881**	1						
CN	.583*	.033	.368	-.380	-.673*	-.482	-.792**	1					
Bulk.d	.845**	.068	.691**	-.872**	-.939**	-.920**	-.958**	.754**	1				
Moist	-.815**	-.063	-.637*	.827**	.888**	.872**	.937**	.747**	-.955**	1			
Sand	.622*	.014	.703**	-.612*	-.690**	-.655*	-.603*	.460	.672*	-.643*	1		
Clay	-.592*	-.194	-.731**	.513	.570*	.547	.536	-.521	-.664*	.650*	-.909**	1	
Silt	-.593*	.079	-.639*	.620*	.703**	.665*	.596*	-.398	-.629*	.595*	-.977**	.799**	1

*. Correlation is significant at the 0.05 level (2-tailed)

**. Correlation is significant at the 0.01 level (2-tailed)

The relation between depth, bulk density, moisture content and organic matter in the sediment Core III was similar to the other two cores (Table 8.9).

The pH of sediment core in St.3 was acidic similar to St.1, where mangrove litter decomposition and release of organic acids from mangrove litter was active, a situation similar to St.1. This was evident from the negative correlation of pH with TIC (r = - 0.675, $p < 0.05$), TN (r = - 0.623, $p < 0.05$) and clay content (r = - 0.827, $p < 0.01$). The Eh of the sediment was positively correlated to bulk density (r = 0.706, $p < 0.05$) similar to Core I. It was negatively correlated to total carbon and moisture content of the sediment and showed a very reducing nature throughout the core which lead to anoxic conditions. Only two depth intervals showed high Eh values (-85mV, 70 mV) where sand content was maximum and organic matter was minimum. The organic carbon in the sediment Core III, was positively correlated to TN and negatively correlated to bulk density. The strong correlation of TOC with TN is an indication of nitrogen fixation by heterotrophic bacteria and cyanobacteria in the mangrove sediment,that has been observed previously and found to be a major nitrogen source in mangrove sediment (Sheridan, 1991; Alongi et al., 1992). In Core III, there was no marked change in sediment texture compared to Core II. Therefore TC, TOC and TN did not significantly correlate with sediment texture.

The stable isotope signature of carbon and nitrogen in the core sediment of St.3 confirmed the origin of mangrove-derived organic carbon throughout the depth of the core. However, the nitrogen source was indicating a marine origin. The cyanobacterial nitrogen fixation may be the reason for the marine signal rather than mangrove litter (Mann and Steinke,1989; Lee and Joye, 2006; Reis et al., 2016). Gabriela Alfaro-Espinoza and Ullrich (2015) studied the nitrogen source of mangrove environments and reported the presence of Diazotrophs (nitrogen-fixing bacteria) which nourish the mangrove sediment with nitrogen and aid mangrove plant growth. Since St. 3 was a bird sanctuary

and a historical migratory bird nesting site, the birds droppings may also act as a source of nitrogen in this station. However, further studies are needed to determine the source of nitrogen in St.3.

Table 8.9 Correlation analysis of physico-chemical parameters in sediment Core III

	Depth	pH	Eh	TOC	TIC	TC	TN	CN	Bulk.d	Moist	Sand	Clay	Silt
Depth	1												
pH	.385	1											
Eh	.409	.350	1										
TOC	-.905**	-.500	-.542	1									
TIC	-.854**	-.675*	-.393	.783**	1								
TC	-.957**	-.425	-.580*	.955**	.816**	1							
TN	-.881**	-.623*	-.544	.982**	.814**	.924**	1						
CN	-.042	.484	.411	-.218	.074	-.087	-.314	1					
Bulk. de	.843**	.401	.706*	-.845**	-.757**	-.915**	-.817**	.124	1				
Moist	-.320	-.151	-.812**	.408	.326	.477	.388	-.222	-.751**	1			
Sand	.037	.380	.244	-.222	-.086	-.178	-.214	.366	.326	-.306	1		
Clay	-.491	-.827**	-.180	.457	.733**	.454	.552	-.163	-.504	.192	-.501	1	
Silt	.433	.399	-.081	-.207	-.614*	-.251	-.308	-.223	.145	.133	-.557	-.439	1

*. Correlation is significant at the 0.05 level (2-tailed).
**. Correlation is significant at the 0.01 level (2-tailed).font

b. Carbon burial

The organic carbon burial rate in St.1 was high, 875.54 g OC $m^{-2}yr^{-1}$ (8.76 t C ha^{-1} yr^{-1}) compared to the global rate (163 g OC $m^{-2}yr^{-1}$; Breithaupt et al., 2012). The net primary productivity through litterfall in this station was 10.37 t C ha^{-1} yr^{-1}. Therefore 84.43% of the mangrove primary production was buried in this habitat indicating an excellent carbon sink. Globally burial contributed only ~10% of mangrove primary production (Duarte et al., 2005; Bouillon et al., 2008b; Breithaupt et al., 2012). However, in St.1, most of the

primary production was buried in the sediment. Since we used only litterfall as a proxy for net primary production without taking biomass increment, the contribution of organic carbon burial in the sediment from primary production may be overestimated. In addition, global estimates are based on centennial mean and in the present study, we had to restrict with 54 years in the St.1 age model. The carbon burial rate in this station was exceptionally high compared to the mangrove forest of the Florida Everglades (Breithaupt et al., 2014) and mangroves in Port Aransas, Texas (Bianchi et al., 2013) (Table 8.9). The Florida mangroves have a mean 50-year organic burial rate of 176 ± 31 g OC m^{-2} yr^{-1} where as Texas mangroves have a mean 50-year organic burial rate of 253 ± 11 g OC $m^{-2}yr^{-1}$. Similarly, high organic carbon burial rates were reported by Sanders et al. (2010a) and reported 1129, 949 and 353 g C m^{-2} yr^{-1} from the mud flat, mangrove forest fringe region and inside mangrove forest respectively in the mangroves of Brazil. Exceptionally high organic carbon burial rate (1722 ± 183 g C m^{-2} yr^{-1}) was also reported in Indonesian mangroves in a recent study by Kusumaningtyas et al. (2019). The comparison of the organic carbon burial rate of the present study with different studies of the world are summarized in Table 8.9

The high organic carbon burial rate in St.1 may be due to high primary production, high input of autochthonous sedimentary organic matter and also high sedimentation rate. The high primary production, in turn, depends on the age of the mangrove stand (Alongi, 2014; Marchand, 2017). In St.1, the presence of structurally matured trees and high litterfall production may have resulted in high soil carbon stock. St.1 was a lower energy region (the clayey-silt sediment texture will accumulate more organic matter in the sediment and therefore resulted in low export of organic matter and therefore moving of energy will be less in that region) with more silt and clay instead of higher

energy zone (sandy nature of sediment is less bound to organic matter and there will be high export of organic matter from those substratum and therefore will contribute to more energetic region) like St.2 and St.3. This will reduce the export of litterfall via physical transport (waves and tides). The density of herbivorous mangrove crabs was also abundant in this region (13.0 ind.m^{-2} as described in chapter 5.4) which will again limit the export of mangrove primary production and lead to higher carbon burial in this station.

The organic carbon burial rate in St.2 was very low (40.28 g C m^{-2} yr^{-1}) compared to St.1 even though they had similar sedimentation rates (0.09 g m^{-2} yr^{-1}). It contributed only 7.23 % of the primary production (litterfall production) in the station and indicated that the mangrove habitat might act as a source of carbon rather than a sink. Otherwise, there may be a possibility of export of mangrove-derived organic carbon or inorganic carbon to adjacent coastal water bodies. The low carbon burial rate in St.2 may be attributed to the presence of organic matter input as a mixture of autochthonous and allochthonous origin in contrast to St.1 with autochthonous organic matter origin from mangrove litter. The litterfall production (5.57 t C ha^{-1} yr^{-1}), biomass stock and soil carbon stock in this station were also less compared to St.1. The crab density was very low (0.13 ind.m^{-2}) in this station which in turn may enhance export of litterfall and therefore may be a relevant reason for this low carbon stock in sediment leading to very low carbon burial in St.2. The loss of carbon may also be in the form of GHG (Green House Gases) since this site was converted into an aquaculture farm in the 1980s. Conversion of mangrove forest into aquaculture farm has been shown to trigger GHG emission (Pendleton et al., 2012; Sidik and Lovelock, 2013; Kauffman et al.,2014;Jarvio et al.,2018). The sand dominated the high energy region in St.2,

which favours the export of organic matter, also limited the carbon stock in that region.

St.3 was also a sand-dominated site and had a higher organic carbon burial rate (193.97 g C m^{-2} yr^{-1}) than St.2. The organic carbon burial rate in St.3 contributed 35.73% of primary production calculated from litterfall production. Even though the mass accumulation rate in St.3 was very high(0.44 g cm^{-2} yr^{-1}) compared to the other two stations, it had a lower organic carbon burial rate than St.1. Many studies reported that sedimentation rate played a significant role in determining the carbon burial rate in a mangrove ecosystem (Jennerjahn and Ittekkot, 2002; Kristensen et al., 2008 and Kusumaningtyas et al.,2019). However, in this study, carbon stock played a significant role in determining the carbon burial rate in these habitats. The carbon stock, in turn, depends on total biomass stock and soil carbon stock. The study suggests that sedimentation rate and sediment texture are least important to biological pump (majorly through crabs) played a major role in elevating the carbon stock in mangrove sediments. This is evident in St.1 and St.3 (11.4 ind.m^{-2}) having higher crab density than St.2 and their respective carbon burial rates. Even though St.3 was similar to St.2 in the case of sand dominated sediment and primary productivity through litterfall, the age of the mangrove stand was very old, and biomass stock was also very high, which led to high soil carbon stock via the biological pump. The significant difference noticed between St.3 and St.2 was in crab density. Therefore biological density (e.g. crabs) could be a primary control of carbon burial rate in a particular mangrove ecosystem together with mangrove stand age and biomass stock.

A significant portion of mangrove primary productivity (mainly in the case of St.2 and St.3) may be exported to adjacent estuarine areas, and ultimately into oceanic systems through outwelling of mangrove nutrients may

be possible. A recent study on outwelling of mangrove carbon through dissolved inorganic carbon (DIC) proved that mangrove primary production fate is beyond carbon burial. A major portion of the primary production may be exported that resulted in long term sinking of atmospheric carbon as DIC together with alkalinity (Maher et al., 2018). InSt.3, the export of mangrove-derived organic carbon was evident through stable isotope analysis (Chapter 6) to the Cochin estuary via a feeder canal. However, a more detailed study is required on DIC export, CO_2 and CH_4 flux from estuarine and mangrove systems in order to confirm whether the remainder of the mangrove primary production undergoes lateral exchange and thereby will help in assessing whether these low carbon buried mangrove ecosystems (St.2 and St.3)act as source or sink of atmospheric carbon.

8.5.2 Ecosystem Carbon stock

The ecosystem carbon stock of Cochin mangroves (345.80 ± 202.04 t C ha^{-1}) was well within the global average of 956 t C ha^{-1} (Alongi et al., 2014) and 885 t C ha^{-1} (Kauffman and Bhomia, 2017). The ecosystem carbon stock of Cochin mangroves was compared with other mangrove forests of the world. Kauffman et al., 2011 and 2014 reported very high ecosystem carbon stock in Micronesian mangroves and the Northwest Dominican Republic mangroves. They reported 479 t C ha^{-1} to 1068 t C ha^{-1} in Palausite region and 853 to 1385 t C ha^{-1} in Yap site in Micronesian mangroves, and ecosystem stock of mangroves of Dominican Republic was 706 to 1131 t C ha^{-1}. Among different carbon pools in their study, the highest contribution was from the soil pool (~70% of ecosystem carbon stock). However, in the present study, we got aboveground biomass as the biggest carbon pool compared to soil pool.

The ecosystem carbon storage of different monoculture stands and mixed stands of mangroves in Southern China (212.88 to 443.13 t C ha^{-1}, Wang et al., 2013) was comparable with the present study (186.85 to 559.47 t C ha^{-1}). Bhomia et al. (2016b) reported high carbon stocks from the Pacific coast to the Caribbean coast and Bay Islands (570 to 1000 t C ha^{-1}).

They also assessed the difference in Ecosystem C stock in terms of mangrove structure. According to their study, tall and short mangroves showed high ecosystem carbon stock compared to middle ones. However in the present study, the mangrove habitat with tall mangroves together with high DBH (St.1 and St.3) had high ecosystem carbon stock compared to mangroves with low structural development and this finding was comparable with Kauffman and Bhmoia,2017. They studied in detail on the ecosystem C stock in a long latitudinal gradient along West-Central Africa and reported a mean C stock of 799 t C ha^{-1} with 86% of ecosystem C stock as soil pool. The highest carbon stock was recorded in small mangroves of Liberia and Gabon North (>1,000 t C ha^{-1}), and minimum carbon stock was in Senegal (463 t C ha^{-1}). The mangroves of Amazon, Brazil, was studied by Kauffman et al. (2018) and reported comparatively low carbon stock (361 to746 t C ha^{-1}) than African and Micronesian mangroves. Low soil carbon stocks may be related to coarse-textured soils coupled with a high tidal range. Thus it is seen that even though the ecosystem carbon stock of Cochin mangroves was in a medium range, the soil carbon burial or soil carbon sequestration of Cochin mangroves was very high that was above the global average.

The CO_2 e of ecosystem carbon stock of Cochin mangrove is 521759.31t CO_2 e and indicated the high capacity of these small, patchy, degrading ecosystem in capturing and storing of atmospheric CO_2 as its biomass and also in the soil for a long period.

Table 8.10 Comparison of organic carbon burial rate of different mangrove habitats of the world with the present study

Location	SAR (mm yr^{-1})	OC %	OC burial rate (g m^{-2} yr^{-1})	OC method	Dating method	source
Terminos Lagoon-Boca Chica	4.4,1.3	10.2,5.1	237, 79	OM	^{210}Pb, ^{137}Cs	Lynch et al., 1989
Terminos Lagoon-Estero Pargo	2.9,1	14.6,19.1	157,75	OM	^{210}Pb, ^{137}Cs	Lynch et al., 1989
Celestun Lagoon, Mexico	3	7	55,70	TOC	^{210}Pb	Gonnea et al.,2004
Chelem Lagoon, Mexico		4.3	85.5	TOC	^{210}Pb	Gonnea et al.,2004
Terminos Lagoon, Mexico		4.3,4	53,65	TOC	^{210}Pb	Gonnea et al.,2004
Ilha Grande, Brazil	1.8	4.1	186	TOC	^{210}Pb	Sanders et al.,2008
Tamandare, Brazil	2.8,5	5.8,6.9	353,949	TOC	^{210}Pb	Sanders et al.,2010a
Cananeia, Brazil	2.5,2.9	3,2.9	192,234	TOC	^{210}Pb	Sanders et al.,2010c
Guaratuba, Brazil		2	337	OM	^{210}Pb	Sanders et al.,2010b
Paranagua, Brazil		2	168	OM	^{210}Pb	Sanders et al.,2010b
Paraty, Brazil		2.8	169	OM	^{210}Pb	Sanders et al.,2010b
Florida Keys, USA	4.2,3.9,1.9 ,1.9,4.2	32,32,36,3 6,36	209,177,67, 91,192	OM	^{137}Cs	Callaway et al., 1997
Shark river, Florida, USA	3.6	19	51	TOC	^{210}Pb	Smoak et al.,2013
Harney river, Florida, USA	2.5	30.8	168	TOC	^{210}Pb	Smoak et al.,2013
Hinchinbrook Channel, Australia	1.8,8.5,1.8		168,84,336, 300,100,26	TOC	^{210}Pb, ^{137}Cs	Brunskill et al.,2002
Missionary Bay, Australia	1.9,1.9		71,97	TOC	^{210}Pb, ^{137}Cs	Brunskill et al.,2002
Jiulongjiang Estuary, China	13.5	1.8	1,491,891,9 92,161,020	TOC	^{210}Pb , ^{137}Cs	Alongi et al.,2005
Jiulongjiang Estuary, China	80	1.4	667	TOC	^{210}Pb, ^{137}Cs	Alongi et al.,2005
Leizhou Peninsula, southern China	9.1 -25.0	0.01 -2.36	37-205	OM	^{210}Pb	Yang et al.,2014
Irian Jaya, Indonesia		12.4,5.5,4. 9,6.5	558,412,637 ,717	TOC	^{210}Pb,^{137}Cs	Brunskill et al.,2004
Sawi Bay, Thailand	1.1		226,203,281 ,184	TOC	^{210}Pb, ^{137}Cs	Alongi et al.2001
Rookery Bay, FL, USA			20,39		^{210}Pb , ^{137}Cs	Cahoon and Lynch, Chmura et al. (2003)
Berau, Indonasia	>18	5.7	1722	TOC	^{210}Pb,^{137}Cs	Kusumaningtyas et al.,2019
Central SAL,Indonesia	36	2.4	658	TOC	^{210}Pb, ^{137}Cs	Kusumaningtyas et al.,2019
Eastern SAL, Inonesia	>3.3	7.7	194	TOC	^{210}Pb,^{137}Cs	Kusumaningtyas et al.,2019
Florida Everglades	3.7		176	TOC	^{210}Pb	Breithaupt et al.,2014
Cochin mangroves		10.67	875.35	TOC	^{210}Pb, ^{137}Cs	Present study
		0.43	40.28	TOC	^{210}Pb,^{137}Cs	Present study
		0.46	193.97	TOC	^{210}Pb, $^{137}C^{s}$	Present study

The CO_2 emission of Kochi was 260000 t in the2007-2008 period (Sridhar, 2010). Similarly, a study by Kochi Metro Rail Ltd, Final Report, 2013 reported 1,47,650 t of CO_2 emitted annually by motor vehicle emissions alone in Kochi. Thus, a substantial amount of CO_2 was removed by these ecosystems and therefore disturbing these ecosystems or deforestation may result in an increased level of CO_2 emission instead of the sinking of CO_2 in these habitats. The results indicate that economic valuation of mangrove carbon was very high, and we need to adopt conservative methods based on the carbon economy with the help of national and international organisations for mitigating climate change. REDD+ programmes should be requested in the policy level for better management of these precious blue carbon depositor based on carbon credits.

Thus from the carbon sequestration potential of mangroves through burial and the ecosystem carbon stock of Cochin mangroves revealed that these habitats are significantly potential environments to store atmospheric carbon. Therefore it is understood that the deforestation of these habitats will result in an increased loss in sequestered carbon in this wonderful muddy environment, thereby triggering the release of CO_2 to the atmosphere. Therefore immediate action should be undertaken for the conservation and restoration of mangroves.

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Chapter 9

SUMMARY AND CONCLUSION

The carbon sequestration efficiency of mangrove habitat is the best ecosystem service that can combat climate change, and the carbon sink capacity of these coastal environments, will help in achieving the goals of the Paris Climate Agreement 2016 for sustainable low carbon future. The Paris Agreement supports to intensify efforts for conservation of these valuable carbon sinks on earth. However, the efforts need accurate scientific documentation on the carbon stock in different compartments of the trophic environment, together with long term carbon sequestration in various aquatic ecosystems. Globally wetland ecosystem contributes only 5-8% of global land area, in which mangroves are only 0.5% of the global coastal area. However, the carbon sequestration potential of wetlands are high having a carbon sink capacity of 830 Tg/year and a sequestration rate of 118 g C m^{-2} yr^{-1} (Mitsch et al., 2013). The global carbon sequestration potential of mangroves through burial mechanism contributes 163 g OC $m^{-2}yr^{-1}$ with 26.1 Tg OC to the soil (Breithaupt et al., 2012). The more interesting factor is that approximately 10% of the mangrove productivity is sequestered through burial mechanism. The rest of the carbon gets exported to the adjacent estuaries and ultimately gets buried in the deep ocean, and this carbon is not yet quantified. Therefore a

large amount of atmospheric carbon is removed by the vegetated coastal habitats and stored as carbon in biomass, soil and even in the deep ocean.

This thesis has attempted to quantify the carbon stock and its path from Cochin mangroves and also elucidated the biotic and abiotic control in differentiating the carbon stock in different mangrove sites of the study area. Effort has been made in the thesis to estimate the carbon sequestration potential of Cochin mangroves through burial mechanism and also the carbon source characterisation through stable isotope analysis.

A general understanding of the mangrove plant and its ecosystem characters, a background on mangrove distribution and its extent, the classification of mangroves and different ecosystem services rendered by this ecosystem are briefly explained in chapter 1. A detailed account on carbon cycling and different carbon pools in the carbon pathway in mangrove ecosystem and a brief background on these aspects is also understood from the introductory part. Based on the literature survey, gap areas and the significance of carbon structuring of mangrove habitat, a suitable hypothesis and objectives of the PhD thesis was structured in the chapter.

In chapter 2, a detailed account on the structural attributes of Cochin mangroves is presented. Eight mangrove habitats such as Aroor, Malippuram, Mangalavanam, Chellanam, Valanthakad, Vallarpadam, Panambukad and Puthuvypin were investigated for phytosociological analysis. From the study, 13 true mangrove species was revealed from the Cochin mangroves. Some species like *A. marina*, which are abundant in northern Kerala, was facing extinction from the study area. It could be seen that Cochin mangroves are under threat due to the vast destruction of the habitat from reclamation, construction activities and also for aquaculture conversion purpose. Aroor,

Mangalavanamand Puthuvypin were the most structurally developed mangrove habitats. The average stand basal area of Cochin mangrove tree was 66.97 ± 23.04 m^2 ha^{-1}.The basal area of mangrove trees ranges from 0.1 to 94.32m^2 $ha^{-1,}$ and *A. officinalis* species have the highest basal area among the mangrove trees. The importance value index(IVI) of each mangrove species was computed from the structural data. This IVI index was used to identify the preferred habitats of mangrove species, and this can be used for suitable scientific management and restoration of respective mangrove species. Three mangrove habitats were selected from this study for further community and carbon dynamics study. The community study, including biotic and abiotic analysis in three selected mangrove habitats, revealed that there was a significant difference among these habitats according to plant diversity, structure and also on physicochemical characters. Sediment characters (mainly particle size, moisture content, total carbon, total nitrogen) influenced more on mangrove plant density and its structural parameters. The substratum preference and other optimum abiotic parameters for good structural development of each mangrove species could be understood from this study. This scientific knowledge generated can be used for restoration programmes and conservation practices for mangrove ecosystems in future.

Chapter 3 provides information on biomass stock of mangroves from selected three mangrove ecosystems of Cochin. The biomass of mangrove trees was estimated using wood density measurement of each mangrove species in different DBH (diameter at breast height) class. It provided the first data base for the wood density of mangroves in Kerala and first data base for many mangrove species in India. Among the mangrove trees in the study area, *Rhizophora apiculata* and *Rhizophora mucronata* were the densest mangrove species (0.88, 0.81g/cm^3). The low, dense mangrove trees was *Sonneratia*

caseolaris (0.41 g/cm^3). The above ground biomass of mangrove trees obtained through different common allometric equations revealed that diameter based common allometric equations (Chave et al., 2005 and Komiyama et al., 2005) were suited for the present study. Among the diameter based equation, Chave et al., 2005 was best suited. Above ground biomass was highest in St.3, Mangalavanam and lowest biomass stock were observed in St.2. *A.officinalis* was having the highest above ground biomass, followed by *S.caseolaris* and *E.agallocha* in the study area. *A. officinalis* contributed around 66.02 % of total AGB of mangrove trees in the study area followed by 16.28 % by *S.caseolaris*, and all the other mangroves contributed negligibly to the total AGB. The average total above ground biomass of Cochin mangroves was comparatively higher (381.50 ± 232.04 t ha^{-1}, according to Eq.1) compared to many global estimates and the total below ground biomass was 240.45 ± 152.60 t ha^{-1}. Therefore from the present study, the estimated average mangrove biomass stock of Cochin mangroves was 621.95 t ha^{-1}. The results of Eq.1 was used for carbon stock assessment for Cochin mangroves, as this equation was best suited for the structural attributes of Cochin mangroves. The average carbon stock as biomass of Cochin mangroves was estimated to be 265.45 ± 163.94 t C ha^{-1}. This stock was higher compared to Sundarban mangroves and lower than African mangroves.

Chapter 4 represents the results on litterfall dynamics contributing to Net Primary Productivity (NPP_L) and phenology in three selected mixed mangrove habitats in Cochin estuarine system, south-west coast of India. The annual litterfall and its contribution to NPP were high in the study area and was comparable with riverine type and the lower latitudinal mangrove forests in the world. The mean annual litterfall production in Cochin mangroves was 16.57 ± 6.58 t ha^{-1} y^{-1} in which leaves (53.90 %) contributed more, followed by

flowers, propagules (28.66 %) and twigs (17.44 %). The spatial variability in litterfall recorded highest in lower latitudinal mangrove habitat (2413.36 ± 873.72 in St.1, 1295.65 ± 401.09 in St.2, 1263.28 ± 255.28 g DW $m^{-2}y^{-1}$ in St.3). Site differences in litterfall production were statistically significant for total litterfall and for litter components between the three mangrove habitats. Litter components and total litterfall showed significant seasonality. Highest litterfall was recorded in the pre-monsoon period followed by post-monsoon and the least in monsoon period. The temporal trend of litterfall was explained through rainfall and mean atmospheric temperature, and a negative correlation emerged with rainfall during the period. The primary productivity through litterfall in the study area was estimated to be 7.12 ± 2.81 t C ha^{-1} y^{-1}. This litter productivity will act as the major source of carbon input to the mangrove ecosystem and surrounding coastal ecosystems and in turn, reflected in NPP. The results of the study and other reports confirmed the role of species biomass, environmental and geographical conditions play a major role in determining the litterfall production rate.This study will thus contribute to global litterfall estimates and NPP estimation studies and in turn, carbon export and carbon sequestration studies in mangrove ecosystems and adjacent coastal wetlands. The potentiality for carbon sequestration of Cochin mangroves in terms of litterfall could be understood from the study. However, the ultimate fate of litterfall determines whether the mangrove ecosystem act as source or sink of carbon.

Chapter 5 elaborates on the role of sesarmid crabs in carbon cycling in mangrove ecosystems through field and experimental studies. As a part of this study, a new species of sesarmid crab, *Pseudosesarma glabrum* was discovered during the crab density assessment. A new record of sesarmid crab to India (*Parasesarma bengalense*) was also a major finding from this study, that has

helped to resolve many taxonomic ambiguities in the identification of mangrove crabs. The experimental crab selected was identified based on morpho-taxonomy and molecular methods as *Parasesarma plicatum*. The crab density was high in St.1 and St.3, and very low crab density was observed in St.2. The results of gut content analysis of *Parasesarma plicatum* indicated that it prefers mangrove litter (more than 75 %) in the field and there by indicates its role in nutrient cycling. The feeding experiments with different species and with different state of leaves revealed that senescent partially degraded brown leaves were preferred by the crabs since it is having less tannin content (present study) compared to green and yellow leaves and which is also rich in microbes (from the literature). The ingestion egestion assay of *Parasesarma plicatum* revealed that it assimilates an average of 65.75 ± 10.30 % of mangrove litter. The assimilated carbon (80.04 ±9.8 %) and nitrogen (72.51 ± 31.2) was slightly high for *Parasesarma plicatum* compared to other sesarmid crabs. Many studies revealed that the C: N ratio determines the palatability of mangrove leaves. But this study revealed that more than its nutritional value, crabs preferred leaves with less inhibiting factors like tannin. The salinity is a major factor for decreasing the tannin content in senescent leaves. The mangrove forest having species of high carbon assimilation efficiency will be helping in carbon storage majorly through crab biomass and the mangrove species having low assimilation efficiency (*A. marina*) will bring the carbon to the ecosystem majorly through faeces. The analysis of carbon and nitrogen variants in the experimental water indicates that handling of leaves by the crab also helps in the export of nutrients to adjacent water bodies. There was significant variation in carbon and nitrogen fractionation among species and *Avicennia officinalis* species that showed high DOC and POC compared to other species. Thus the handling, fragmentation and burial of litter by crabs was helping in the better

decomposition of litter and retaining of litter in the ecosystem and there by helping in carbon nutrient cycling.

The flux of carbon in different forms through the water body, and the source characterisation of carbon in mangrove intertidal water and also its probability of export to adjacent Cochin estuary is elaborated in Chapter 6.The high concentration of carbon content was reported from the study compared to many literatures. The very shallow nature of the intertidal water inside the mangrove habitat in the study area, which facilitates mixing of sediment and organic matter (mainly mangrove litter) with the water column resulted this high carbon concentration. The stable isotope analysis of carbon and nitrogen ($\delta^{13}C$, $\delta^{15}N$) revealed that the source of POM in mangrove tidal water is mangrove origin and was not phytoplankton origin. The study has also revealed that there is a probability for export of this mangrove-derived organic matter to adjacent coastal waters mainly as DOC (dissolved organic carbon) or DIC (dissolved inorganic carbon) rather than POM (particulate organic matter). The tidal cycle based stable isotope study in the Cochin estuary, including two sites adjacent to the mangrove patches revealed that the estuary is mainly depending on phytoplankton-derived organic matter. The depleted mangrove areas in and around the Cochin estuary actually declined the contribution of nutrients from mangroves to the estuary. However, the stable isotope study revealed that there is considerable export of organic carbon from the Mangalavanam Bird sanctuary to the estuary during the tidal cycle. However, the study revealed that Cochin estuary receives organic carbon only in few kilometres distant from mangroves since the distant stations in the Cochin estuary from the mangrove station did not show marine POM origin in the sample. Further detailed study is required to confirm the source of organic carbon by analysing the $\delta^{13}C$ from all the possible source materials in that area

by applying suitable mixing models. There may be chances for the mineralisation of mangrove-derived organic carbon and getting exported to the estuary as DIC. Therefore, in future, $\delta^{13}C$ of DIC together with groundwater discharge studies are required in the field of export studies to estimate the fate of missing mangrove productivity.

In Chapter 7, the soil carbon stock was assessed from three selected mangrove stations of Cochin mangroves. The stock assessment revealed that there was a significant variation in soil carbon stock among the selected mangrove habitats. The total carbon and organic carbon was comparatively very low in St.2 and high in the other two stations. The diversity of mangrove plants and corresponding litterfall influenced the sediment carbon stock. The variation in sediment texture among the stations also limits soil carbon stock. St.1 was silt and clay dominated site and which helps in retaining the organic matter within the substratum. However, it is evident from the study that another major biotic component, crabs also controlled the carbon stock in the sediment. The low carbon stock in St.2 could be related to low crab density and low crab burrowing activity. Thus the presence and absence of crabs in mangrove ecosystem makes a big difference in carbon density in a mangrove ecosystem. The stable isotope study also confirmed that carbon source in our mangrove ecosystems is mangrove litter origin and not by marine particulate organic carbon. Even though Cochin mangroves are small patches, the sediment carbon pool or sediment carbon density was comparable with world literature.

Chapter 8, estimated the total ecosystem carbon stock of Cochin mangroves and also estimated sediment carbon sequestration potential through burial mechanism in three mangrove habitats of Cochin. The burial estimates showed high rate in St.1 followed by St.3. Low burial rate was estimated in St.2. The estimated mean total carbon burial rate in St.1 was 10.41 ± 2.50t C

$ha^{-1}yr^{-1}$ (1041.43 ± 250.26 g C $m^{-2}yr^{-1}$), and the total carbon burial rate was very low in St.2 and was 0.57 ± 0.24 t C $ha^{-1}yr^{-1}$ (56.59 ± 23.84 g C $m^{-2}yr^{-1}$). The total carbon burial rate in St.3 was 2.95 ± 0.79 t C $ha^{-1}yr^{-1}$(294.85 ± 79.00 g C $m^{-2}yr^{-1}$). Thus it could be seen that above 80% of the net primary productivity of mangroves was stored in the sediment pool through sediment burial mechanism in St.1. Thus the sediment pool of that mangrove habitat act as an excellent carbon sink. The sediment texture, topography and biological pump through mangrove crabs act as the relevant reasons for this high burial rate in St.1. In St.2, only 7.23 % of NPP_L (net primary productivity through litterfall) was buried in the sediment. A major portion of the fixed carbon in St.2 may be emitted back to the atmosphere as green house gases or may export to adjacent water bodies, due to the conversion of this mangrove habitat to aquaculture farm and may be acting as a source of carbon. In St.3, 35.73% of NPP_L was buried in the sediment indicating a good carbon sink and rest of the primary productivity may be exported to adjacent Cochin estuary. The average (median) total carbon burial rate in mangroves of Cochin was estimated as 2.95 t C ha^{-1} yr^{-1}, and the organic carbon burial rate was 1.93± 0.75 t C $ha^{-1}yr^{-1}$.

The highest ecosystem carbon pool was observed in St.3 (572.43 t C ha^{-1}) followed by St.1 (280.46 t C ha^{-1}), and the lowest was in St.2 (184.52 t C ha^{-1}). Total ecosystem carbon pool of the Cochin mangroves was estimated at 345.80 ± 202.04 t C ha^{-1}. The above ground biomass contributed more to ecosystem carbon stock than soil pool and was 171.68 ± 104.42 t C $ha^{-1.}$ The belowground biomass was 93.78 ± 59.52 t C $ha^{-1,}$ and soil carbon pool was 73.22 ± 39.40tC $ha^{-1,}$ and litterfall carbon as dead biomass was 7.12 ± 2.81 t C ha^{-1}. The CO_2 e of ecosystem carbon stock of Cochin mangroves was very high (521759.31t CO_2 e). It indicated that even though the Cochin mangroves are in degrading

stage, with patchy distribution, it is capturing and storing a substantial amount of atmospheric CO_2 in its biomass and also in the soil for a long period. Disturbance or destruction of the blue carbon habitats will trigger the emission of this stored carbon to the atmosphere and accelerate global warming. On the other hand, conservation and restoration of these carbon reservoirs will remove a significant amount of CO_2 and will help in mitigating climate change. A pictorial representation in Fig.9.1 depicted the overall summary of this phD thesis.

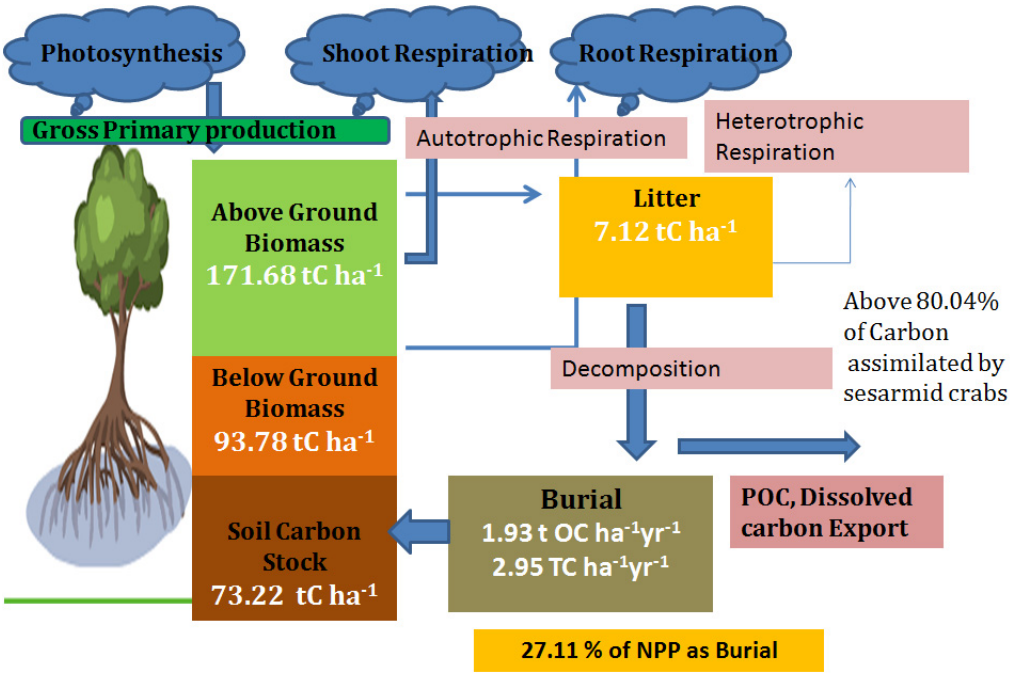

Figure 9.1 Pictorial summary of the study

Based on the findings from the PhD work, some recommendations area put forth for sustainable management of mangroves and reducing CO_2 emissions for a better future.

- The study observed that even though Cochin mangroves are in degraded stage, due to various anthropogenic activities, the remaining plants

posess good structural development. The present study documented the structural attributes of each mangrove species in Cochin and the preferred habitat for each mangrove species based on the structural characters and abiotic preferences. This scientific data from the study could be used in any future management and restoration programmes for getting best results in rejuvenating the depleting mangrove habitats elsewhere.

- In this threatened condition also, Cochin mangrove habitats act as an excellent reservoir of carbon or it act as a sink of carbon in its biomass stock and also in its sediment stock. The remaining carbon stock of Cochin mangroves in aboveground and below ground biomass of mangroves in the present study was comaparable with global mangroves. Therefore, the biomass and soil carbon stock should be balanced or maintained. Disturbance or degradation of this carbon stock will exaborate emission of stored CO_2 as green house gases to the atmosphere. Therefore, managing the carbon stock of mangroves should be the vital action of today's need. This Ph.D work also suggests the need for creating protected zones and even artificial habitats for maintaining the carbon stock by enhancing the plant density throughprogrammes like 'Bring back the native plants'. The major hindrance in mangrove conservation is that a significant portion of Kerala mangroves are under private ownership. Therefore Government departments are unable to take any serious action on mangrove conservation and long term management. However, NGO's together with industries can create artificial habitats or even manage private owned mangrove habitats for effective conservation. The 'carbon neutrality' of such coastal

environment, should be possible only by diversified management strategies.

- The study revealed that conversion of mangroves to aquaculture farms might also cause low storage of carbon in the sediment pool and may also act as a source of carbon by CO_2 and methane emission due to the disturbance in the bottom substratum. Global studies have also revealed the threat of conversion of mangrove habitats to aquaculture farms, is a major reason for global mangrove loss. Therefore, proper legislation should be enacted to stop the conversion of mangrove habitat to aquaculture farms. If aquaculture farming is necessary, legislation should be allowed only by following sustainable practices without disturbing the nearby mangrove habitats. The Indian laws such as The Forest conservation act, 1980, The wild life protection act, 1972 and Coastal Regulation Zone norms 2019 should be strengthened well for the conservation of mangroves. Therefore, the study recommends that "a separate entity in the laws" should be given for the mangrove forest as these forests are mostly seen in coastal cities and the mangrove forest cover is very small compared to the area to be declared as a forest in the Indian laws.
- Mangrove zones are hot spots of biodiversity, which are still under explored, that has crucial role in carbon structuring through the biological pump. So new species and new records of crabs from these muddy environment as outlined in the present study is important in supporting the biodiversity of the habitat. The study also highlighted the role of biotic component, especially, crabs in regulating the carbon sequestration potential of each mangrove habitat.'Crab density enhancement programmes' and more crab taxonomic studies should be encouraged in

future for improving the soil carbon stock and also for increasing the long term storage of carbon through burial in mangrove habitats. Therefore proper legislation should be done for the conservation of the key-stone species and 'carbon regulators of the ecosystem; like crabs and several other organisms from the mangrove ecosystem. The CRZ (Coastal Regulation Zone) rule 2019 may also trigger the destruction of more mangrove habitats in the country. So, the CRZ norms should also take into account the value of the prized biodiversity resources and their role in carbon stock management in the mangroves.

- The study revealed that a major portion of mangrove primary productivity may be exported to adjacent estuaries and may be buried in the deep oceanic sink, which can serve as recalcitrant carbon stock. Detailed scientific studies to quantify the export of mangrove-derived carbon through submarine groundwater discharge (SGD) together with green house gas emission studies should be implemented in future.
- Carbon stock and long term burial of carbon in the sediment pool in mangrove environment can remove a substantial amount of CO_2 from the atmosphere mitigating global warming and climate change related problems. The estimates showed that at the global level, mangroves are able to buffer only 0.42 % of fossil fuel emissions. However, nowadays, blue carbon strategies for climate change mitigation practices are most effective at the national scale. The countries with long coastal extent can efficiently buffer the fossil fuel emission through mangrove conservation and restoration. Therefore, as a coastal city, and a major vulnerable area for flood and sea level rise, the Cochin city should adopt mangrove carbon sequestration as a major 'climate change mitigation programme' in the future in accordance with the Paris Agreement.

- The Ph.D thesis also suggests the mangrove conservation by adopting carbon credits through the carbon stock assessment in the entire Kerala coastal belt. It also recommends a detailed study for the preparation of scientific carbon stock map for entire Kerala for accounting the carbon credits and this data should project at Policy level in order to get the benefits of REDD+ for developing countries for the sustainable management of mangroves.

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Chapter 10

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APPENDIX

Table 2.1 Structural characters of mangroves in St.1

Species	Density (m2 ha^{-1})	Relative density (%)	Frequency (%)	Abundance (no.)	Relative frequency (%)	Basal area(m2 ha^{-1})	Relative basal area (%)	IVI	RIVI
A. Ilicifolius	0.168	15.01	40.0	11	9.52	0.73	0.97	25.50	8.501
A. officinalis	0.208	35.58	100.0	5	23.81	26.50	35.07	94.47	31.488
B. gymnorrhiza	0.048	5.30	40.0	3	9.52	1.03	1.37	16.39	5.46
R. mucronata	0.144	15.67	80.0	5	19.05	4.10	5.43	40.15	13.38
B. cylindrica	0.008	0.91	20.0	1	4.76	0.16	0.22	5.89	1.96
K. candel	0.04	4.24	40.0	3	9.52	0.92	1.21	14.98	4.99
S. caseolaris	0.088	13.42	100.0	2	23.81	39.68	52.53	89.76	29.92
R. apiculata	0.008	0.91	20.0	1.0	4.76	0.27	0.41	6.08	2.03
B. sexangula	0.024	3.31	40.0	2	9.52	0.31	0.35	13.18	4.39
A.aureum	0.024	2.73	20.0	3.00	4.76	1.02	1.35	8.84	2.95
E. agallocha	0.024	2.73	20.0	3	4.76	0.82	1.09	8.58	2.86

Table 2.2 Structural characters of mangroves in St.2

Species	Density (m2 ha^{-1})	Relative density (%)	Frequency (%)	Abundance (no.)	Relative frequency(%)	Basal area(m2 ha^{-1})	Relative basal area (%)	IVI	RIVI
A. Ilicifolius	0.04	3.70	20.00	5.00	5.26	0.25	0.46	9.43	3.14
A.officinalis	0.11	7.78	80.00	3.50	21.05	10.35	18.87	47.70	15.90
B. gymnorrhiza	0.17	24.89	60.00	7.00	15.79	6.68	12.18	52.85	17.62
R.mucronata	0.01	0.71	20.00	1.00	5.26	0.52	0.94	6.92	2.31
B. cylindrica	0.15	14.91	60.00	6.33	15.79	5.46	9.95	40.65	13.55
A. aureum	0.06	5.16	40.00	3.50	10.53	2.79	5.09	20.78	6.93
E. agallocha	0.64	42.85	100.00	16.00	26.32	28.80	52.51	121.67	40.56

Table 2.3 Structural characters of mangroves in St.3

Species	Density (m2 ha^{-1})	Relative density (%)	Frequency (%)	Abundance (no.)	Relative frequency(%)	Basal area(m2 ha^{-1})	Relative basal area (%)	IVI	RIVI
A. Ilicifolius	0.72	42.06	60.00	30.00	16.67	1.85	1.79	60.52	20.17
A.officinalis	0.22	34.00	100.00	5.60	27.78	94.32	91.06	152.84	50.95
B. gymnorrhiza	0.02	4.87	40.00	1.00	11.11	0.30	0.29	16.27	5.42
R.mucronata	0.11	9.76	60.00	4.67	16.67	5.01	4.83	31.26	10.42
B. cylindrica	0.02	0.80	20.00	2.00	5.56	0.42	0.41	6.76	2.25
A. aureum	0.06	7.04	40.00	3.50	11.11	1.35	1.31	19.46	6.49
B.sexangula	0.02	1.83	40.00	1.00	11.11	0.33	0.32	13.26	4.42

Table 2.4 Structural characters of mangroves in St.4

Species	Density (m2 ha^{-1})	Relative density (%)	Frequency (%)	Abundance (no.)	Relative frequency(%)	Basal area(m2 ha^{-1})	Relative basal area (%)	IVI	RIVI
A. Ilicifolius	0.20	10.20	20.00	25.00	5.00	0.02	0.04	15.24	5.08
A.officinalis	0.17	15.15	100.00	4.20	25.00	4.01	9.90	50.05	16.68
R.mucronata	0.11	12.18	80.00	3.50	20.00	7.50	18.49	50.67	16.89
B. cylindrica	0.18	24.08	80.00	5.50	20.00	5.74	14.15	58.24	19.41
A. aureum	0.03	1.63	20.00	4.00	5.00	1.02	2.51	9.15	3.05
E. agallocha	0.38	36.75	100.00	12.00	25.00	22.03	54.33	116.08	38.69

Table 2.5 Structural characters of mangroves in St.5

Species	Density (m2 ha^{-1})	Relative density (%)	Frequency (%)	Abundance (no.)	Relative frequency(%)	Basal area(m2 ha^{-1})	Relative basal area (%)	IVI	RIVI
A. Ilicifolius	5.00	34.72	40.00	312.50	7.41	0.40	0.56	42.69	14.23
A.officinalis	0.10	1.89	40.00	6.00	7.41	7.67	10.86	20.16	6.72
R.mucronata	0.18	3.43	60.00	7.33	11.11	22.57	31.95	46.49	15.50
A. aureum	0.70	24.41	100.00	17.40	18.52	9.97	14.11	57.04	19.01
E. agallocha	0.64	26.68	80.00	20.00	14.81	20.11	28.47	69.96	23.32
B. gymnorrhiza	0.05	0.60	40.00	3.00	7.41	2.33	3.30	11.30	3.77
R.apiculata	0.02	0.39	20.00	3.00	3.70	0.13	0.18	4.28	1.43
S.caseolaris	0.07	4.46	60.00	3.00	11.11	5.03	7.12	22.69	7.56
K.candel	0.08	3.39	60.00	3.33	11.11	1.74	2.46	16.96	5.65
B Sexangula	0.01	0.04	20.00	1.00	3.70	0.69	0.98	4.72	1.57

Table 2.6 Structural characters of mangroves in St.6

Species	Density (m2 ha^{-1})	Relative density (%)	Frequency (%)	Abundance (no.)	Relative frequency(%)	Basal area (m2 ha^{-1})	Relative basal area (%)	IVI	RIVI
A. Ilicifolius	0.05	5.71	20.00	6.00	5.56	0.00	0.01	11.28	3.76
A.officinalis	0.10	15.42	80.00	3.25	22.22	17.47	30.49	68.13	22.71
R.mucronata	0.26	40.02	100.00	6.40	27.78	31.00	54.08	121.89	40.63
A. aureum	0.04	4.17	20.00	5.00	5.56	0.82	1.42	11.14	3.71
E. agallocha	0.21	30.01	80.00	6.50	22.22	6.20	10.81	63.05	21.02
B. gymnorrhiza	0.02	2.99	40.00	1.00	11.11	1.57	2.74	16.85	5.62
S.caseolaris	0.01	1.67	20.00	1.00	5.56	0.25	0.44	7.67	2.56

Table 2.7 Structural characters of mangroves in St.7

Species	Density (m2 ha^{-1})	Relative density (%)	Frequency (%)	Abundance (no.)	Relative frequency (%)	Basal area(m2 ha^{-1})	Relative basal area (%)	IVI	RIVI
A. Ilicifolius	1.10	29.03	40.00	68.50	12.50	3.61	6.48	48.01	16.00
A officinalis	0.09	20.00	100.00	2.20	31.25	7.03	12.64	63.89	21.30
R mucronata	0.27	46.22	100.00	6.80	31.25	41.12	73.90	151.37	50.46
E. agallocha	0.02	1.90	20.00	2.00	6.25	0.24	0.42	8.58	2.86
R apiculata	0.02	0.28	20.00	2.00	6.25	0.72	1.29	7.82	2.61
S.caseolaris	0.01	2.00	20.00	1.00	6.25	0.31	0.55	8.80	2.93
B.cylindrica	0.03	0.56	20.00	4.00	6.25	2.63	4.72	11.53	3.84

Table 2.8 Structural characters of mangroves in St.8

Species	Density	Relative density	Frequency (%)	Abundance	Relative frequency	basal area	Relative basal area	IVI	RIVI
S.alba	0.09	17.05	66.67	3.50	13.33	25.94	25.57	55.96	18.65
B. gymnorrhiza	0.08	9.74	100.00	2.00	20.00	8.90	8.77	38.52	12.84
A.officinalis	0.12	14.49	100.00	3.00	20.00	39.37	38.81	73.30	24.43
R.mucronata	0.09	10.26	66.67	3.50	13.33	6.79	6.70	30.29	10.10
Bruguiera cylindrica	0.35	43.33	100.00	8.67	20.00	20.14	19.85	83.19	27.73
A. marina	0.01	1.28	33.33	1.00	6.67	0.05	0.05	8.00	2.67
E. agallocha	0.04	3.85	33.33	3.00	6.67	0.25	0.24	10.76	3.59

Table 2.9 Environmental characters in the intertidal water and sediments of mangroves of Cochin

Station	Month	Year	Season	Ph	Eh	cond	TDS	tds	Salinity	DO	W.temp	Sed.temp	SedpH	Sed.Eh	Moist
1	1	1	1	6.70	43.00	41.10	30.90	5.56	24.10	2.20	28.00	28.00	7.66	-100.10	5.79
1	2	1	1	6.75	-33.40	33.39	31.14	5.58	16.88	2.64	30.50	31.00	6.58	-175.20	5.53
1	3	1	1	6.64	-101.80	28.57	15.08	3.88	29.04	3.54	30.00	31.00	6.74	-61.60	5.90
1	4	1	1	6.48	10.30	19.23	18.05	4.25	3.59	8.43	30.00	29.00	6.78	-118.40	5.74
1	5	1	2	6.97	95.00	1.00	0.94	0.97	1.76	12.70	28.00	27.00	6.20	-61.50	5.91
1	6	1	2	7.56	127.10	1.01	0.95	0.97	1.00	9.00	30.00	29.00	6.78	-23.30	6.00
1	7	1	2	7.51	8.20	3.91	1.96	1.40	1.80	4.94	30.00	29.00	6.49	-38.60	5.97
1	8	1	2	6.76	-12.80	1.25	0.68	0.82	1.00	6.12	29.50	26.50	5.84	-136.80	5.68
1	9	1	3	6.64	14.00	1.88	1.17	1.08	2.56	3.36	29.00	29.00	6.29	-82.00	5.85
1	10	1	3	6.70	-24.00	7.91	4.00	2.00	6.58	2.97	27.00	28.00	6.08	-171.00	5.55
1	11	1	3	6.99	8.80	35.66	26.66	5.16	15.20	2.18	25.00	26.00	6.65	-139.80	5.67
1	12	1	3	7.10	-96.20	36.02	20.09	4.48	13.00	6.51	27.50	28.00	6.38	-253.40	5.16
1	1	2	1	6.82	23.40	54.10	29.82	5.46	17.60	3.36	27.00	28.00	6.40	-191.00	5.47
1	2	2	1	7.07	-51.00	51.02	30.18	5.49	19.60	1.00	30.40	30.80	6.88	-427.40	0.00
1	3	2	1	6.98	-25.00	44.36	24.26	4.93	16.40	4.54	36.20	33.80	6.93	-223.80	5.32
1	4	2	1	7.08	-57.80	14.22	7.52	2.74	8.40	2.18	31.60	31.00	6.87	-407.40	3.04
1	5	2	2	6.82	23.60	15.83	2.50	1.58	1.60	1.79	33.20	31.20	7.09	-275.40	5.03
1	6	2	2	7.07	-120.80	1.16	0.67	0.82	0.00	4.94	25.00	26.00	7.39	-179.80	5.52
1	7	2	2	6.98	-18.33	2.58	2.13	1.46	1.00	4.94	32.00	30.00	7.47	-288.20	4.94
1	8	2	2	7.08	39.00	5.76	3.08	1.75	3.40	2.97	28.00	29.00	7.70	-407.25	3.05
1	9	2	3	7.70	17.00	20.10	9.30	3.05	5.60	1.78	27.50	26.00	8.10	-305.00	4.82
1	10	2	3	8.36	13.20	20.76	11.50	3.39	6.40	4.94	27.00	26.00	8.76	-264.80	5.10
1	11	2	3	7.56	-95.60	39.92	21.62	4.65	17.60	4.94	28.00	26.00	6.84	-273.40	5.04
1	12	2	3	7.44	-5.00	53.93	30.53	5.53	20.75	8.08	32.00	28.00	6.59	-215.00	5.36
1	1	3	1	7.10	-96.00	33.02	17.14	4.14	17.20	3.76	31.00	27.00	7.09	-289.20	4.94
1	2	3	1	7.29	13.75	29.98	14.60	3.82	8.75	1.00	28.00	29.00	7.05	-149.40	5.63
1	3	3	1	7.14	35.70	19.20	8.40	2.90	4.00	8.87	31.00	28.00	7.31	-364.60	4.16
1	4	3	1	7.22	53.40	9.91	6.00	2.45	5.20	2.18	29.00	28.00	7.09	-149.80	5.63

1	5	3	2	7.08	-41.75	4.23	2.14	1.46	1.25	4.54	30.00	30.00	7.06	-200.40	5.43
1	6	3	2	6.93	-92.80	6.37	3.35	1.83	3.40	2.97	30.00	27.00	6.87	-303.00	4.83
2	1	1	1	6.82	23.00	38.70	22.00	4.69	20.10	2.80	28.00	27.00	7.91	-87.00	5.79
2	2	1	1	6.62	-63.80	36.23	33.79	5.81	15.40	2.66	31.20	32.00	7.30	-263.90	5.01
2	3	1	1	6.79	17.00	28.74	14.38	3.79	26.86	4.55	33.00	34.00	7.06	-329.00	4.45
2	4	1	1	6.82	-13.00	15.63	14.66	3.83	3.14	9.15	29.00	31.00	7.01	-249.30	5.11
2	5	1	2	7.31	38.40	5.51	5.17	2.27	2.60	13.60	28.30	29.00	6.87	-286.55	4.85
2	6	1	2	7.87	93.20	5.07	4.76	2.18	3.80	8.20	30.00	30.00	7.45	-314.90	4.60
2	7	1	2	7.87	5.80	7.92	3.96	1.99	3.10	9.27	30.00	27.00	7.16	-37.20	5.93
2	8	1	2	7.53	-17.40	5.45	2.88	1.70	4.35	8.08	30.00	28.00	6.98	-258.20	5.05
2	9	1	3	6.85	5.40	3.01	1.96	1.40	4.03	6.51	29.00	29.00	6.99	-123.60	5.67
2	10	1	3	6.95	8.20	16.50	9.30	3.05	13.92	1.79	26.50	27.50	6.93	-142.60	5.61
2	11	1	3	7.22	29.80	49.40	28.22	5.31	16.80	1.20	24.00	25.50	6.90	-189.00	5.42
2	12	1	3	7.25	-65.20	52.24	29.20	5.40	22.00	3.36	29.00	29.00	6.68	-133.00	5.64
2	1	2	1	6.72	14.00	55.20	24.30	4.93	17.75	2.57	27.00	29.00	6.99	-278.60	4.91
2	2	2	1	7.25	-41.20	64.18	29.24	5.41	24.80	3.76	32.90	30.90	7.15	-253.20	5.08
2	3	2	1	7.57	28.20	48.32	27.52	5.25	20.00	8.87	35.00	34.40	7.23	-207.00	5.33
2	4	2	1	7.26	18.40	18.44	10.38	3.22	7.40	2.18	32.20	32.10	6.99	-318.00	4.57
2	5	2	2	7.29	15.20	8.65	7.23	2.69	5.00	4.54	30.40	31.40	7.19	-248.60	5.11
2	6	2	2	7.40	-102.60	2.82	1.60	1.27	0.50	6.90	28.00	26.00	7.51	-199.50	5.37
2	7	2	2	8.12	-48.80	7.28	5.54	2.35	2.40	12.81	32.00	30.00	7.51	-406.50	2.07
2	8	2	2	8.20	20.80	5.92	3.04	1.74	3.60	3.36	28.50	30.00	7.86	-413.40	0.00
2	9	2	3	8.10	13.00	15.50	10.20	3.19	5.90	2.50	27.00	25.00	8.50	-214.00	5.30
2	10	2	3	8.50	21.60	16.08	13.33	3.65	5.60	2.18	27.00	25.50	9.12	-182.60	5.45
2	11	2	3	6.81	-25.40	38.56	22.10	4.70	17.00	4.15	26.00	26.00	7.38	-184.00	5.44
2	12	2	3	7.31	52.00	60.40	35.06	5.92	20.60	1.79	25.00	25.00	6.96	-338.00	4.34
2	1	3	1	7.56	-124.80	32.08	17.30	4.16	16.60	6.90	29.00	29.00	7.13	-259.60	5.04
2	2	3	1	7.46	30.80	30.04	15.80	3.97	7.40	1.20	29.00	29.50	7.27	-168.20	5.51
2	3	3	1	7.71	45.60	18.52	9.35	3.06	5.40	10.45	30.00	29.00	7.42	-204.60	5.35
2	4	3	1	8.05	45.20	23.20	11.02	3.32	4.80	2.18	27.00	29.00	6.94	-251.00	5.10
2	5	3	2	7.23	-4.00	6.11	3.19	1.79	2.60	12.81	31.00	29.00	6.68	-156.20	5.55
2	6	3	2	8.30	-78.75	13.10	11.64	3.41	6.20	12.81	28.00	28.00	7.10	-187.80	5.42
3	1	1	2	7.27	10.00	12.38	6.20	2.49	3.98	4.94	28.00	27.00	6.52	-102.00	5.65
3	2	1	2	7.14	5.50	11.10	4.50	2.12	4.20	4.50	28.00	28.00	6.64	-135.20	5.53
3	3	1	3	7.01	4.25	4.95	2.65	1.63	5.02	8.08	29.50	27.50	7.05	-232.40	5.04
3	4	1	3	6.92	-50.40	20.02	11.14	3.34	16.74	2.97	27.00	28.00	6.16	-152.40	5.46

3	5	1	3	7.25	22.80	51.74	30.28	5.50	18.60	2.57	26.00	27.00	6.68	-130.40	5.55
3	6	1	3	7.10	-35.00	50.20	25.50	5.05	19.10	1.00	28.00	28.00	6.48	-74.80	5.74
3	1	2	1	6.73	10.75	62.40	31.08	5.57	20.75	5.72	30.00	28.00	6.49	-128.60	5.55
3	2	2	1	7.48	19.75	50.55	27.27	5.22	19.75	4.94	34.30	33.60	6.45	-52.20	5.81
3	3	2	1	7.16	40.00	44.84	23.02	4.80	17.20	2.18	32.80	32.10	6.64	-43.20	5.84
3	4	2	1	7.27	-130.20	39.94	20.82	4.56	16.20	1.00	31.80	30.90	6.18	-386.00	0.00
3	5	2	2	6.82	41.80	9.90	5.87	2.42	4.40	2.18	28.70	30.40	7.22	-91.60	5.69
3	6	2	2	7.51	-93.40	0.81	0.50	0.70	0.00	4.54	25.00	25.00	7.44	-279.60	4.68
3	7	2	2	8.10	-57.60	4.40	2.40	1.55	1.20	4.15	29.00	28.00	7.52	-273.20	4.73
3	8	2	2	8.35	10.00	8.90	4.13	2.03	2.00	3.36	28.00	30.00	8.07	-201.50	5.22
3	9	2	3	8.20	20.00	35.20	12.40	3.52	6.00	3.20	27.00	27.00	8.60	-150.30	5.47
3	10	2	3	8.55	24.00	37.40	21.90	4.68	10.50	1.79	27.90	26.00	8.41	-108.25	5.63
3	11	2	3	7.22	-86.00	43.55	24.45	4.94	22.50	2.57	27.00	26.00	7.10	-175.80	5.35
3	12	2	3	7.31	-28.00	59.66	34.30	5.86	21.75	4.94	26.00	25.00	6.47	-111.75	5.62
3	1	3	1	7.36	-60.60	26.64	13.80	3.71	10.60	1.00	31.00	28.00	6.80	-148.00	5.48
3	2	3	1	7.27	30.00	36.25	20.50	4.53	9.00	1.00	26.00	27.00	6.81	-145.00	5.49
3	3	3	1	6.94	51.80	18.42	9.86	3.14	6.20	4.94	28.00	28.00	6.81	-131.00	5.55
3	4	3	1	7.10	51.50	11.45	6.43	2.54	3.75	1.00	27.00	29.00	6.73	-149.60	5.47
3	5	3	2	7.02	48.00	17.47	10.21	3.20	4.50	1.00	31.00	30.00	6.95	-365.75	3.06
3	6	3	2	6.51	-46.00	12.63	7.30	2.70	6.40	1.00	28.00	27.00	6.86	-166.40	5.40

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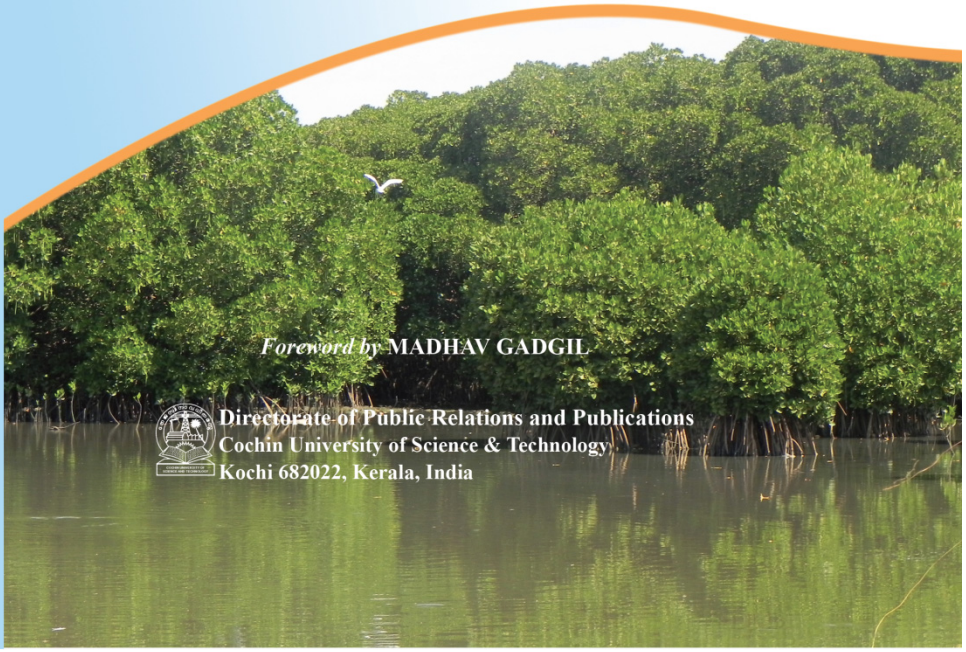
MANUAL ON MANGROVES

S. Bijoy Nandan



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MANUAL ON MANGROVES

APPENDIX

Table 2.1 Structural characters of mangroves in St.1

Species	Density (m2 ha^{-1})	Relative density (%)	Frequency (%)	Abundance (no.)	Relative frequency (%)	Basal area(m2 ha^{-1})	Relative basal area (%)	IVI	RIVI
A. Ilicifolius	0.168	15.01	40.0	11	9.52	0.73	0.97	25.50	8.501
A. officinalis	0.208	35.58	100.0	5	23.81	26.50	35.07	94.47	31.488
B. gymnorrhiza	0.048	5.30	40.0	3	9.52	1.03	1.37	16.39	5.46
R. mucronata	0.144	15.67	80.0	5	19.05	4.10	5.43	40.15	13.38
B. cylindrica	0.008	0.91	20.0	1	4.76	0.16	0.22	5.89	1.96
K. candel	0.04	4.24	40.0	3	9.52	0.92	1.21	14.98	4.99
S. caseolaris	0.088	13.42	100.0	2	23.81	39.68	52.53	89.76	29.92
R. apiculata	0.008	0.91	20.0	1.0	4.76	0.27	0.41	6.08	2.03
B. sexangula	0.024	3.31	40.0	2	9.52	0.31	0.35	13.18	4.39
A.aureum	0.024	2.73	20.0	3.00	4.76	1.02	1.35	8.84	2.95
E. agallocha	0.024	2.73	20.0	3	4.76	0.82	1.09	8.58	2.86

Table 2.2 Structural characters of mangroves in St.2

Species	Density (m2 ha^{-1})	Relative density (%)	Frequency (%)	Abundance (no.)	Relative frequency(%)	Basal area(m2 ha^{-1})	Relative basal area (%)	IVI	RIVI
A. Ilicifolius	0.04	3.70	20.00	5.00	5.26	0.25	0.46	9.43	3.14
A.officinalis	0.11	7.78	80.00	3.50	21.05	10.35	18.87	47.70	15.90
B. gymnorrhiza	0.17	24.89	60.00	7.00	15.79	6.68	12.18	52.85	17.62
R.mucronata	0.01	0.71	20.00	1.00	5.26	0.52	0.94	6.92	2.31
B. cylindrica	0.15	14.91	60.00	6.33	15.79	5.46	9.95	40.65	13.55
A. aureum	0.06	5.16	40.00	3.50	10.53	2.79	5.09	20.78	6.93
E. agallocha	0.64	42.85	100.00	16.00	26.32	28.80	52.51	121.67	40.56

Table 2.3 Structural characters of mangroves in St.3

Species	Density (m2 ha^{-1})	Relative density (%)	Frequency (%)	Abundance (no.)	Relative frequency(%)	Basal area(m2 ha^{-1})	Relative basal area (%)	IVI	RIVI
A. Ilicifolius	0.72	42.06	60.00	30.00	16.67	1.85	1.79	60.52	20.17
A.officinalis	0.22	34.00	100.00	5.60	27.78	94.32	91.06	152.84	50.95
B. gymnorrhiza	0.02	4.87	40.00	1.00	11.11	0.30	0.29	16.27	5.42
R.mucronata	0.11	9.76	60.00	4.67	16.67	5.01	4.83	31.26	10.42
B. cylindrica	0.02	0.80	20.00	2.00	5.56	0.42	0.41	6.76	2.25
A. aureum	0.06	7.04	40.00	3.50	11.11	1.35	1.31	19.46	6.49
B.sexangula	0.02	1.83	40.00	1.00	11.11	0.33	0.32	13.26	4.42

Table 2.4 Structural characters of mangroves in St.4

Species	Density (m2 ha^{-1})	Relative density (%)	Frequency (%)	Abundance (no.)	Relative frequency(%)	Basal area(m2 ha^{-1})	Relative basal area (%)	IVI	RIVI
A. Ilicifolius	0.20	10.20	20.00	25.00	5.00	0.02	0.04	15.24	5.08
A.officinalis	0.17	15.15	100.00	4.20	25.00	4.01	9.90	50.05	16.68
R.mucronata	0.11	12.18	80.00	3.50	20.00	7.50	18.49	50.67	16.89
B. cylindrica	0.18	24.08	80.00	5.50	20.00	5.74	14.15	58.24	19.41
A. aureum	0.03	1.63	20.00	4.00	5.00	1.02	2.51	9.15	3.05
E. agallocha	0.38	36.75	100.00	12.00	25.00	22.03	54.33	116.08	38.69

Table 2.5 Structural characters of mangroves in St.5

Species	Density (m2 ha^{-1})	Relative density (%)	Frequency (%)	Abundance (no.)	Relative frequency(%)	Basal area(m2 ha^{-1})	Relative basal area (%)	IVI	RIVI
A. Ilicifolius	5.00	34.72	40.00	312.50	7.41	0.40	0.56	42.69	14.23
A.officinalis	0.10	1.89	40.00	6.00	7.41	7.67	10.86	20.16	6.72
R.mucronata	0.18	3.43	60.00	7.33	11.11	22.57	31.95	46.49	15.50
A. aureum	0.70	24.41	100.00	17.40	18.52	9.97	14.11	57.04	19.01
E. agallocha	0.64	26.68	80.00	20.00	14.81	20.11	28.47	69.96	23.32
B. gymnorrhiza	0.05	0.60	40.00	3.00	7.41	2.33	3.30	11.30	3.77
R.apiculata	0.02	0.39	20.00	3.00	3.70	0.13	0.18	4.28	1.43
S.caseolaris	0.07	4.46	60.00	3.00	11.11	5.03	7.12	22.69	7.56
K.candel	0.08	3.39	60.00	3.33	11.11	1.74	2.46	16.96	5.65
B Sexangula	0.01	0.04	20.00	1.00	3.70	0.69	0.98	4.72	1.57

Table 2.6 Structural characters of mangroves in St.6

Species	Density (m2 ha^{-1})	Relative density (%)	Frequency (%)	Abundance (no.)	Relative frequency(%)	Basal area (m2 ha^{-1})	Relative basal area (%)	IVI	RIVI
A. Ilicifolius	0.05	5.71	20.00	6.00	5.56	0.00	0.01	11.28	3.76
A.officinalis	0.10	15.42	80.00	3.25	22.22	17.47	30.49	68.13	22.71
R.mucronata	0.26	40.02	100.00	6.40	27.78	31.00	54.08	121.89	40.63
A. aureum	0.04	4.17	20.00	5.00	5.56	0.82	1.42	11.14	3.71
E. agallocha	0.21	30.01	80.00	6.50	22.22	6.20	10.81	63.05	21.02
B. gymnorrhiza	0.02	2.99	40.00	1.00	11.11	1.57	2.74	16.85	5.62
S.caseolaris	0.01	1.67	20.00	1.00	5.56	0.25	0.44	7.67	2.56

Table 2.7 Structural characters of mangroves in St.7

Species	Density (m2 ha^{-1})	Relative density (%)	Frequency (%)	Abundance (no.)	Relative frequency (%)	Basal area(m2 ha^{-1})	Relative basal area (%)	IVI	RIVI
A. Ilicifolius	1.10	29.03	40.00	68.50	12.50	3.61	6.48	48.01	16.00
A officinalis	0.09	20.00	100.00	2.20	31.25	7.03	12.64	63.89	21.30
R mucronata	0.27	46.22	100.00	6.80	31.25	41.12	73.90	151.37	50.46
E. agallocha	0.02	1.90	20.00	2.00	6.25	0.24	0.42	8.58	2.86
R apiculata	0.02	0.28	20.00	2.00	6.25	0.72	1.29	7.82	2.61
S.caseolaris	0.01	2.00	20.00	1.00	6.25	0.31	0.55	8.80	2.93
B.cylindrica	0.03	0.56	20.00	4.00	6.25	2.63	4.72	11.53	3.84

Table 2.8 Structural characters of mangroves in St.8

Species	Density	Relative density	Frequency (%)	Abundance	Relative frequency	basal area	Relative basal area	IVI	RIVI
S.alba	0.09	17.05	66.67	3.50	13.33	25.94	25.57	55.96	18.65
B. gymnorrhiza	0.08	9.74	100.00	2.00	20.00	8.90	8.77	38.52	12.84
A.officinalis	0.12	14.49	100.00	3.00	20.00	39.37	38.81	73.30	24.43
R.mucronata	0.09	10.26	66.67	3.50	13.33	6.79	6.70	30.29	10.10
Bruguiera cylindrica	0.35	43.33	100.00	8.67	20.00	20.14	19.85	83.19	27.73
A. marina	0.01	1.28	33.33	1.00	6.67	0.05	0.05	8.00	2.67
E. agallocha	0.04	3.85	33.33	3.00	6.67	0.25	0.24	10.76	3.59

Table 2.9 Environmental characters in the intertidal water and sediments of mangroves of Cochin

Station	Month	Year	Season	Ph	Eh	cond	TDS	tds	Salinity	DO	W.temp	Sed.temp	SedpH	Sed.Eh	Moist
1	1	1	1	6.70	43.00	41.10	30.90	5.56	24.10	2.20	28.00	28.00	7.66	-100.10	5.79
1	2	1	1	6.75	-33.40	33.39	31.14	5.58	16.88	2.64	30.50	31.00	6.58	-175.20	5.53
1	3	1	1	6.64	-101.80	28.57	15.08	3.88	29.04	3.54	30.00	31.00	6.74	-61.60	5.90
1	4	1	1	6.48	10.30	19.23	18.05	4.25	3.59	8.43	30.00	29.00	6.78	-118.40	5.74
1	5	1	2	6.97	95.00	1.00	0.94	0.97	1.76	12.70	28.00	27.00	6.20	-61.50	5.91
1	6	1	2	7.56	127.10	1.01	0.95	0.97	1.00	9.00	30.00	29.00	6.78	-23.30	6.00
1	7	1	2	7.51	8.20	3.91	1.96	1.40	1.80	4.94	30.00	29.00	6.49	-38.60	5.97
1	8	1	2	6.76	-12.80	1.25	0.68	0.82	1.00	6.12	29.50	26.50	5.84	-136.80	5.68
1	9	1	3	6.64	14.00	1.88	1.17	1.08	2.56	3.36	29.00	29.00	6.29	-82.00	5.85
1	10	1	3	6.70	-24.00	7.91	4.00	2.00	6.58	2.97	27.00	28.00	6.08	-171.00	5.55
1	11	1	3	6.99	8.80	35.66	26.66	5.16	15.20	2.18	25.00	26.00	6.65	-139.80	5.67
1	12	1	3	7.10	-96.20	36.02	20.09	4.48	13.00	6.51	27.50	28.00	6.38	-253.40	5.16
1	1	2	1	6.82	23.40	54.10	29.82	5.46	17.60	3.36	27.00	28.00	6.40	-191.00	5.47
1	2	2	1	7.07	-51.00	51.02	30.18	5.49	19.60	1.00	30.40	30.80	6.88	-427.40	0.00
1	3	2	1	6.98	-25.00	44.36	24.26	4.93	16.40	4.54	36.20	33.80	6.93	-223.80	5.32
1	4	2	1	7.08	-57.80	14.22	7.52	2.74	8.40	2.18	31.60	31.00	6.87	-407.40	3.04
1	5	2	2	6.82	23.60	15.83	2.50	1.58	1.60	1.79	33.20	31.20	7.09	-275.40	5.03
1	6	2	2	7.07	-120.80	1.16	0.67	0.82	0.00	4.94	25.00	26.00	7.39	-179.80	5.52
1	7	2	2	6.98	-18.33	2.58	2.13	1.46	1.00	4.94	32.00	30.00	7.47	-288.20	4.94
1	8	2	2	7.08	39.00	5.76	3.08	1.75	3.40	2.97	28.00	29.00	7.70	-407.25	3.05
1	9	2	3	7.70	17.00	20.10	9.30	3.05	5.60	1.78	27.50	26.00	8.10	-305.00	4.82
1	10	2	3	8.36	13.20	20.76	11.50	3.39	6.40	4.94	27.00	26.00	8.76	-264.80	5.10
1	11	2	3	7.56	-95.60	39.92	21.62	4.65	17.60	4.94	28.00	26.00	6.84	-273.40	5.04
1	12	2	3	7.44	-5.00	53.93	30.53	5.53	20.75	8.08	32.00	28.00	6.59	-215.00	5.36
1	1	3	1	7.10	-96.00	33.02	17.14	4.14	17.20	3.76	31.00	27.00	7.09	-289.20	4.94
1	2	3	1	7.29	13.75	29.98	14.60	3.82	8.75	1.00	28.00	29.00	7.05	-149.40	5.63
1	3	3	1	7.14	35.70	19.20	8.40	2.90	4.00	8.87	31.00	28.00	7.31	-364.60	4.16
1	4	3	1	7.22	53.40	9.91	6.00	2.45	5.20	2.18	29.00	28.00	7.09	-149.80	5.63

1	5	3	2	7.08	-41.75	4.23	2.14	1.46	1.25	4.54	30.00	30.00	7.06	-200.40	5.43
1	6	3	2	6.93	-92.80	6.37	3.35	1.83	3.40	2.97	30.00	27.00	6.87	-303.00	4.83
2	1	1	1	6.82	23.00	38.70	22.00	4.69	20.10	2.80	28.00	27.00	7.91	-87.00	5.79
2	2	1	1	6.62	-63.80	36.23	33.79	5.81	15.40	2.66	31.20	32.00	7.30	-263.90	5.01
2	3	1	1	6.79	17.00	28.74	14.38	3.79	26.86	4.55	33.00	34.00	7.06	-329.00	4.45
2	4	1	1	6.82	-13.00	15.63	14.66	3.83	3.14	9.15	29.00	31.00	7.01	-249.30	5.11
2	5	1	2	7.31	38.40	5.51	5.17	2.27	2.60	13.60	28.30	29.00	6.87	-286.55	4.85
2	6	1	2	7.87	93.20	5.07	4.76	2.18	3.80	8.20	30.00	30.00	7.45	-314.90	4.60
2	7	1	2	7.87	5.80	7.92	3.96	1.99	3.10	9.27	30.00	27.00	7.16	-37.20	5.93
2	8	1	2	7.53	-17.40	5.45	2.88	1.70	4.35	8.08	30.00	28.00	6.98	-258.20	5.05
2	9	1	3	6.85	5.40	3.01	1.96	1.40	4.03	6.51	29.00	29.00	6.99	-123.60	5.67
2	10	1	3	6.95	8.20	16.50	9.30	3.05	13.92	1.79	26.50	27.50	6.93	-142.60	5.61
2	11	1	3	7.22	29.80	49.40	28.22	5.31	16.80	1.20	24.00	25.50	6.90	-189.00	5.42
2	12	1	3	7.25	-65.20	52.24	29.20	5.40	22.00	3.36	29.00	29.00	6.68	-133.00	5.64
2	1	2	1	6.72	14.00	55.20	24.30	4.93	17.75	2.57	27.00	29.00	6.99	-278.60	4.91
2	2	2	1	7.25	-41.20	64.18	29.24	5.41	24.80	3.76	32.90	30.90	7.15	-253.20	5.08
2	3	2	1	7.57	28.20	48.32	27.52	5.25	20.00	8.87	35.00	34.40	7.23	-207.00	5.33
2	4	2	1	7.26	18.40	18.44	10.38	3.22	7.40	2.18	32.20	32.10	6.99	-318.00	4.57
2	5	2	2	7.29	15.20	8.65	7.23	2.69	5.00	4.54	30.40	31.40	7.19	-248.60	5.11
2	6	2	2	7.40	-102.60	2.82	1.60	1.27	0.50	6.90	28.00	26.00	7.51	-199.50	5.37
2	7	2	2	8.12	-48.80	7.28	5.54	2.35	2.40	12.81	32.00	30.00	7.51	-406.50	2.07
2	8	2	2	8.20	20.80	5.92	3.04	1.74	3.60	3.36	28.50	30.00	7.86	-413.40	0.00
2	9	2	3	8.10	13.00	15.50	10.20	3.19	5.90	2.50	27.00	25.00	8.50	-214.00	5.30
2	10	2	3	8.50	21.60	16.08	13.33	3.65	5.60	2.18	27.00	25.50	9.12	-182.60	5.45
2	11	2	3	6.81	-25.40	38.56	22.10	4.70	17.00	4.15	26.00	26.00	7.38	-184.00	5.44
2	12	2	3	7.31	52.00	60.40	35.06	5.92	20.60	1.79	25.00	25.00	6.96	-338.00	4.34
2	1	3	1	7.56	-124.80	32.08	17.30	4.16	16.60	6.90	29.00	29.00	7.13	-259.60	5.04
2	2	3	1	7.46	30.80	30.04	15.80	3.97	7.40	1.20	29.00	29.50	7.27	-168.20	5.51
2	3	3	1	7.71	45.60	18.52	9.35	3.06	5.40	10.45	30.00	29.00	7.42	-204.60	5.35
2	4	3	1	8.05	45.20	23.20	11.02	3.32	4.80	2.18	27.00	29.00	6.94	-251.00	5.10
2	5	3	2	7.23	-4.00	6.11	3.19	1.79	2.60	12.81	31.00	29.00	6.68	-156.20	5.55
2	6	3	2	8.30	-78.75	13.10	11.64	3.41	6.20	12.81	28.00	28.00	7.10	-187.80	5.42
3	1	1	2	7.27	10.00	12.38	6.20	2.49	3.98	4.94	28.00	27.00	6.52	-102.00	5.65
3	2	1	2	7.14	5.50	11.10	4.50	2.12	4.20	4.50	28.00	28.00	6.64	-135.20	5.53
3	3	1	3	7.01	4.25	4.95	2.65	1.63	5.02	8.08	29.50	27.50	7.05	-232.40	5.04
3	4	1	3	6.92	-50.40	20.02	11.14	3.34	16.74	2.97	27.00	28.00	6.16	-152.40	5.46

3	5	1	3	7.25	22.80	51.74	30.28	5.50	18.60	2.57	26.00	27.00	6.68	-130.40	5.55
3	6	1	3	7.10	-35.00	50.20	25.50	5.05	19.10	1.00	28.00	28.00	6.48	-74.80	5.74
3	1	2	1	6.73	10.75	62.40	31.08	5.57	20.75	5.72	30.00	28.00	6.49	-128.60	5.55
3	2	2	1	7.48	19.75	50.55	27.27	5.22	19.75	4.94	34.30	33.60	6.45	-52.20	5.81
3	3	2	1	7.16	40.00	44.84	23.02	4.80	17.20	2.18	32.80	32.10	6.64	-43.20	5.84
3	4	2	1	7.27	-130.20	39.94	20.82	4.56	16.20	1.00	31.80	30.90	6.18	-386.00	0.00
3	5	2	2	6.82	41.80	9.90	5.87	2.42	4.40	2.18	28.70	30.40	7.22	-91.60	5.69
3	6	2	2	7.51	-93.40	0.81	0.50	0.70	0.00	4.54	25.00	25.00	7.44	-279.60	4.68
3	7	2	2	8.10	-57.60	4.40	2.40	1.55	1.20	4.15	29.00	28.00	7.52	-273.20	4.73
3	8	2	2	8.35	10.00	8.90	4.13	2.03	2.00	3.36	28.00	30.00	8.07	-201.50	5.22
3	9	2	3	8.20	20.00	35.20	12.40	3.52	6.00	3.20	27.00	27.00	8.60	-150.30	5.47
3	10	2	3	8.55	24.00	37.40	21.90	4.68	10.50	1.79	27.90	26.00	8.41	-108.25	5.63
3	11	2	3	7.22	-86.00	43.55	24.45	4.94	22.50	2.57	27.00	26.00	7.10	-175.80	5.35
3	12	2	3	7.31	-28.00	59.66	34.30	5.86	21.75	4.94	26.00	25.00	6.47	-111.75	5.62
3	1	3	1	7.36	-60.60	26.64	13.80	3.71	10.60	1.00	31.00	28.00	6.80	-148.00	5.48
3	2	3	1	7.27	30.00	36.25	20.50	4.53	9.00	1.00	26.00	27.00	6.81	-145.00	5.49
3	3	3	1	6.94	51.80	18.42	9.86	3.14	6.20	4.94	28.00	28.00	6.81	-131.00	5.55
3	4	3	1	7.10	51.50	11.45	6.43	2.54	3.75	1.00	27.00	29.00	6.73	-149.60	5.47
3	5	3	2	7.02	48.00	17.47	10.21	3.20	4.50	1.00	31.00	30.00	6.95	-365.75	3.06
3	6	3	2	6.51	-46.00	12.63	7.30	2.70	6.40	1.00	28.00	27.00	6.86	-166.40	5.40

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